GLOBAL PST CONSORTIUM

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NREL Transforming ENERGY

Stability With 100% Inverter-Based Resources (IBR)

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Agenda

- Previous Lesson
- Stability Definition in Systems With High Penetration of IBR
- New Stability Phenomena in Systems With IBR
- Challenges in Systems With High Penetration of IBR

Summary of Previous Lesson

- In the last lesson we studied:
- Effects of low short-circuit level (SCL) on voltage and rotor angle stability
- Effects of reduced system inertia on frequency stability
- Key control issues of IBR affecting system stability.





Previous lesson

Previous Lesson (1)

- Effects of low SCL on voltage and rotor angle stability:
  - During contingencies, weak systems with low SCLs may experience extremely depressed voltages over a wide network area, which may make the voltage recovery difficult after the fault clearance.
  - Severe voltage dips may speed up considerably the rotors of the nearby machines, which in turn may provoke their loss of synchronism.

➔ **Weak systems with low SCLs are more prone to face voltage instabilities or collapse and rotor angle instability.**

- Effects of reduced system inertia on frequency stability:
  - More frequent and larger frequency excursions following a power imbalance.

➔ **Low-inertia systems** have more risk of **activation of protection schemes** like underfrequency load shedding schemes and energy not supplied.

Previous lesson

Previous Lesson (2)

- Key control issues of IBR affecting system stability:
  - The control system of IBR comprises control loops with fast response times: phase locked loop (PLL), the inner current control loop, and the outer power/voltage control loop.

➔ Controls of IBR faster than the control systems of SG.

- The fast control loops of IBR are often among the key instability drivers in IBR-based power plants.
  - Especially in weak networks, the experience has shown that the **PLL** is among the key **instability** drivers in IBR.



Agenda

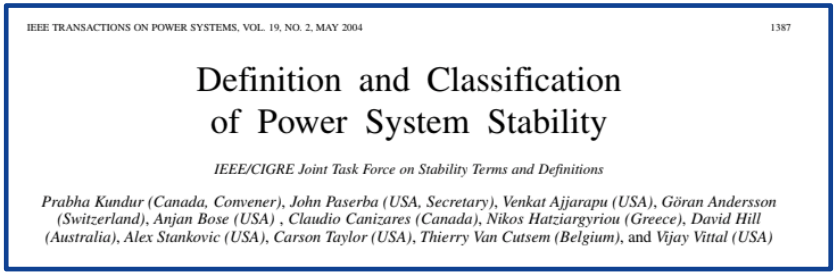
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Introduction

- In 2004, a Task Force of the Institute of Electrical and Electronics Engineers Power System Dynamic Performance (IEEE PSDP) Committee and the International Council on Large Electric Systems (CIGRE) addressed the definition and classification of stability in power systems.
  - At the time this document was published, the dynamic behavior of power systems was mostly determined by the dynamic performance of SG and their controls.

➔ **Primarily dealt with slow electromechanical phenomena, typically present in power systems dominated by synchronous machines while fast transients of the network and other fast-response devices were neglected.**

– In power systems dominated by synchronous generators (SGs), fast electromagnetic transients decay very rapidly → There is little justification for modelling their effects in stability studies.



IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 19, NO. 2, MAY 2004 1387

Definition and Classification of Power System Stability

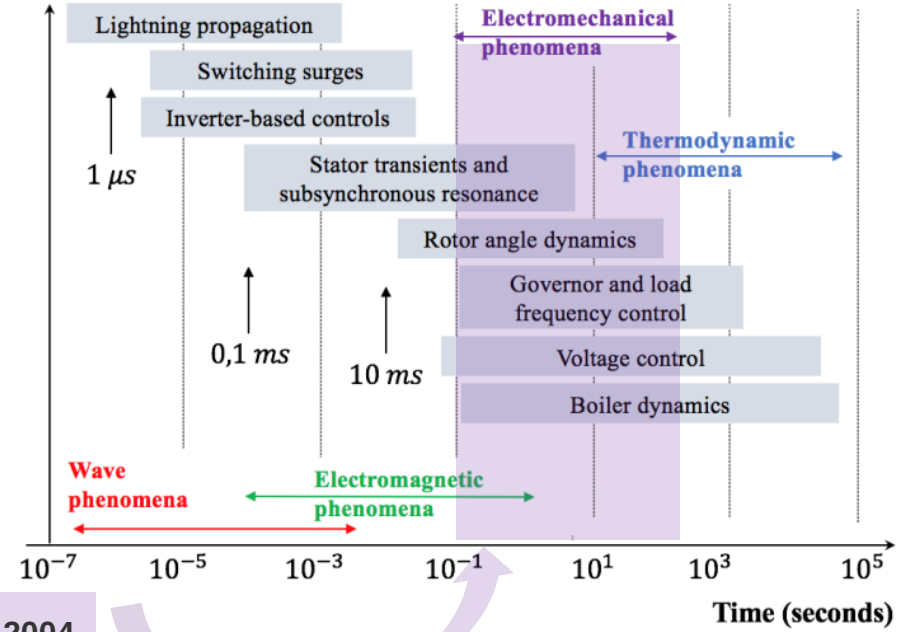
IEEE/CIGRE Joint Task Force on Stability Terms and Definitions

Prabha Kundur (Canada, Convener), John Paserba (USA, Secretary), Venkat Ajjarapu (USA), Göran Andersson (Switzerland), Anjan Bose (USA) , Claudio Canizares (Canada), Nikos Hatziargyriou (Greece), David Hill (Australia), Alex Stankovic (USA), Carson Taylor (USA), Thierry Van Cutsem (Belgium), and *Vijay Vittal (USA)*

Power Systems Time Scale (1)

- The figure shows the time scales of the dynamic phenomena that can be observed in electricity systems.
  - The transient response cover a broad range of phenomena ranging from fast transients to “slow” electromechanical transients.

- The relevant time constants for stability studies in power systems dominated by SGs are within the **electromechanical window.**

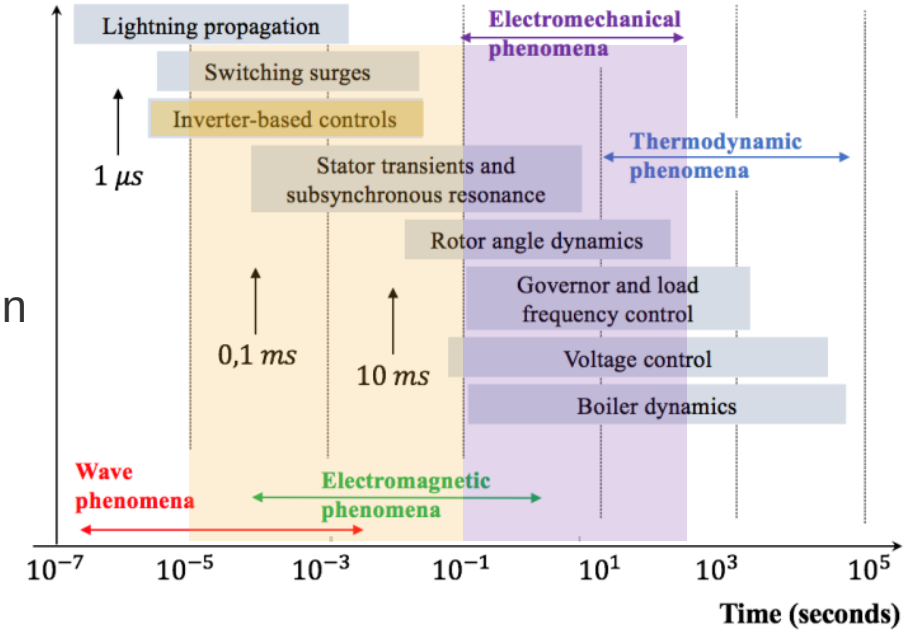


Task Force of 2004

Power Systems Time Scale (2)

- The time scale related to the **controls of IBR** is very fast.
  - Ranging from a few microseconds to several milliseconds, thus encompassing electromagnetic phenomena.
- As IBR increases, system dynamic response starts to be more dependent on fast-response power electronic devices.
  - Fast transients start to play a role in the dynamic behavior of the system.

➔ **System response becomes faster.**

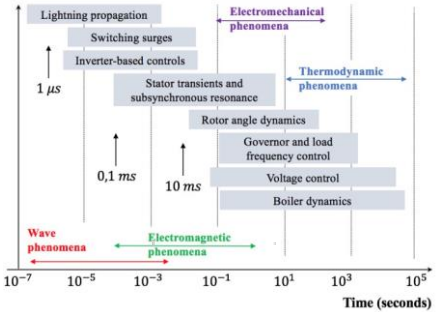


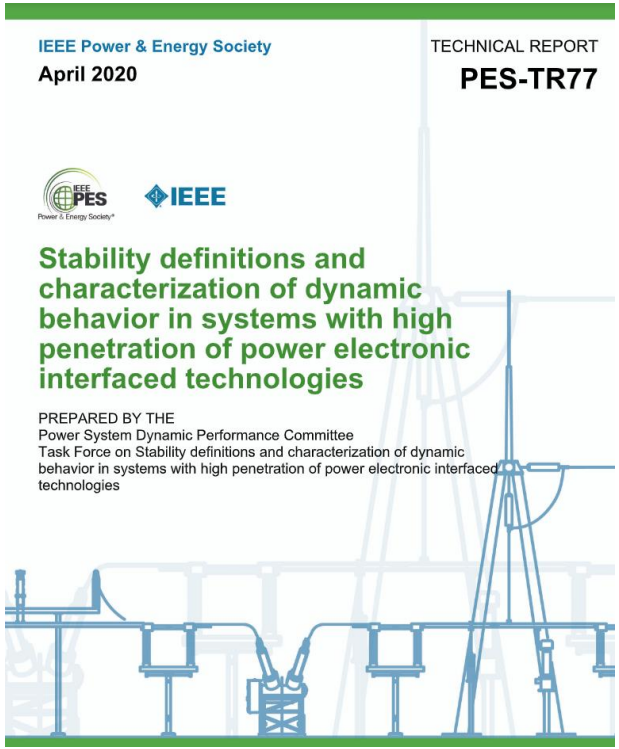
Need to Review Stability Definition and Classification

- Due to IBR time scales → Need to extend the bandwidth of phenomena to be examined in stability studies and include **faster dynamics** within electromagnetic time scales.

➔ In 2016, a Task Force of the IEEE PSDP Committee addressed the classification and definition of system stability, including additional considerations due to IBR.

➔ **Results of Task Force were published in 2020.**





Stability definition in systems with high penetration of IBR

Scope of the 2016 Task Force

- This Task Force focuses on classifying and defining power system stability as impacted by IBR from a bulk power system perspective.

- The Task Force does not address:
  - Cases where an incorrect control setting causes a local instability or when the instability of a control loop can be directly characterized without modeling the system
  - Stability issues associated with microgrids
  - Impacts of distributed resources (connected at the distribution level) on the transmission system.

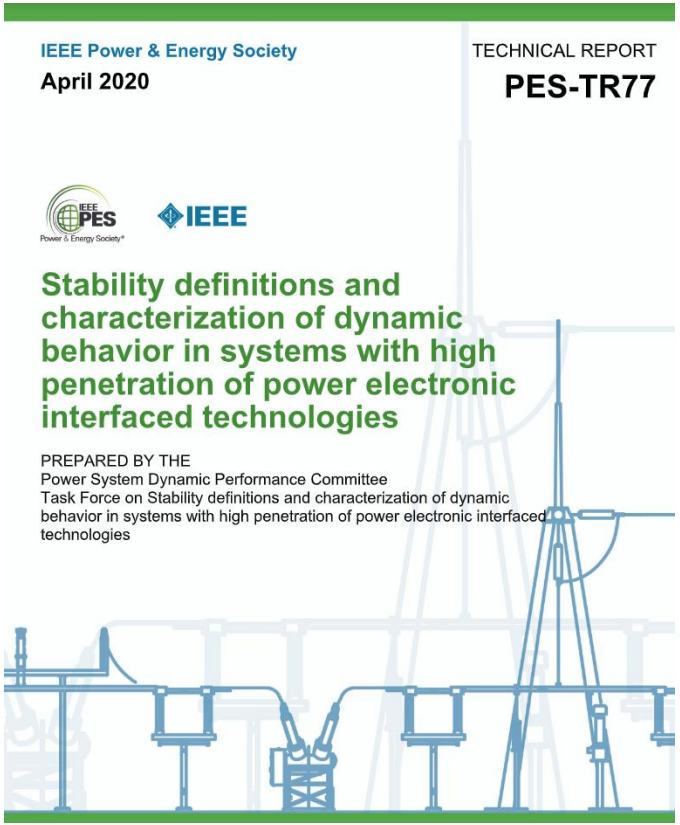
Formal Stability Definition

- Regarding the formal definition of power system stability, the definition originally presented in the report of the Task Force of 2004 remains unchanged.

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

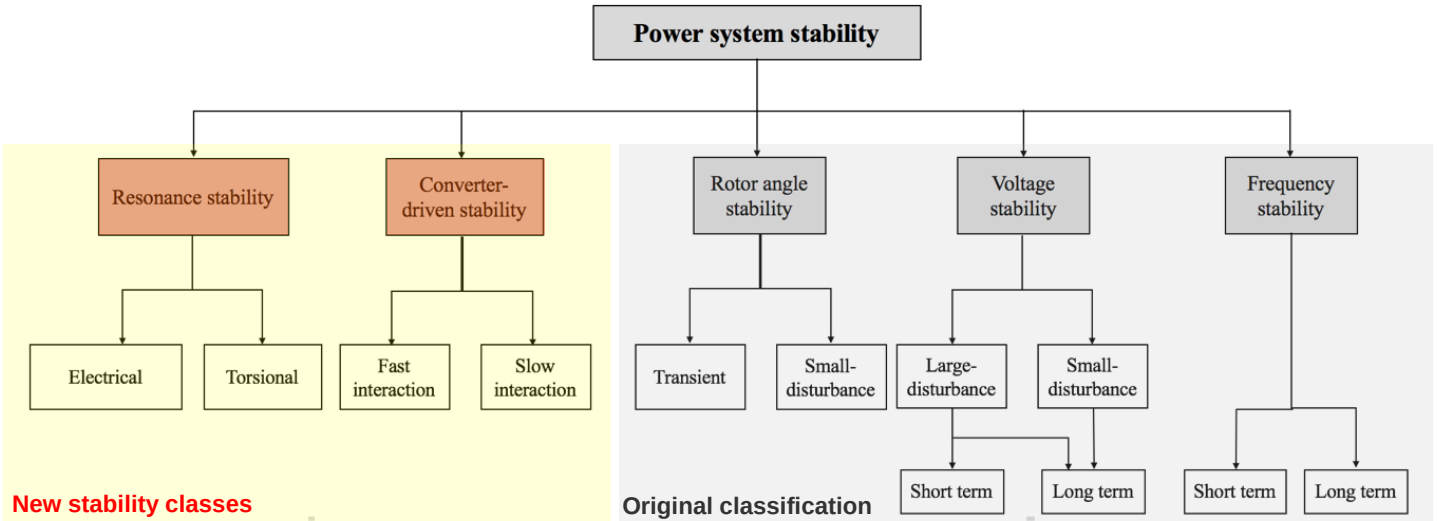
- Is there any change in the definition of each type of stability?





Stability Classification With IBR

- The figure shows the classification proposed by this Task Force.
- With respect to the original classification, two new stability classes were introduced motivated by the increasing use of IBRs.
  - "Resonance stability" and "Converter-driven stability."

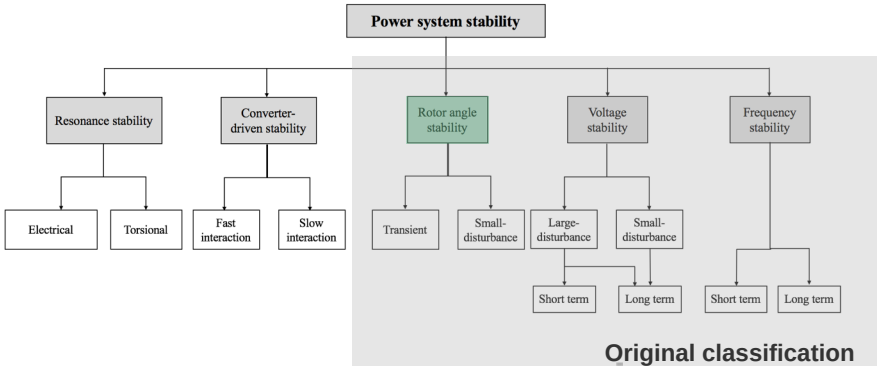


Previous time scale separation still applied (when appropriate):

- "Short-term" (including electromechanical dynamics)
- "Long-term" (after electromechanical transients have died out).

Rotor Angle Stability (1)

- *Rotor angle stability is concerned with the ability of the interconnected synchronous machines in a power system to remain in synchronism under normal operating conditions and to regain synchronism after being subjected to a small or large disturbance.*



CIG ~ IBR

Table. 1. Categories of power system stability.

Categories of Power System Stability	Additional considerations with respect to Ref. [1]
Rotor Angle Stability • Transient • Small Disturbance	• Definition unaffected. • Effect of CIGs in both subcategories highlighted.
Voltage Stability • Short-term • Long-term	• Definition unaffected. • Effects of HVDC links in short-term voltage stability
Frequency Stability • Short-term • Long-term	• Definition unaffected. • Effects of CIGs in changing and the potential of controlling system frequency.
Resonance Stability • Electrical • Torsional	• New category added. • Effect of HVDC and FACTs on torsional and of DFIG controls on electrical resonance stability
Converter-driven Stability • Fast interaction • Slow interaction	• New category added. • Fast dynamic interactions of the control systems of power electronic-based systems with fast-response components of the power system and other power electronic-based devices. • Slow dynamic interactions of the control systems of power electronic-based devices with slow-response components of the power system.

Rotor Angle Stability (2)

- **The integration of IBR does not change the definition of rotor angle stability.**
- Still, as SGs are displaced by IBR, the total inertia of the system is reduced.
  - This impacts rotor angle stability and the electromechanical modes of the system.
- The displacement of SG by IBR affects the rotor-angle stability of the remaining generators by:
  - Changing the flows on major tie-lines, which may in turn affect damping of inter-area modes and transient stability margins.
  - Displacing large SG, which may in turn affect the mode shape, modal frequency, and damping of electromechanical modes of rotor oscillations.
  - Affecting the damping torque of nearby SG. This is reflected in changes in the damping of modes that involve those synchronous generators.
  - Displacing SG that have crucial power system stabilizers (PSS).

Small-Disturbance Rotor Angle Stability

- Significant effort has been devoted to understanding and describing the effects of IBR on small-disturbance rotor angle stability.
  - However, results and conclusions obtained are to a large extent influenced by the power system used and operating conditions.



- The effects can be small and large, and the presence of IBR beneficial or detrimental.
  - The impacts depend on several factors, including number of IBR, type of controls used, network topology and strength, load conditions, and other similar factors.

➔ **No general consensus regarding the effects of increased penetration of IBR on electromechanical modes and on small-disturbance rotor angle stability.**

Transient Rotor Angle Stability

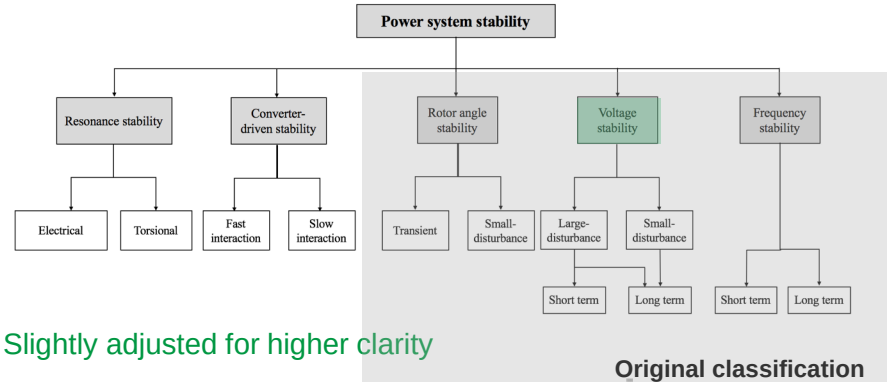
- Efforts have also been made to understand the effects of IBR on transient rotor angle stability.
  - Lowering the total system inertia may result in larger and faster rotor swings, thus making the system more prone to stability problems.

- As before, studies have shown that increased penetration of IBR can have both beneficial and detrimental effects on transient rotor angle stability depending on:
  - Grid layout, location of IBR, as well as the control of IBR during and after the fault and (ride-through capability)
  - The effects are also impacted by other factors such as the type of disturbance and its location with respect to IBR and large SG.

➔ **No general consensus regarding the effects of increased penetration of IBR on transient rotor angle stability.**

Voltage Stability (1)

- *Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance.*



Slightly adjusted for higher clarity

Original classification

Table. 1. Categories of power system stability.

Categories of Power System Stability	Additional considerations with respect to Ref. [1]
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Voltage Stability (2)

- **The integration of IBR does not change the definition of voltage stability.**
- Still, the displacement of conventional SGs by IBR leads to a reduction of system strength in the area where conventional machines are displaced.

➔ Power systems become weaker.

  – In steady state, small disturbances in power flows may significantly change the network voltages in weak areas of the system.

➔ **Voltage control in weak network areas can be extremely challenging.**

- Modern IBR have voltage-control and reactive support capabilities.

  – However! IBR are current limited resources.

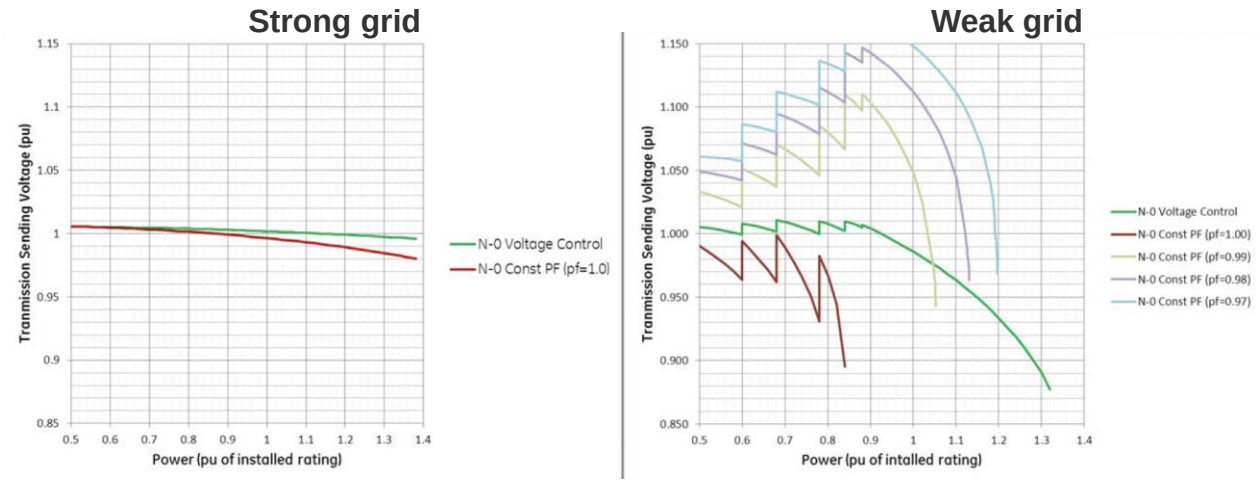
➔ **Reduction of the voltage control/reactive support capability of the system.**

  – However! The effects strongly depend on the IBR control.

Voltage Stability (3)

- The effects of IBR on voltage regulation depend on the control of the converter.
  - For instance, constant power factor/voltage control mode.

- The figure shows how the control mode of IBR impact voltage stability (source: GE).



➔ **The negative effects of IBR on voltage control depends on the control of IBR.**

Voltage Stability (4)

- **The displacement of SGs by IBRs leads to a weakening of power systems.**
  - Synchronous machines strongly support voltage stability by injecting high short-circuit currents during faults.
  - IBR have limited capacity of injecting fault current during contingencies.

➔ **The replacement of SG by IBR impair the dynamic performance during contingencies.**

- During contingencies, weak grids with low fault currents may experience extremely depressed voltages over wide network areas.
  - This may make the voltage recovery difficult after the fault clearance.

➔ **Power systems with high levels of IBR have higher risk of voltage instability or collapse.**

Frequency Stability (1)

- *Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset, resulting in a significant imbalance between generation and load.*

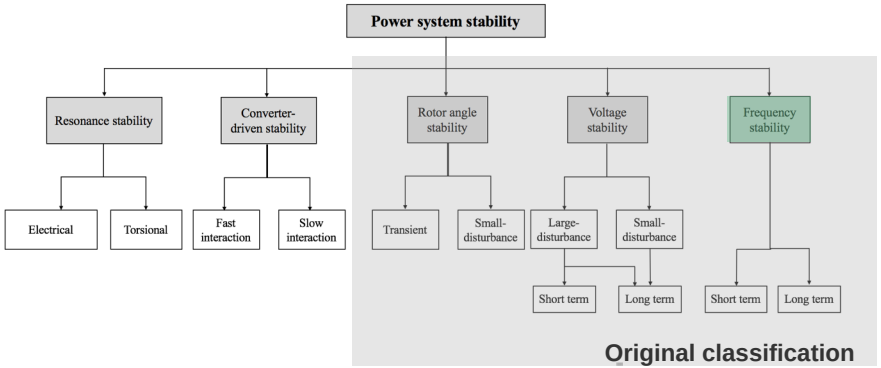


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Frequency Stability (2)

- **The integration of IBR does not change the definition of frequency stability.**
- Still, reduced grid inertia due to the displacement of SG leads to steeper RoCoF and lower frequency nadirs during power imbalances.

➔ **Frequency dynamics become faster.**

  – Conventional control and protection schemes may become too slow to successfully ride through large frequency deviations.

➔ **Increase the risk of loss of load due to activation of shedding schemes.**

➔ **Low inertia systems are more prone to frequency instabilities.**

➔ **Need for fast acting controllers to arrest fast frequency drops and avoid load shedding or instabilities.**

Frequency Stability (3)

- **IBR can effectively support system frequency, and even faster than SG.**
- However! Dynamics of converters are on similar time scales as the grid dynamics.

➔ **Possible dynamic couplings between the control of IBR and the grid, eventually leading to unstable behaviors.**

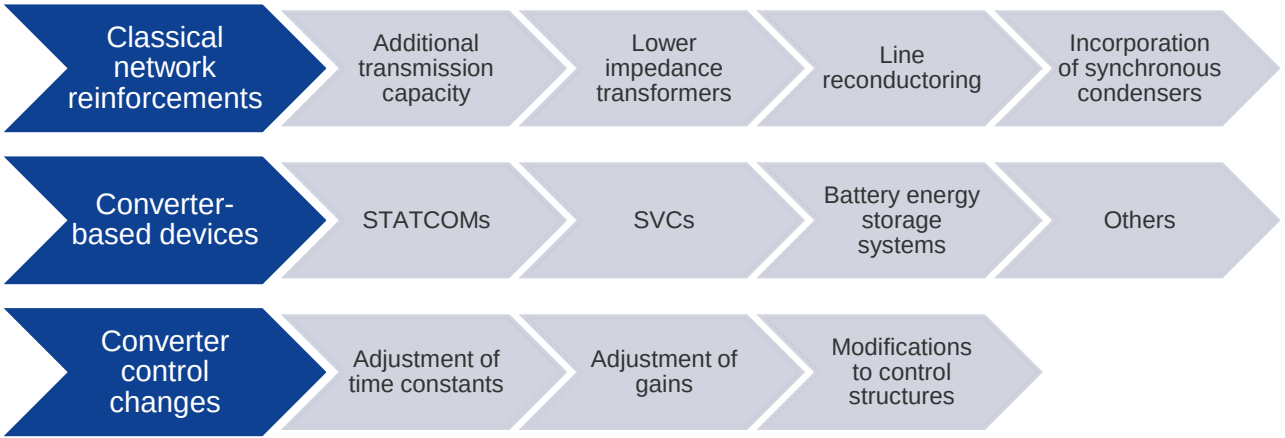
- The inertial response of SG is instantaneous and guaranteed.
  - On short time scales, SG contribute to recover the power balance through the kinetic energy stored in their rotating parts (without any control).
- However! Converters do not respond “naturally” to power unbalances but through a control loop.
  - Frequency support of IBR is subject to delays, malfunctioning, and instabilities.

➔ **Frequency response capability of IBR is not fully comparable to the inertial response of SG.**

Current Solutions (1)

- Today, there are several potential solutions to mitigate the stability problems that may arise due to weak grid conditions as IBR increases.

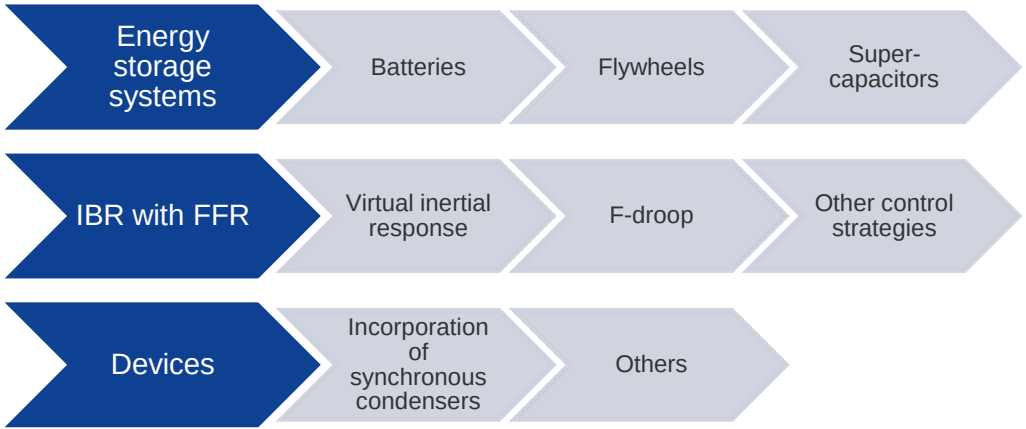
- **Low short-circuit levels**



Current Solutions (2)

- Today, there are several potential solutions to mitigate the stability problems that may arise due to weak grid conditions as IBR increases.

- **Reduced inertia**

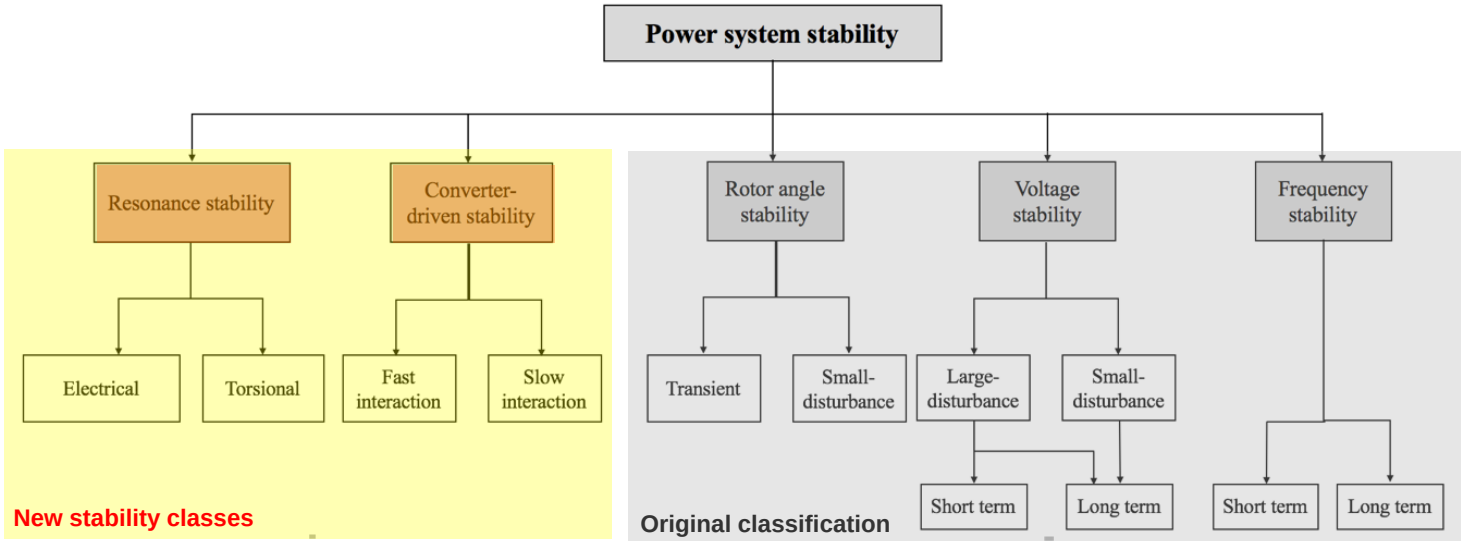


Agenda

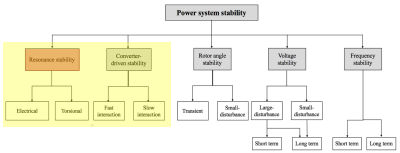
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New Stability Classes

- The figure shows the classification proposed by this Task Force.
  - With respect to the original classification, two new stability classes were introduced, namely “Resonance stability” and “Converter-driven stability.”



Resonance Stability (1)

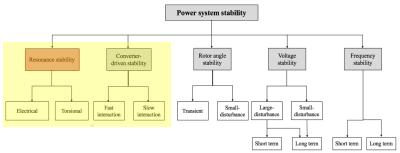


- In general, resonance occurs when an energy exchange takes place periodically in an oscillatory manner.
  - In case of insufficient dissipation of energy in the flow path, the oscillations grow, which is observed as an increase of voltage/current/torque magnitudes.
  - When these magnitudes exceed specified thresholds, it is said that a resonance instability has occurred.



- The term resonance stability encompasses subsynchronous resonance (SSR), whether it be associated with an electromechanical resonance or an entirely electrical resonance.

Resonance Stability (2)

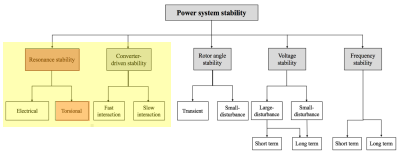


- SSR can manifest two possible forms:
  - Due to a resonance between series compensation (series compensated electrical network) and the mechanical modes of torsional oscillations on the turbine-generator shaft
  - Due to a resonance between series compensation and the electrical characteristics of the generator → This kind of resonance is purely electrical resonance, termed Induction Generator Effect (IGE).

➔ **Resonance stability has been split into two categories:**

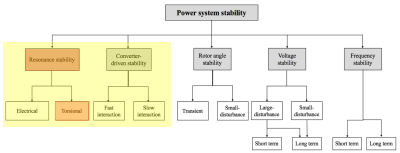
- Torsional Resonance Stability
- Electrical Resonance Stability.

Torsional Resonance Stability (1)



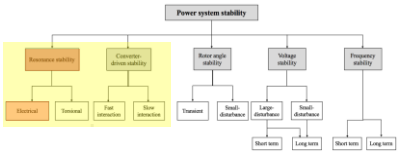
- **Torsional resonance:** Torsional interactions between series compensated lines and the turbine-generator mechanical shaft:
  - It is well documented in the literature as it pertains to conventional SGs.
- SSR involves a system condition where the network exchanges significant energy with a turbine-generator at one (or more) of the natural sub-synchronous torsional modes of oscillation of the combined turbine-generator mechanical shaft.
  - The oscillations can be poorly damped, undamped, or even negatively damped and growing, thus threatening the mechanical integrity of the turbine-generator shaft.
- Subsynchronous oscillations can also be related to device-dependent subsynchronous oscillations (DDSSO).

Torsional Resonance Stability (2)



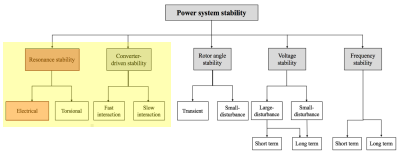
- DDSSO arise due to the interaction of fast-acting control devices with the torsional mechanical modes of nearby turbine-generators.
  - Examples: HVDC lines, static Var compensators (SVCs), static synchronous compensators (STATCOM), and power system stabilizers (PSS).
- DDSSO are not always detrimental; in some cases, the interaction can be beneficial and in fact improve torsional damping.

Electrical Resonance Stability (1)



- **Electrical resonance:** Due to a resonance between series compensation and the electrical characteristics of the generator:
  - Never observed in real power systems with conventional SG only.
  - Variable speed doubly fed induction-generators (DFIG) are susceptible to Induction Generator Effect (IGE), because the induction generator used in the wind turbine is directly connected to the grid.
- Self-excitation type SSR occurs when, at sub-synchronous frequencies, a series capacitor forms a resonant circuit with the effective inductance of the induction generator and, at these frequencies, the net apparent resistance of the circuit is negative.
  - Negative resistance of the induction generator rotor (as seen on the stator side)
  - Action of the DFIG controls governing the converter between the stator and rotor circuits.

Electrical Resonance Stability (2)



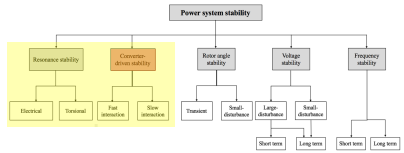
- If the total negative resistance from these sources exceeds the positive resistance of the circuit at or near the resonant frequencies, self-excitation SSR occurs.
  - The resultant resonance leads to large current and voltage oscillations that can damage the electrical equipment.

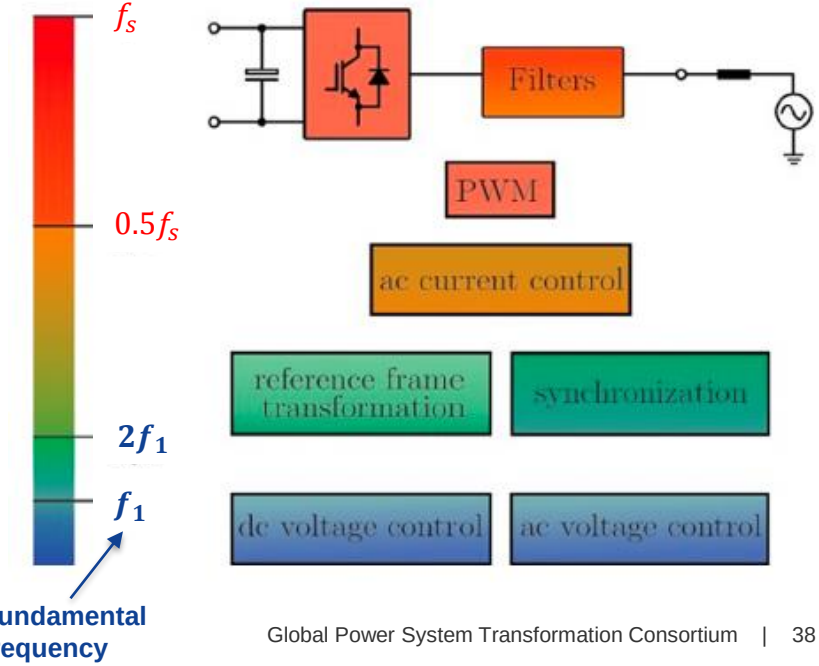
- This phenomenon has been also termed Subsynchronous Control Interaction (SSCI) in the literature.

Converter-Driven Stability (1)

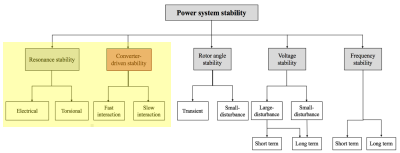
- IBR have control loops with different response times.
  - PLL
  - Inner-current controls
  - External control loops.
- The figure shows the IBR control layers and the frequency range of operation.
  - f_1 fundamental frequency
  - f_s converter switching frequency.

➔ **Time scale associated with the control systems of IBR is wide.**



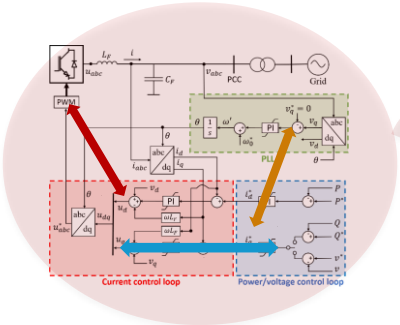


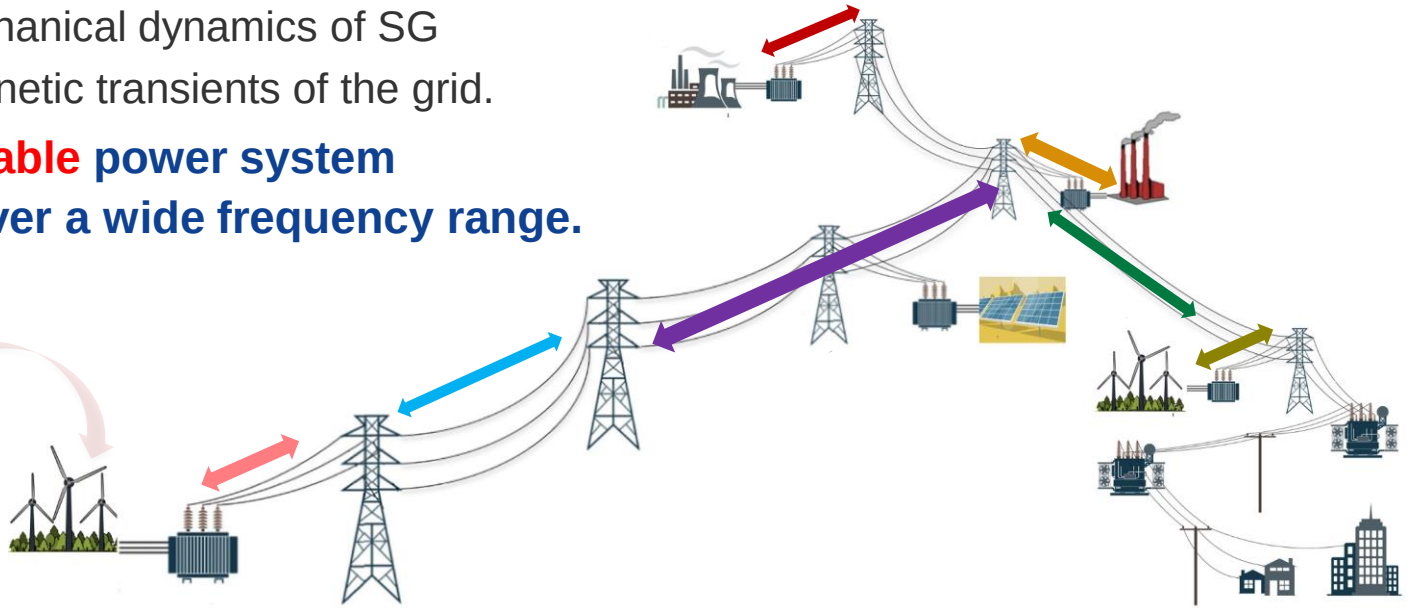
Converter-Driven Stability (2)



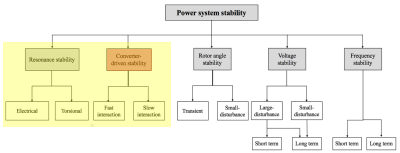
- The wide time scale related to the controls of IBR can result in cross couplings and interactions with several system components and devices.
  - Electromechanical dynamics of SG
  - Electromagnetic transients of the grid.

➔ **Possible unstable power system oscillations over a wide frequency range.**

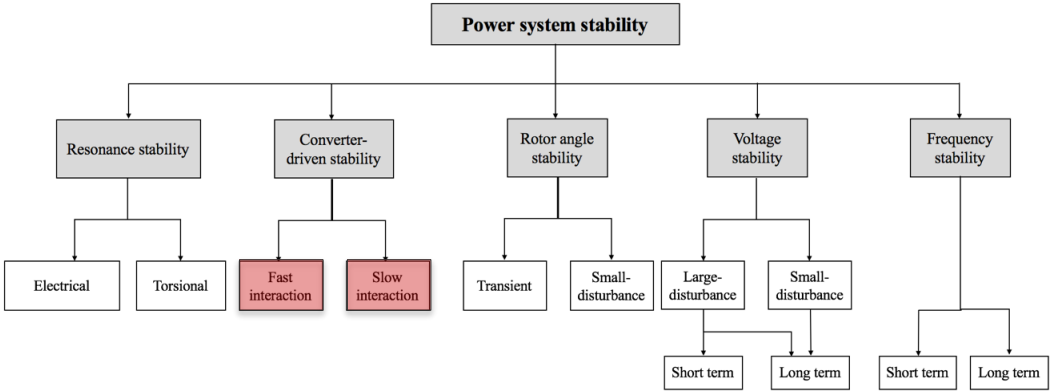




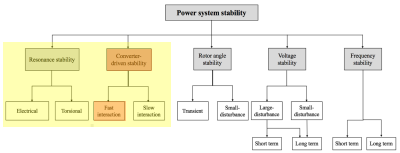
Converter-Driven Stability (3)



- Converter-driven stability is split into two categories, according to the frequencies of the observed phenomena.
  - **Slow-interaction Converter-driven Stability** phenomena showing relatively low frequencies:
    - Typically, less than 10 Hz.
  - **Fast-interaction Converter-driven Stability** phenomena with high frequencies:
    - Typically, tens to hundreds of Hz, and possibly into kHz.



Fast-Interaction Converter-Driven Stability (1)



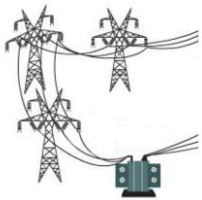
- **Fast-interaction:** In power systems, instabilities due to fast interactions may arise in a number of different ways.
  - These instabilities involve system-wide stability problems driven by **fast dynamic interactions of the control systems of power electronic-based devices**, such as IBRs, HVDC, FACTS **with other fast-response components** like the transmission network, SG stator dynamics, or other power electronic-based devices.







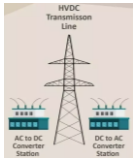








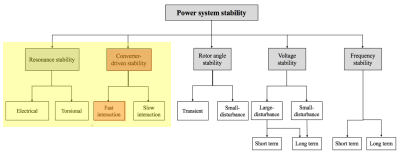








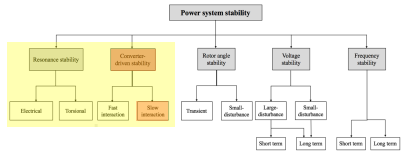
Fast-Interaction Converter-Driven Stability (2)

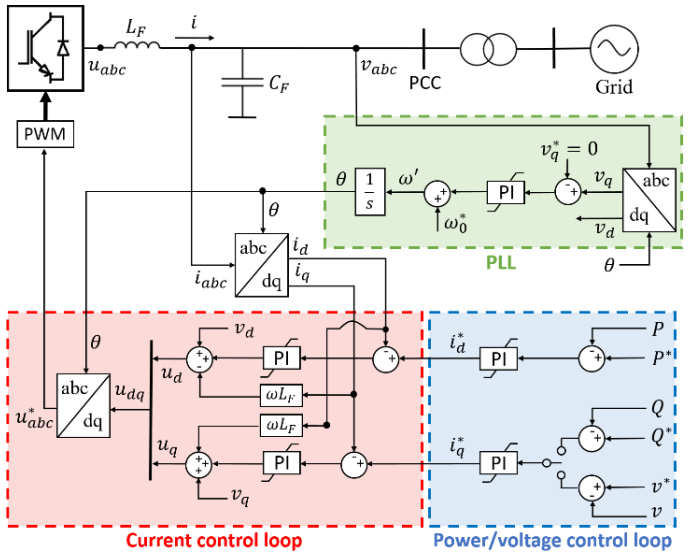


- Examples:
  - Interactions of the fast inner-current loops of IBR with passive system components may cause high frequency oscillations up to several kilohertz.
    - Referred to as *harmonic instability* in the power electronics community.
  - Several inverters in close proximity to each other may also generate interactions leading to multi-resonance peaks.
  - Interactions induced by the coupling between the converters and the grid.
    - Dynamics of the control system of IBR are on similar time scales as the grid dynamics.

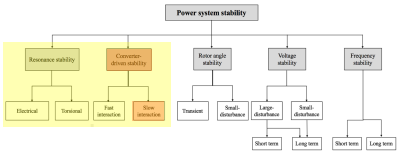
Slow-Interaction Converter-Driven Stability (1)

- **Slow-interaction:** These types of instabilities involve system-wide instabilities driven by **slow dynamic interactions of the control systems of power electronic-based devices** with **slow-response components such as SGs and some generator controllers.**





Slow-Interaction Converter-Driven Stability (2)



- Unstable low-frequency oscillations can appear due to interactions between the controllers of the converters and other components.
  - The outer control loops (power and voltage) and PLL can lead to unstable low-frequency oscillations.
    - System strength at the connection point of IBR has significant influence on the stability of low-frequency oscillations.
      - In weak systems with low short-circuit ratios ($SCR < 2$), the oscillations may become unstable and could lead to growing low-frequency oscillations.

$$SCR = \frac{S_{grid}}{S_{IBR}}$$

  - Online capacity of IBR and control strategies and parameters of the converters also affect the stability of low-frequency oscillations.

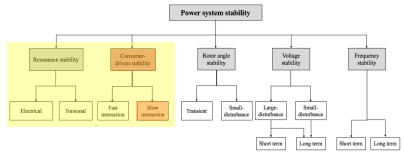
PLL Loss of Synchronism (1)

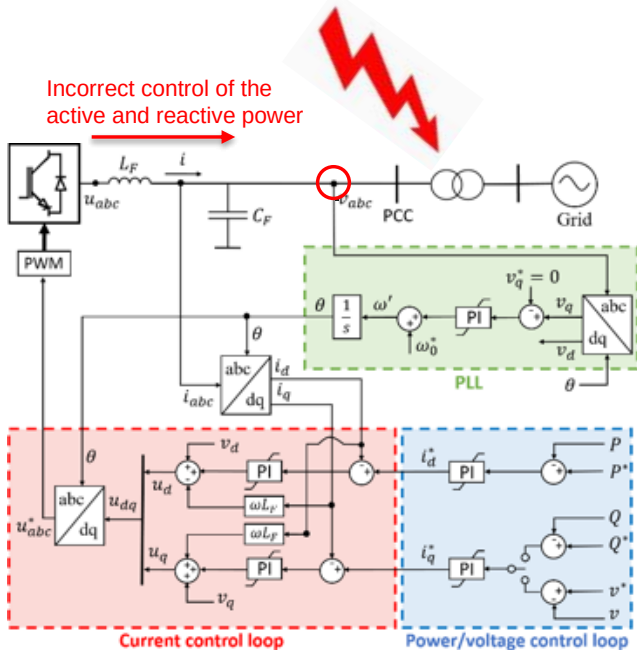
- The ability of the PLL to synchronize with the grid in the case of nearby faults can be extremely challenging in weak networks.
- If, during a **short circuit**, the PLL is not able to track large changes in the phase angle of the voltage at the PCC, this may result in inaccurate calculations of the phase angle by the PLL.

➔ PLL provides an erroneous value of angle to the inner current controller.

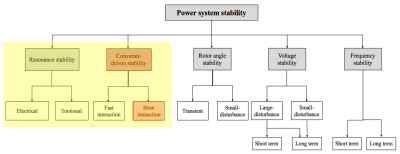
➔ **Current injected by the IBR** into the grid may be at the **wrong phase,** which could result in further voltage magnitude and angle degradation.

➔ **Possible instability.**



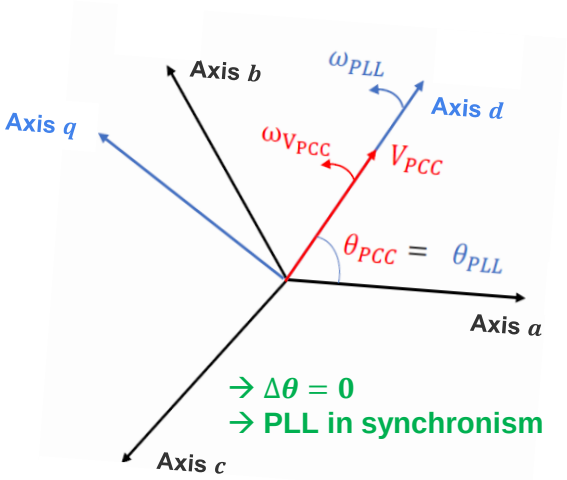


PLL Loss of Synchronism (2)

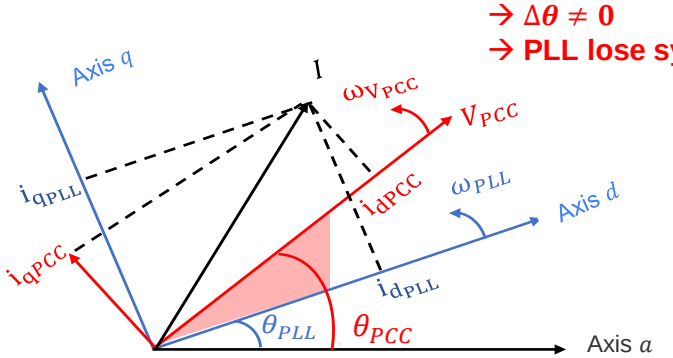


- During a short circuit in the system, a “jump” occurs in the phase angle of the voltage vector at the point of common coupling (PCC).
  - This can lead to the PLL losing synchronism with the vector V_{PCC}.
  - Due to this loss of synchronism, a difference $\Delta\boldsymbol{\theta}$ arises between the phase of the $\boldsymbol{d}$-axis and the phase angle of the voltage vector at the PCC V_{PCC} according to:

$$\Rightarrow \Delta\boldsymbol{\theta} = \theta_{PCC} - \theta_{PLL}$$



During a contingency



Summary

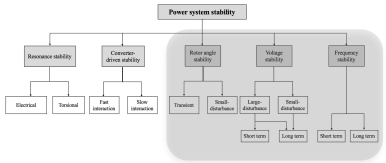
- IBR have significant effects on power system stability and control.
- However, there are several solutions that can be deploy to mitigate them.
  - We need to learn how to deal with the challenges of high levels of IBR.

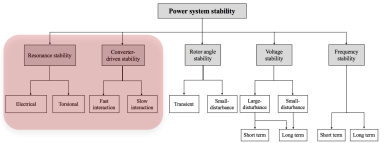


Massive integration of IBR

Main effects	*Main stabilities affected*
Reduction of inertia	• **Frequency stability** • **Rotor angle stability**
Reduction of system strength	• **Voltage stability** • **Rotor angle stability**

Introduction of fast controllers	• **New stability phenomena**
	  • Resonance stability
	  • Converter-driven stability - weak grid





Study Exercise

Exercise 3: Impacts of grid-following and grid-forming controllers on the small-signal and dynamic stability of a 100% IBR system

Consider the system shown in Figure 1, which consists of two IBRs supplying a common load through their respective step-up transformers and transmission lines. The objective of this exercise is to investigate the stability of a power system 100% based on IBR. For this, we will perform a small-signal stability assessment and time domain simulations. The study includes different scenarios in terms of the control of the IBR.

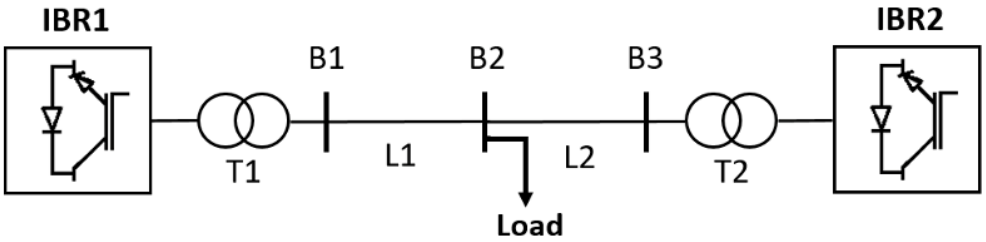


Figure 1: Single-line diagram of a power system based on 100% IBR.



Agenda

- Previous Lesson
- Stability Definition in Systems With High Penetration of IBR
- New Stability Phenomena in Systems With IBR
- Challenges in Systems With High Penetration of IBR

From Grid-Following to Grid-Forming Converters (1)

Need to transition from grid-following to grid-forming converters

- SGs have key functionalities for ensuring system operation and stability.
  - Frequency and voltage regulation of power systems have generally been provided by conventional SGs.
  - Rotating machines naturally provide high fault currents during contingencies, thereby strongly supporting system stability and recovery after faults.
  - SGs have black-start capability.

➔ **SGs are grid-forming sources with key functionalities for ensuring system operation and stability.**

From Grid-Following to Grid-Forming Converters (2)

Need to transition from grid-following to grid-forming converters

- Today, nearly all grid-connected IBR are controlled in **grid-following mode.**
  - For its correct operation, a well-defined terminal voltage is needed.
- **Grid-following IBR** require that other generators participate in the process of forming frequency and voltage.

➔ **As the penetration of IBR increases**, at least some of these units will be required to operate in **grid-forming mode.**

  - Can regulate the terminal voltage
  - Do not require a PLL
  - Can coexist with other grid-following and grid-forming IBR as well as with SGs on the same power system.

From Grid-Following to Grid-Forming Converters (3)

- **Grid-forming IBR** can be designed to provide black-start capability and support system restoration following a blackout.
  - Grid-following converters do not have black-start capability.



- Restoration-support capability of modern **grid-following converters** is limited.
  - After a blackout, **grid-following** units cannot support system restoration unless other generators can black start the system.



Grid-Following	Grid-Forming
Assumes grid already formed in normal operation	Assumes it has responsibility to form and maintain healthy grid
Control of current injected into the grid	Control of voltage magnitude and f/phase
Decoupled control of P and Q	Slight coupling between P and Q
Needs PLL	PLL not necessary
Without black-start capability	With black-start capability
Cannot operate at 100% IBR without other grid-forming sources	Can theoretically operate at 100% IBR

From Grid-Following to Grid-Forming Converters (4)

- Integration of IBR reduces the levels of fault current and short-circuit strength.

➔ **As the penetration of IBR increases, power systems become weaker.**



- **Grid-following converters** can easily lose stability under weak grid conditions.
  - Ride-through low voltages during contingencies is extremely challenging for grid-following IBR, especially under weak grid conditions.
  - However, modern grid codes usually require fault ride-through capability.

➔ As the penetration of IBR increases and the network becomes weaker, grid-following converters will have increased risk of losing stability.

➔ **The level of grid-following converters in power systems is limited due to their stability problems under weak grid conditions.**

From Grid-Following to Grid-Forming Converters (5)

Need to transition from grid-following to grid-forming converters ✓

- **The maturation process of grid-forming inverters still requires time.**
  - Current real applications can be seen in microgrids and in off-grid installations.
  - However, there is no practical experience in operating grid-forming inverters connected to real large-scale power systems.



➔ **Lack of this experience hinders the massive integration of grid-forming IBR.**

- Scaling from small microgrids to more complex networks will require several research efforts and field implementations.

Challenge: ***To solve existing research questions and demonstrate key functionalities of grid-forming converters in the field***

Landscape in Future Systems



- Future power systems dominated by IBR will be less secure, faster, more complex and difficult to control than systems dominated by conventional SGs.
- However! Shift of energy supply is not only taking place toward IBR at high voltage levels but also toward smaller producers connected to distribution grids.
  - Other actors at distribution level: distributed storage devices, electric vehicles.

➔ New actors at distribution level will put even more strain on bulk power systems.

➔ Future power systems will have a huge number of IBR and emerging devices widely deployed at all voltage levels.

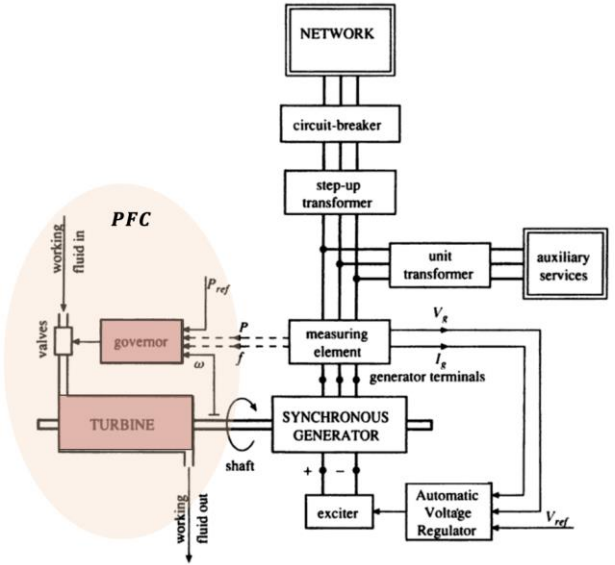
➔ Current monitoring and control approaches will reach their limits.

➔ **Need for a fundamental change in the way power systems are operated and controlled.**

Frequency and P-Balance in a 100% IBR System (1)

- In conventional power systems:
  - Frequency is dependent on the active power balance
  - The grid frequency is coupled to the speed of SG.
- Coupling between SGs and grid frequency allows to use the frequency deviation for monitoring the power balance in the system:

$$2H\frac{d\omega}{dt} = P_m - P_e$$



➔ **We do not monitor power balance, but frequency!**

- Frequency deviation Δf is thus used as signal to control the power output of SGs.

- However! This only works due to the coupling between the speed of SGs and the grid frequency



Frequency and P-Balance in a 100% IBR System (2)



- In 100% IBR-based power systems (i.e., a system in which there is no synchronous generators at all) $\Rightarrow \boldsymbol{H \approx 0}$**.**
- Taking the limit $H \to 0$ in the swing equation:

$$\boldsymbol{2H\frac{d\omega}{dt} = P_m - P_e = 0 \quad \Rightarrow 0 = P_m - P_e}$$



➔ **Frequency is fully decoupled from the power balance in the system.**

  - Frequency is not a *physical* variable coupled to synchronized rotating machines anymore
  - Frequency variation has "***no meaning***" for monitoring the power balance.

- In this scenario, no system element responds "naturally" to power imbalances.

Frequency and P-Balance in a 100% IBR System (3)

- In power systems without inertia, frequency has no meaning for the determination of the power balance.

➔ **Need of novel control approaches that do not use frequency measurement as control signal for keeping the balance between load and generation.**

- Although some alternatives have been proposed, **up to date, there is no consensus on the best alternative** to follow.
  - Strategies proposed so far have been explored in theory.

➔ **Further research is needed in order to conceive novel control strategies able to keep the power balance in electricity systems without inertia.**

Operating and Controlling Future Systems (1)

- Future power systems dominated by IBR will be less secure and with thousands of power electronic devices broadly deployed across all voltage levels of the grid.

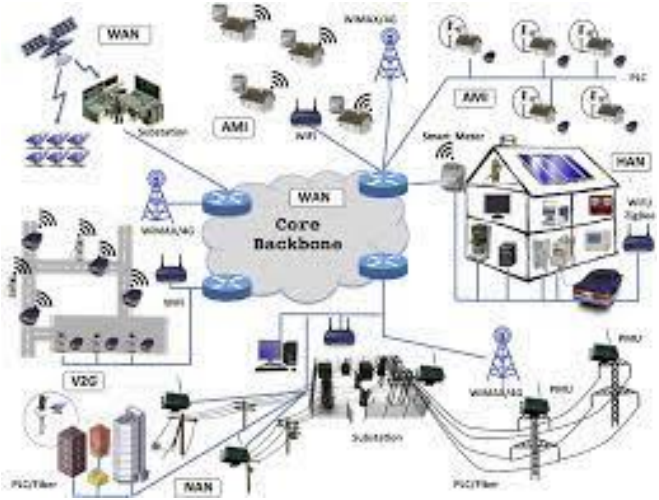


➔ **More complex to control.**

- The dimension and complexity of future networks will require exploring advanced control methods.
  - More active and collaborative control approaches.



- **How this new control approach should look is still an open question.**



Operating and Controlling Future Systems (2)

Challenge: ***To conceive a brand-new way of controlling power systems able to handle complex and fast networks with thousands power electronic devices broadly deployed across all voltage levels of the grid***

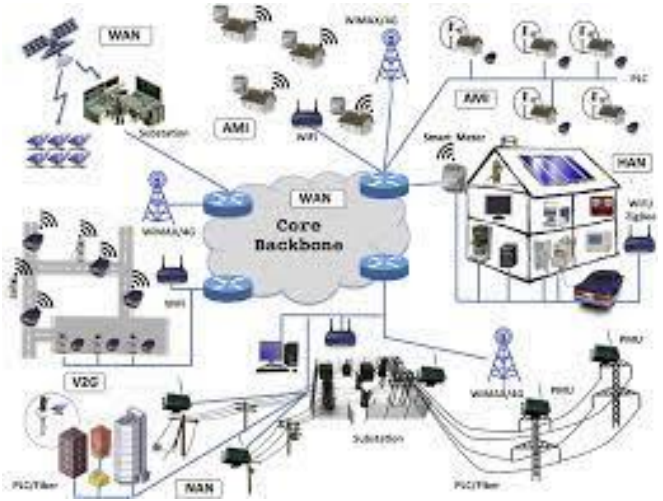
- **Power converters allow a wide variety of control alternatives.**
- **There are still several paradigms and questions to be resolved.**



➔ **Further research is needed.**

Active research field





Thank you

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