What is Natural Frequency?

Combination of R, L, C = natural frequency
What is Resonance?

When you hit the prongs of one tuning fork, it vibrates due to the resonance as the mechanical excitation (hit) excites the natural frequency of the tuning fork. If you hold vibrating fork suddenly, the kinetic energy of the vibrations travel in the air and due to resonance, excites the other two tuning forks with the same frequency, and they vibrate even without touching them....
What is Resonance..?

Soldiers walking rhythm creates forces when coincides with natural frequency of the bridge, the bridge may collapse due to resonance.
What is Resonance?
Mathematical Analysis of a Simple RLC Network

\[ i(t) = A \sin(\omega_s t + \psi_1) + B e^{-\zeta \omega_d t} \sin(\omega_d t + \psi_2) \]

\[ \omega_n = \sqrt{\frac{1}{LC}} \]

\[ \zeta = \frac{R}{2\sqrt{\frac{C}{L}}} \]

\[ \omega_d = \omega_n \sqrt{1 - \zeta^2} = \frac{1}{2L} \sqrt{\frac{4L - R^2C}{C}} \]
A series-compensated network has a natural resonant frequency \( f_n \) given by \( f_n = f_0 \sqrt{\frac{X_c}{X_L} f_n} \) (where \( f_0 \) is the synchronous frequency in Hz). At this subsynchronous frequency \( f_n \), the slip \( s_1 \) is given by

\[
s_1 = \frac{f_n - f_m}{f_n}
\]  
(1)
Sub harmonic Interactions : IGE

Purely Electrical self excitation or Induction generator effect (IGE), no interactions with Mechanical System

\[ i(t) = A \sin(\omega_s t + \psi_1) + B e^{-\zeta \omega_d t} \sin(\omega_d t + \psi_2) \]
Sub harmonic Interaction: TI, MTA

- System electrical dynamics
  - current
  - voltage

- Generator electromagnetic dynamics

- Turbine mechanical dynamics
  - Shaft speed

- Torsional interaction (TI)

- Capacitor fault induced voltage
  - current

- Generator electromagnetic dynamics
  - Electro magnetic torque

- Turbine mechanical dynamics
  - Mechanical torque

- Mechanical Torque Amplifications (MTA)
Sub harmonic Interactions: SSCI – Similar to IGE With Controller Participation

- **SSCI** – Sub Synchronous Control Instability
  - Interaction Between Power Electronics Devices (Wind Turbine-type 3 DFIGs, HVDC, SVC etc.) and Series Compensated Transmission System.

(Source: Electranix Corporation, Winnipeg, Canada)

Sub Synchronous Controller Instability (SSCI)
This Phenomena’s ultimate effect is similar to IGE, but the controller plays a significant role with other parameters of the Wind Systems such as dispatch, wind speed etc.
• 2008 -- Xcel Energy – Minneapolis – USA – Lakefield Substation– Captured by TESLA DFR

• 2009 – ERCOT Region– TEXAS- USA – Wind Turbine Electronics Damage and Series Compensation System Damage

• 2012 – North China – SSR developed over 500s, with 4 stages, and the effective compensation was only 6.67%!!

• 2013 – North China – SSR event noticed and Manual Series Caps By pass saved the system
2008- Wind Interaction
Real Event – Xcel Energy (USA)
System Single Line Diagram

Remote Sub 1
- Bkr22
- Bkr23

Series Cap Sub
- Bkr40

345kV line 1

Switching Sub
- Bkr4
- Bkr2
- Bkr3

345kV line 2

Remote Sub 2
- Bkr84
- Bkr85

Wind Generation Sub

Combustion Turbines Generators
- TR1
- TR2
- TR3

4kV bus

Gen 1
- to T4

Gen 2

Gen 3

Gen 4

Gen 5
- to T5

Gen 6
1- Breaker 1 & 2 opened for regular system switching procedure

2- CT1, CT2, and W start feeding radially through series capacitor

3- Tripped the CT generator unit

Figure 1: System one line diagram – All breakers were closed except CT1 breaker and Breaker -7.
9 Hz & 13Hz dominant sub harmonics

High speed recording of 3 phase currents captured by the DFR
Low Speed Capture of the Event

Slow speed (swing) recording of one of the phase
23 ~ 25 Hz dominant sub harmonics
SSR was observed between 6 ~ 8 Hz with only 6.67% effective series compensation!!

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How does the Wind controller interact with the system?
What are the consequences?

- Damage to the wind turbine
- Damage to the series compensation system
- Damage to the electronics – convertor
- Possible saturation of the transformers at low frequency sub harmonics
Solar (PV) Controller Issues with Weak System

Gangui Yan, et. al, “DC link voltage stability analysis for single stage photovoltaic VSIs connected to weak grid”. IPEMC-ECCE Asia, 2016
Micro processor based Sub Harmonic Protection Relay (SPRO)

- Can detect sub harmonics in the range of 5 Hz – 45 /55 Hz (depending on 50/60 Hz sys freq) for upto 10 channels with two trigger levels or with no summations, upto four trigger levels.

- Faster detection of sub harmonics (100 ms - 400 mS) depending on the sub harmonic amplitude and frequency.

- *Suitable for faster detection of rapidly growing SSCI (sub synchronous controller instability) phenomena in convertor controlled DFIG (doubly fed induction generator) Wind Systems.*

- Accurate estimation and tracking of decimal (or inter) sub harmonic frequencies (e.g. 22.4 Hz) within 5 Hz to 45 Hz range.
• Capture sub harmonics in HVDC / FACTS or other power controller interactions such as the Solar (PV) specifically with the **weak power systems**

• Can be used for both mitigation and protection against sub harmonic resonance in the range of 5 Hz – 45 / 55 Hz Hz in a series compensated or over compensated power system network.

• **Suitable for detection of sub harmonic “Ferro Resonance”, in the range of 5- 45 / 55 Hz.**
Sub Harmonic Detection

Logic Diagram

- Nominal Sub-harmonic Detector
  - Fmin
  - Fmax
  - Nominal Level
  - V OR I a/b/c

- Fundamental Sub-harmonic Detector
  - Fmin
  - Fmax
  - V OR I a/b/c
  - Fundamental Levels

- Total Sub-harmonic Distortion Detector
  - V OR I a/b/c
  - Fundamental Levels
  - V OR I a/b/c
  - Sub-harmonic Levels

- V OR I Detector Pickup
- ProLogic Input

- OR

- Falling Edge Detector
- Operation Per Minute Detector

- OR

- Trip / Alarm
Conclusions

• SSOs are inevitable in the day-to-day operation of growing complex power system network

• With the increase use of wind and Solar (PV) generators feeding HV and EHV utility networks with weak /and or series compensation, it is necessary to ensure that sub harmonic oscillations are monitored, and that the electrical grid is protected from any resulting detrimental effects.

• Micro Processor Based Relay can be used to reliably mitigate / protect from SSO) :
  – SSR – sub synchronous resonance (Generators, HVDC, FACTS, PV - Convertor etc..)
  • SSI – sub synchronous interactions
    – SSCI – sub synchronous controller instability/interactions- New phenomena in Wind Turbines controller interactions in Type 3 DFIG system.
    – SSTI – sub synchronous torsional interactions
  • IGE- Induction generator effect

  – SSFR – sub synchronous ferro resonance (in distribution system transformers) and in overcompensated power system network
THANK YOU!!

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