ELEMENTS OF FACTS CONTROLLERS

Rajiv K. Varma, PhD
Associate Professor
Hydro One Chair in Power Systems Engineering
University of Western Ontario
London, ON, CANADA
rkvarma@uwo.ca
POWER SYSTEMS -
Where are we heading?

• A historic change overtaking electrical power industry
  – Large scale grid integration of renewable energy sources
  – Implementation of Smart Grids

• ULTIMATE AIM: to provide reliable, quality power at minimum cost
• Overwhelming need for
  – increased transmission capacity on lines
  – control of power flow in specific corridors
  – assurance of system reliability in the event of faults

• Possible through:
  – FLEXIBLE AC TRANSMISSION SYSTEMS (FACTS)
FACTS

• **Flexibility of Electric Power Transmission**
  – The ability to accommodate changes in the electric transmission system or operating conditions while maintaining sufficient steady state and transient margins

• **Flexible AC Transmission Systems (FACTS)**
  – *Alternating current* transmission systems incorporating *power-electronic based* and other static controllers to enhance *controllability* and increase *power transfer capability*
Comparison of different limits of power flow

Thermal Limit (MW)

Steady-State-Stability Limit (MW)

Transient-Stability Limit (MW)

Electrical Damping Limit (MW)
ADVANTAGES OF FACTS DEVICES/CONTROLLERS

• Increase / control of power transmission capacity in a line
  – prevent loop flows
• Improvement of system transient stability limit
• Enhancement of system damping
• Mitigation of subsynchronous resonance
• Alleviation of voltage instability
• Limiting short circuit currents
• Improvement of HVDC converter terminal performance
• Load Compensation
• Grid Integration of Renewable Power Generation Systems
Compensators

• Synchronous Condensers
• FACTS
  – THYRISTOR-BASED FACTS
    • Static Var Compensator (SVC) - Shunt
    • Thyristor Controlled Series Capacitor (TCSC) - Series
  – VOLTAGE SOURCE CONVERTER BASED FACTS
    • Static Synchronous Compensator (STATCOM) - Shunt
    • Static Synchronous Series Compensator (SSSC) - Series
    • Unified Power Flow Controller (UPFC) - Composite
Concept of FACTS

\[ P_{12} = \frac{V_1 V_2}{X_L} \sin \delta \]

To increase Power Transfer \( P_{12} \)

- Increase \( V_1, V_2 \)
- Decrease \( X_L \)
  - install parallel line
  - provide midline shunt reactive compensation (Shunt FACTS)
  - insert series capacitor (Series FACTS)
  - inject in the line a voltage in phase-opposition to the inductive voltage drop (VSC FACTS)
- Control angular difference across transmission line
Thyristor Based FACTS CONTROLLERS
Static Var Compensator: A single-phase Thyristor Controlled Reactor (TCR)
Current and voltages for different firing angles $\alpha$ in a TCR
Features of SVC Operation

• SVCs are meant to provide dynamic voltage support not steady state voltage support
• SVCs are floating in steady state (i.e. do not exchange reactive power with the system)

• Fixed Capacitor-TCR: High Steady state losses even when the SVC is floating
• Capacitors are made switchable:
  – Mechanically Switched Capacitors (MSC-TCR)
  – Thyristor Switched Capacitor (TSC-TCR)
Basic elements of SVC

where

\[ B_{\text{min}} = B_{\text{SVC}} \] at the TCR only

\[ B_{\text{max}} = B_{\text{SVC}} \] at all TSCs only

\[ B_{\text{TOT}} = B_{\text{max}} - B_{\text{min}} \]

\[ K_R = \text{the static gain (full range for the voltage change of } 1/K_R) \]

\[ T_R = \text{the regulator time constant} \]

\[ B_{\text{SVC0}} = \text{the net susceptance at the SVC HV bus} \]
Concept of SVC Voltage Control

SVC Contribution depends on:

- System strength $X_s$

- SVC Rating

SVC more effective in weak systems!

SVC response slows down as system becomes stronger.
SVC APPLICATIONS
POWER TRANSFER IMPROVEMENT

\[ P_{12} = \frac{V_1 V_2}{X_L} \sin \delta \]

If, \( V_1 = V_2 = 1 \text{pu} \) and \( \delta = 90^\circ \)

\[ P_{12,\text{max}} = \frac{1}{X_L} \]

\[ P_{12} = V_1 V_m \frac{\sin \frac{\delta}{2}}{X_L/2} \]

If, \( V_1 = V_2 = V_m = 1 \text{pu} \) and \( \delta = 180^\circ \)

\[ P_{12,\text{max}} = \frac{2}{X_L} \]

Power Transfer Doubles
Variation in real and reactive power in SMIB system
Real power of the SMIB system with varying compensation
POWER TRANSFER IMPROVEMENT

\[ P_{12} = \frac{V_1V_2}{X_L} \sin \delta \]

If, \( V_1 = V_2 = 1 \text{pu} \) and \( \delta = 90^\circ \)

\[ P_{12\text{max}} = \frac{1}{X_L} \]

\[ P_{12} = \frac{V_1V_m}{X_L/2} \sin \frac{\delta}{2} \]

If, \( V_1 = V_2 = V_m = 1 \text{pu} \) and \( \delta = 180^\circ \)

\[ P_{12\text{max}} = \frac{2}{X_L} \]

**Power Transfer Doubles - with large SVC**

**Power Transfer Increases Substantially - with realistic SVC**
TRANSIENT STABILITY ENHANCEMENT

Power angle curve for improving transient stability margin
If \( \Delta \delta \) is positive, i.e., rotor is accelerating due to built-up kinetic energy, the FACTS device is controlled to increase generator electrical power output.

If \( \Delta \delta \) is negative, i.e., rotor is decelerating due to loss of kinetic energy, the FACTS device is controlled to decrease generator electrical power output.

SVC bus voltage not kept constant but modulated in response to auxiliary signals.
Choice of Auxiliary Signals For Damping Control

• **Local Signals**
  – line current
  – real power flow
  – bus frequency
  – bus voltage / angle

• **Remote Signals** *(Synthesized/Telecommunicated/ PMU)*
  – rotor angle / speed deviation of a remote generator
  – angle / frequency difference between remote voltages at the two ends of the transmission line

• Signals should be effective for power flow in either direction
Two Area System Study

Diagram showing power system components and connections between areas G1, G2, G3, and G4. The diagram includes lines labeled with distances such as 25 km, 10 km, and 110 km, and symbols representing power generation and lines of communication.
Simulation Results

- System Response without SVC
Simulation Results (Cont’d)

- System Response comparison with SVC different auxiliary control signals
Mitigation of Sub Synchronous Resonance (SSR)
Subsynchronous Resonance (SSR)

Simple radial system to study SSR:

Fig. 1. Turbine-Generator feeding infinite bus through series compensated transmission network
Subsynchronous Resonance (SSR)

- Subsynchronous Resonance (SSR) phenomenon is usually associated with synchronous machine connected to series compensated transmission network.

- Definition of SSR by IEEE SSR Task Force:
  - Subsynchronous resonance is an electric power system condition where the electric network exchanges energy with the turbine-generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system.
Damping of torsional mode 3 with an SVC
PREVENTION OF VOLTAGE INSTABILITY

- Voltage instability is caused due to the inadequacy of power system to supply the reactive power demand of certain loads such as induction motors.

- A drop in the load voltage leads to an increased demand for reactive power in such cases which, if not met by the power system, results in a further fall in bus voltage.

- This eventually leads to a progressive, yet rapid decline of voltage at that location which may have a cascading effect on neighbouring regions resulting in system voltage collapse.
A case study system
System transient response for opening one circuit
System transient response for opening one circuit with FC-TCR SVC
IMPROVEMENT OF HVDC LINK PERFORMANCE

- Voltage regulation
- Support during recovery from large disturbances
- Suppression of temporary over voltages
The inverter ac bus voltage during a permanent inverter block
SVC Application in Large Wind Power Integration: Dynamic Reactive Power Support
System Description

- Study investigates several alternatives of integrating:
  - 1000 MW of power generation including conventional induction wind generation.
  - To transmit power from Dakotas to Twin Cities, Wisconsin, Iowa and Illinois.

- One alternative comprises 500 MW coal generation at a new 345 KV station near Hettinger.

- And 5 new 100 MW wind parks one at Hettinger and the other 4 are at Marmarth, Bowman, Belfield and New England.
Conventional induction generator example.
3-phase fault at the vicinity of wind farm.
Solution (Contd.)

Conventional induction generation with SVCs
THYRISTOR CONTROLLED SERIES COMPENSATOR (TCSC)
A TCSC module: (a) a basic module; (b) A practical module
Bypassed - Thyristor Mode

Blocked - Thyristor Mode

Partially Conducting Thyristor (Capacitive Vernier Mode)

Partially Conducting Thyristor (Inductive Vernier Mode)

Different operating modes of a TCSC
TCSC reactance characteristic
TCSC waveforms in the capacitive mode ($\alpha = 150^\circ$)
TCSC waveforms in the inductive mode (\(\alpha = 130^\circ\))
APPLICATIONS OF TCSC
Damping Enhancement by modulated TCSC
MITIGATION OF SUBSYNCHRONOUS RESONANCE (SSR)

• At subsynchronous frequencies the TCSC presents an inherently resistive-inductive impedance.
• The subsynchronous oscillations cannot be sustained in this situation and get damped.
Damping transient shaft torque by a TCSC
PREVENTION OF VOLTAGE INSTABILITY

• TCSC in conjunction with series capacitors generate reactive power which increases with line loading.

• Helps in regulating local network voltages and also in alleviating voltage instability situations.
Voltage profile of the critical bus with 50% TCSC compensation
Voltage Sourced Converter (VSC) Based FACTS CONTROLLERS
Static Synchronous Compensator (STATCOM)
The STATCOM principle diagram: (a) power circuit; (b) an equivalent circuit; (c) a power exchange
Operation of STATCOM in Different Modes

(a) Capacitive Operation;  (b) Inductive Operation
V-I Characteristics of STATCOM and SVC
Applications of STATCOM

- Improves system steady state and transient stability
- Enhances system damping
- Prevents voltage collapse by rapid voltage control
- Mitigates SSR
- Compensates HVDC transmission systems
- More effective than SVC
Static Synchronous Series Compensator (SSSC)
Static Synchronous Series Compensator (SSSC)

(a) Generalized synchronous voltage source;
(b) different operating modes
Applications of SSSC

- Controls power flow
- Provides series compensation; does not introduce SSR
- Enhances system damping
- Prevents voltage collapse by reducing line series impedance
Unified Power Flow Controller (UPFC)
UPFC

• Most versatile FACTS Controller developed so far
• All encompassing capabilities of voltage regulation, series compensation and phase shifting.
• Provides independent control of both the real and reactive power flows in a transmission line at an extremely rapid rate.
Implementation of UPFC using two back to back VSC
UPFC (cont’d)

- Comprises two voltage source converters (VSCs) coupled through a common dc terminal.

- One VSC - Converter 1 is connected in shunt with the line through a coupling transformer and the other VSC - Converter 2 is inserted in series with the transmission line through an interface transformer.

- DC voltage for both converters provided by a common capacitor bank.

- Series converter is controlled to inject a voltage $V_{pq}$ in series with the line, which can be varied between 0 and $V_{pq\text{max}}$.

- The phase angle of the phasor $V_{pq}$ can be independently varied between $0^\circ$ and $360^\circ$. In this process the series converter exchanges both real and reactive power with the transmission line.

- While the reactive power is internally generated/absorbed by the series converter, the real power generation/absorption is made feasible by the dc energy storage device i.e. the capacitor.
UPFC (cont’d)

• Shunt connected Converter 1 is mainly used to supply the real power demand of Converter 2, which it derives from the transmission line itself.

• In addition, the shunt converter functions like a STATCOM and independently regulates the terminal voltage of the interconnected bus by generating/absorbing requisite amount of reactive power.

• Shunt converter maintains the voltage of the dc bus constant.

• Net real power drawn from the ac system is equal to the losses of the two converters and their coupling transformers.

• While the reactive power is internally generated/absorbed by the converters, no reactive power transfer can take place through the dc capacitor.
Operation of UPFC (cont’d)

Phasor diagram showing the simultaneous regulation of terminal voltage, line impedance, and phase angle by appropriate series-voltage injection.
Applications of UPFC

• Provides effective voltage regulation and power flow control
• Independent control of active and reactive power flows
• Improves system transient stability
• Allows phase shift control (injected voltage can have any phase shift with line current)
• Modulates line impedance
• Enhances system damping
• Prevents voltage collapse by rapid voltage control
• Provides wind farm interface
A case-study system

Diagram:
- 19,000 MW 3100 MVAR
- 345 kV
- 138 kV
- Reference Bus
- UPFC
- 100 MW 45 MVAR
- $P_D + jQ_D$
- 1500 MW 3000 MVAR
Power Transfer Improvement with UPFC

With UPFC, transfer is 357 MW

Without UPFC, max. transfer is 176 MW
Coordination of FACTS

• Need for Coordination:
  – Adverse interaction due to fast controls
  – Usually controls are tuned optimally assuming the remaining power system to be passive
  – Above parameters not optimal when dynamics of other controller are existent (PSS, HVDC, FACTS)
  – Coordination: Simultaneous tuning of controllers to effect an overall positive improvement in control schemes
AREAS OF FUTURE R&D

- Placement of FACTS Devices
  - extensive contingency analysis
- Coordination of FACTS Controllers
  - similar controllers
  - dissimilar controllers
  - FACTS and HVDC
- Wide Area Measurement System (WAMS) Based Signals for control of FACTS Devices
CONCLUSIONS

• FACTS controllers are very effective in improvement of power system performance

• FACTS Controller interactions must be carefully understood and avoided to secure optimal performance.