Role of FACTS Technology on Transmission Grid Reliability

IEEE San Francisco PES
Spring Banquet
May 15, 2003
Hitchhiker’s Guide\(^1\) to FACTS Technology describes the role technology plays in increasing reliable power transfers thereby relieving transmission congestion.

Hitchhiker’s Guide – Table of Contents

- Transmission Characteristics
- Impact of Deregulation on Transmission – *Theory of Indeterminacy*
- Transmission Provider Response – *Marvin the Paranoid Android*
- Cost of Congestion
- Congestion Relief Technologies – *Don’t Panic!*
  - System Analysis
  - Reconductoring
  - FACTS – *Infinite Improbability Drive*
  - HVDC – *Hyper Space Bypass*
- Application Examples
- Conclusions – *Restaurant at the End of the Universe*
AC Transmission Network Characteristics

- Power flow uncontrolled
- Circuits may be overloaded or underutilized
- Reserve capacity required for contingencies
- Variable reactive power demand
- Requires voltage control and dynamic reactive power reserve
- Often limited to less than thermal by instability or inadequate voltage support
- Transmission capacity a function of distance and intermediate voltage support
- Finite limit to cable length
- Synchronous
Impact of Deregulation on Transmission

- Transmission transactions growing
- Transmission investment declining
- Resource diversity declining
- Generators access to markets limited
- More regional transmission assessment by non-owners
- Regulatory power struggle
- Market manipulation - *e.g.* Deathstar
- Transmission congestion is increasing– attack of the free-riders
- Economic incentives to relieve congestion inadequate
Barriers to Transmission Investment

- Public opposition
- Lengthy and uncertain process
- Asset utilization
- Will it be bypassed?
- Regulatory uncertainty
- How will market risk be rewarded?
- Financial viability
- Obligation to serve

Theory of Indeterminacy
Response of the Transmission Provider

- Cut costs
- Sell assets
- Merge, spin off, change name
- Diversify
- Join an ISO\textsuperscript{1), form an RTO\textsuperscript{2)}
- Never mind - form a larger RTO
- If I build it, will anybody come?
- Accept regulated rate of return?
- FTR’s, CRR’s
- Do I really want to be in this business?

\textbf{Marvin the Paranoid Android}

\textsuperscript{1)} Independent System Operator
\textsuperscript{2)} Regional Transmission Organization
Cost of Congestion

- FERC estimated costs for 16 individual constraints that ranged up to $700M/y (eastern NY) - Electric Transmission Constraint Study

- ISO New England estimates the costs of congestion in New England are $125-600M/y - 2001 Regional Transmission Expansion Plan

- Cost of congestion on Path 15 > $222M over 16 mo prior to 12/00 - California ISO

- Congestion relief – overall net efficiency gain but there are individual winners and losers!
Interregional Congestion

- Congestion curtails economic dispatch
- Interregional or localized
- Congestion - time is money
- Raise limits by new lines or by technology
- Solutions – FACTS\(^1\) & HVDC \(^2\)

1) Flexible Alternating Current Transmission Systems
2) High Voltage Direct Current

Source: National Transmission Grid Study - DOE May, 2002
Congestion Relief Technologies – *DON’T PANIC!*

- System Analysis – Limits and Cost of Congestion
- Re-conductor – Increases Reactive Power Demand
- FACTS
  - Dynamic Shunt Compensation – SVC and STATCOM
  - Controlled Series Compensation - TCSC
  - Power Flow Control – UPFC and SSSC
- HVDC
  - Conventional - LCI
  - Capacitor Commutated Converter – CCC
  - VSC Based Transmission
  - Grid Power Flow Controller – GPFC
FACTS Benefits

- AC transmission lines generally operate below their thermal capacity
- Limitations often due to Voltage and Stability
- FACTS devices raise transfer capability towards thermal limit

Transmission constraints as functions of line length
Source: Eric Hirst, Edison Electrical Institute
Cost of Congestion - Case Study Pacific DC Intertie

PDCI(N2S) Power Flow Duration Curve
When Price Cap is 250 $/MWH in 2004
### Line Re-conductoring

Comparison of 1033 kcmil 54/7 SSAC \(^1\) and ACSR\(^2\)

<table>
<thead>
<tr>
<th></th>
<th>ACSR</th>
<th>SSAC</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Current Rating (A)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Summer (95°F)</td>
<td>1300</td>
<td>2190</td>
<td>168%</td>
</tr>
<tr>
<td>Line Rating (MVA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Summer (95°F)</td>
<td>(\sqrt{3} (1300) V_{\text{ll}})</td>
<td>(\sqrt{3} (2190) V_{\text{ll}})</td>
<td>168%</td>
</tr>
<tr>
<td>Maximum Line Inductive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactive Power Demand (excluding (V_{\text{ll}}^2 Bc))</td>
<td>(3*(1300)^2 X_l)</td>
<td>(3*(2190)^2 X_l)</td>
<td>284%</td>
</tr>
</tbody>
</table>

Increase in line capacity by reconductoring but must supply the additional reactive power demand – application for FACTS!

1) Steel-Supported Aluminum Conductor
2) Aluminum Conductor Steel-Reinforced
Minimal environmental impact
Maximize use of existing resources
Adapted to new electric market
Controllable
Responsive

Study - New Technology FACTS, HVDC, SSAC

Congestion Relief

- Thermal Limit
- Voltage
- Stability Limit
- FACTS & HVDC

New Thermal Limit
SVC and STATCOM - Established Technologies

**STATCOM - VSC**
- 19 VSCs installed since 1997
- In service today >1500 MVA
- >300 MVA in manufacturing

![Image of STATCOM - VSC](VSC_w_BtB_Eagle_Pass_TX)

**SVC**
- +/- 160 Mvar, 420 kV, Sylling, Norway
- >160 SVC utility inst. since 1975
- In service today > 32 000 MVA
- > 500 MVA in manufacturing

![Image of SVC](SVC_v2_10_08_01 revolution)
Increased Transfer with Voltage Support

- Maximum power flow depends on network and **voltage support**
- Steady state voltage via slow devices, e.g., switched capacitors, tap changers
- Dynamic reactive power reserve required for contingencies
- Dynamic voltage support requires fast action, e.g., generators, SVC\(^1\) or STATCOM\(^2\) - *all VARS are not the same*

1) **Static Var Compensator**
2) **Static Compensator** (ABB SVC Light)

**Infinite Improbability Drive**
Increased Transfer with Voltage Support

- Top: P-V curve at bus – all lines in service
- Middle: P-V curve at bus – post contingency without compensation
- Bottom: P-V curve at bus – post contingency with compensation

Normal System Conditions – 2000 MVA Short Circuit

n-1 Contingency – 1500 MVA Short Circuit Level

Static Var Compensation

Yonder there be dragons!

Improved Post-Contingency Voltage Profile due to Dynamic Reactive Support by SVC or STATCOM
SVC Building Blocks

SVC configurations used to control reactive power compensation in electric power systems

a. TSR-TSC configuration
b. TCR-TSC configuration
c. TCR-MSC configuration

$Q_{rel}$ Net reactive power flow to network
STATCOM – SVC Light

- $V_t$: Terminal voltage
- $V_i$: Converter voltage
- $V_{DC}$: Converter output current
- $I_q$: Terminal voltage
- Supplies reactive power when $V_i > V_t$
- Absorbs reactive power when $V_i < V_t$
Power Electronics

SVC - Thyristor Valve

- Controls AC Current – switched (TSC or TCR), phase control (TCR)
- Anti-parallel thyristors (SCR)
- Up to 4000 A, ~ 8 kV per single device

SVC Light - IGBT Valves

- AC/DC VSC converter
- Insulated gate bipolar transistor
- High switching frequency for PWM
- Anti-parallel diodes
- Up to 1500 A, 2.5 kV per parallel array
Insulated Gate Bipolar Transistor (IGBT)

- Same IGBT for all applications

The IGBT
- Nominal current: 1300 A
- Rated voltage: 2500 V
- Switching frequency: 1350 Hz
- Presspack
TSC/TCR Operation

Total current \( I_N \)

Capacitor current \( I_C \)

Reactor current \( I_R \)
Pulse Width Modulation

\[ u_{Va - \text{ref}} \]

\[ u \]

\[ u_{dc} \]

\[ -u_{dc} \]

\[ \hat{u} \]

(1) - max (SPWM)
STATCOM – 3-Level Converter with PWM

- Basic three-level voltage source converter
  - S1–12: IGBT stacks
  - D1–6: Diode stacks
  - C: DC capacitor

- Converter terminal voltage waveforms with pulse-width modulation
  - a, b: Line-to-midpoint voltage
  - c: Line-to-line voltage
Filter Bus Voltage

Voltage at Filterbus, kV. No filter

Voltage at Filterbus, kV.
Harmonic Spectrum

Harmonic spectrum in pu of $U_d$ pole voltage

RMS values in pu of $U_d$

Harmonic order
Current-Voltage Characteristic - STATCOM

- SVC curve
- Limitation due to transformer reactance

U_{ac} vs. I

Capacitive limit vs. Inductive limit
Shunt Compensation – Fixed + Dynamic

- Fixed compensation to hold unity voltage at nominal conditions with \( S_{sc} = 10 \text{p.u.} \) (\( X_s = 0.1 \text{p.u.} \))
- SVC and STATCOM MVAR equal to 0.5p.u. @ 1.00p.u. voltage
- Load equal to 2.3 + j0.8 p.u.
- Load voltage sensitivity: power \( m_p = 1 \), reactive power \( m_q = 2 \)
Both SVC and STATCOM regulate the voltage up to an Xs of about 0.25p.u.

Above this level both compensators hit their limit.

If the contingency reduces Xs to 0.33p.u., the voltage is about 1.7% less with the SVC.
Overvoltage v. Load Rejection

- Load level is increased up to 4.0 p.u.
- Fixed compensation is increased from 1.1 to 2.5 p.u.
- Typical SVC can absorb reactive power up to OV of 1.3 p.u. until FC are switched off to reach SVC continuous OV rating of 1.1 p.u.
- Typical STATCOM can absorb reactive power up to OV of 1.2 p.u. until FC are switched off to reach continuous OV rating of 1.1 p.u.
600 MW load, 50% induction motor, 50% resistive
Load supplied by two 113 km 230 kV lines
Three-phase permanent fault at midpoint of one line
SVC gain supervised to compensate for weaker systems
Recoveries with Equal Nominal Ratings

- SVC – 200 MVAR @ 1.00 p.u. voltage
- STATCOM – 200 MVAR @ 1.00 p.u. voltage
Recoveries with Functionally Sized SVC

- SVC – 200 MVAR @ 1.00 p.u. voltage rated 260 MVAR dynamic overload
- STATCOM – 200 MVAR @ 1.00 p.u. voltage
Shunt Compensation, building blocks

The building blocks are the base, the arrangement is the solution

TCR TSR  TSC  TCR/FC  TCR/TSC

Classical switched and phase control

VSC
SVC Light® STATCOM
Continuous control
Series Compensation – Improves Voltage Profile

A series-compensated transmission system

- $I_{ij}$: Current between buses $i$ and $j$
- $\theta_{1,2}$: Voltage angle, buses 1 and 2
- $\theta_{1,1}$: Voltage angle, buses $i$ and $j$
- $V_{1,2}$: Voltage magnitude, buses 1 and 2
- $V_{i,j}$: Voltage magnitude, buses $i$ and $j$
- $X_C$: Series capacitor reactance
- $X_{L1,L2}$: Line segment reactances

Voltage profile for a simple power system

- $P$: Power
- $V$: Voltage
- SC: Series capacitor

Graph showing the voltage profile with and without a series capacitor.
Series Compensation – Improves Stability Margin

Enhancing the transient stability margin by means of a series capacitor

- $A_{\text{acc}}$: Accelerating energy
- $A_{\text{dec}}$: Retarding energy
- $\delta$: Generator angle
- $\delta_0$: Pre-fault generator angle
- $\delta_C$: Angle at fault-clearing
- $P_e$: Electrical power from generator
- $P_m$: Mechanical power to generator
- $X_C$: Series capacitor reactance
- $X_L$: Line reactance
- IS: Infinite source
- SC: Series capacitor
Series Compensation – Increases Transfer Capability

- Series capacitors – “shorter” lines and improved voltage profile
- Reactive power supply proportional to current squared
- Passive – Automatic post contingency reactive support to mitigate voltage drop
- Turbo available - thyristor control to boost compensation or damp oscillations (TCSC)
Thyristor Controlled Series Compensation

Series compensation can be boosted, oscillation damped and SSR mitigated by thyristor control, e.g. TCSC

Impedance-current characteristic of the TCSC installed in the Imperatriz substation of Brazil's North-South Interconnection.

- $I$: Line current
- $X_{	ext{TCSC}}$: TCSC reactance
- $X_{\text{ef}}$: Nominal boost level
- $X_C$: Unity boost level
- $X_{\text{bypass}}$: Boost level at TCSC bypass

View of the Imperatriz TCSC
SSR Mitigation by means of CSC
Increased Loading with Support - Remedial FACTS

- Elevation = voltage profile
- Amount of laundry = transmission loading
- Keep clothes off ground = stability criterion
- Distance above ground stability margin
- Main supports (brown) = on-line generators
- Props = intermediate reactive power compensation, e.g. SVC, STATCOM, SC

*Improved Post-Contingency Voltage Profile due to Dynamic Reactive Support by SVC, STATCOM, SC*
Static Synchronous Series Compensator

The basic configuration of a static synchronous series compensator (SSSC)

$+V_C$ - Voltage across SSSC series transformer

Other notation see Fig. 4
Unified Power Flow Controller - UPFC

Basic circuit arrangement of the unified power flow controller (UPFC)

- $P$: Active line power
- $Q$: Reactive line power
- $V_{i,j}$: Voltage magnitudes, buses $i$ and $j$
- $\theta_{i,j}$: Voltage angles, buses $i$ and $j$
DC Transmission Characteristics

- Controllable - power injected where needed
- Bypass congested circuits – no inadvertent flow
- Higher power, fewer lines, no intermediate S/S needed
- Two circuits on less expensive line
- No stability distance limitation
- Reactive power demand limited to terminals
- Narrower ROW
- Lower losses
- No limit to underground cable length
- Asynchronous

Hyper-space bypass
DC Transmission Technologies

HVDC Classic for the Long Heavy Haul
- Power control
- Terminal reactive power demand by shunt bank switching
- Bulk power transmission
- Minimum system short circuit capacity > twice rated power (or > rated power with series compensation)

HVDC Light for the Intermediate Haul
- Real and Reactive Power control
- Dynamic voltage regulation
- Underground transmission
- Replace local inefficient generation
- Modular and expandable
- Black start capability
- No short circuit restriction
The HVDC Classic Converter Station

Converter station

Transmission line or cable

AC bus

Shunt capacitors or other reactive equipment

AC filters

Reactive Power Supply

Power Ratings:

500 - 3000 MW

Converter

Smoothing reactor

DC filter

Telecommunication

Control system
The CCC* Converter Station

*Capacitor-commutated converter station

Weaker Systems
Back-to-Back 100 - 550 MW

Transmission Line, Cable or Back-Back

AC bus

Converter

Smoothing reactor

Commutation capacitors

DC filter

Control system

Telecommunication

Contune AC filters
HVDC Light Station

Converter station

Voltage Source(d) Converter - VSC

Phase Reactor

AC filters

DC Capacitor

Control system

Transmission Cable

Strong or Weak Systems
Dynamic Voltage Control
Underground Transmission
Up to ±150kV, 330MW

AC bus

Dry DC Capacitor

Infinite Improbability Drive

IGBT Valves
VSC Operating Characteristics

PQ diagram, station 1, rect

- Red dashed line: $U = 1.1 \text{ pu}$
- Black solid line: $U = 1 \text{ pu}$
- Blue dotted line: $U = 0.9 \text{ pu}$
- Yellow line: $P_{desired}$
FACTS
Application Examples
Increased Interchange with FACTS

Forbes Static Var Compensator

- Increases interchange capacity
- Innovative dynamic overload
- -150 / 110 MVAR continuous range
- - 450 / 400 MVAR dynamic overload
- 2 x 300 MVAR 500 kV MSC
- Reduces LLP and OOS Tripping
- Single 500 kV line possible due to HVDC controllability
TCSC case - North/South Interconnection, Brazil

<table>
<thead>
<tr>
<th>Location</th>
<th>Rating</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maraba</td>
<td>348 Mvar SC</td>
<td>500 kV</td>
</tr>
<tr>
<td>Miracena</td>
<td>161 Mvar SC</td>
<td>500 kV</td>
</tr>
<tr>
<td>Colinas</td>
<td>2x161 Mvar SC</td>
<td>500 kV</td>
</tr>
<tr>
<td>Imperatriz</td>
<td>161 Mvar SC</td>
<td>500 kV</td>
</tr>
<tr>
<td></td>
<td>107 Mvar TCSC</td>
<td>500 kV</td>
</tr>
</tbody>
</table>

North-South Interconnection: 5 SCs + 1 TCSC
Power Oscillation Damping using TCSC

No TCSC POD active

North TCSC POD active

Both TCSC PODs active
Eagle Pass, BtB Light® Project sponsored by EPRI

Application
- Voltage Support
- Power Transfer (BtB)

Alternatives
- Classic HVDC B-t-B combined with SVC

Challenges
- Short delivery time
- Small site

Solution
- BtB Light®, +/- 2x36 MVA

Foot print +/- 2x36 MVA: 90 x 120 ft
SVC Light® STATCOM for Industry, AvestaPolarit

Application
- Flicker mitigation (EAF Steel)

Alternatives
- New lines
- Conventional SVC

Challenges
- Short delivery time (14 month)
- Flicker reduction > 3 times
- High availability
- Small site (15 X 20 m)

Solution
- SVC Light® : 0/+164 Mvar
SVC Light® STATCOM for Industry

Recordings with & without SVC Light®, AvestaPolarit Stainless Steel, Finland

Recordings made during operation of EAF w and w/o SVC Light®
First EAF batch w/o SVC Light® (13:03-14:25)
Second EAF batch w SVC Light® (14:43-16:10)
Reduced flicker guaranteed to >3.0 – actual > 4.0
Holly STATCOM – SVC Light

Problem
- Old inefficient power plant in residential area
- Environmental concerns
- RMR generation needed for voltage support
- Small, congested site
- Audible noise

Solution
- ±100 MVAR STATCOM (SVC Light)
- 3 x 32 MVAR switched capacitor banks
- Compact design
- Variable rating “modular” solution

Benefits
- Allows retirement of old generating station
- Improves local environment
- Maintains reliable transmission service
PG&E Newark SVC

- **Application**
  - High load growth, increasing import
  - Vintage synchronous condensers used for voltage/ VAR Control

- **Alternatives**
  - Replace synchronous condensers
  - New generation/transmission
  - FACTS: STATCOM or SVC

- **Challenges**
  - Short implementation time
  - High reliability requirement
  - Small footprint required, high seismic

- **Solution**
  - Fixed 225 MVAr Shunt Caps, 230 kV
  - Dyn. -100/+ 200 MVAr SVC FACTS, 230 kV with 10% capacitive overload
Cross Sound Cable – HVDC Light

Problem
- Inadequate interconnection capacity to LI
- High location marginal pricing on LI
- Localized capacity shortages at peak
- High Load growth
- Plant siting difficulties
- All “roads” go through NYC

Solution
- 330MW, ±150kV HVDC Light Submarine Cable from New Haven, CT to Shoreham, NY
- Interconnects NEISO and NYISO
- Merchant Transmission
- Expandable Solution

Benefits
- Improves system reliability
- Relieves congestion - more economic dispatch
- Provides for emergency transfer, reserve sharing
No Change in Reactive Power Demand or AC Voltage
Problem
- Inadequate E-W transfer capacity
- High differential energy costs
- Localized capacity shortages
- Relatively weak ac networks
- Tight Schedule – 19 months

Solution
- 2x100MW modular Back-to-Back Tie
- Optimized aggressive schedule
- Capacitor Commutated Converters
- Expandable Solution

Benefits
- Solves problem with minimal ac system additions
- Relieves congestion - more economic dispatch
- Provides for emergency transfer, reserve sharing
Sylmar Replacement – HVDC Classic

Problem
- Unreliable, aging, obsolete equipment
- Environmentally unfriendly Hg-Arc Valves
- Expensive O&M, contamination
- Seismic vulnerability

Solution
- Replace vintage equipment with 3100MW, ±500kV bipole housed in 1/3 the space
- Elimination of Hg-Arc Valves & auxiliaries
- Reuse existing filtering and switchgear
- Replace control & protection system

Benefits
- Dramatic reduction in area, complexity and O&M
- Meets current seismic requirements
- More reliable & dependable power transfer
Better Asset Utilization Through Technology

- Conventional HVAC
- HVAC with RPC / FACTS
- HVDC
- DC & AC

Future market

Market today

- Environment
- Technology Controllability

- Adequate incentives
- Fast track permitting
- Regional planning
- Multiple solutions
# Facts

<table>
<thead>
<tr>
<th>FACTS</th>
<th>HVDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Flexible AC Transmission System)</td>
<td>(High Voltage Direct Current)</td>
</tr>
<tr>
<td><strong>Static Var Compensator</strong>&lt;br&gt;Avoid voltage collapse&lt;br&gt;(Biggie size available, extra value-meal)</td>
<td><strong>HVDC Classic</strong>&lt;br&gt;Hyper-space bypass for the long, heavy haul&lt;br&gt;(Man-size portions, multi-terminal available)</td>
</tr>
<tr>
<td><strong>SVC Light, a.k.a. STATCOM</strong>&lt;br&gt;For flicker mitigation, dynamic voltage control&lt;br&gt;(Recommended for the light eater, “yuppie fare”)</td>
<td><strong>HVDC Light, a.k.a. VSC Transmission</strong>&lt;br&gt;A favorite on the edge of the galaxy&lt;br&gt;(For smaller appetites, stealthy and healthy)</td>
</tr>
<tr>
<td><strong>Series Capacitor</strong>&lt;br&gt;Try this to carry heavier loads over longer distances!</td>
<td><strong>Capacitor Commutated Converter</strong>&lt;br&gt;Added zest for the traditional favorite&lt;br&gt;(Portions for 2, strengthen your back-to-back relationship)</td>
</tr>
<tr>
<td><strong>Thyristor Controlled Series Capacitor</strong>&lt;br&gt;Damps infinite improbability drive oscillations</td>
<td></td>
</tr>
</tbody>
</table>

## Drinks

<table>
<thead>
<tr>
<th><strong>Pan-Galactic Garble Blaster</strong>&lt;br&gt;A real knock-out punch!&lt;br&gt;(Warning – the 2nd one will kill you.)</th>
<th><strong>Pulse-Width Modulator</strong>&lt;br&gt;Only served with SVC Light &amp; HVDC Light&lt;br&gt;(Shaken – not stirred, Marvin’s favorite refreshment!)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Would you like another pan-galactic garble blaster before the movie starts?