ELE 789 Special Topics in Electrical and Electronics Engineering: Electrical Power Quality

Dr. H. Bilge Mutluer
Course Outline

1. Power Quality (PQ) Definitions and Objectives
2. Power System Modeling and Simulation for PQ Analyses
3. Voltage Quality
4. Harmonics and Harmonic Elimination
5. Reactive Power Compensation
6. EMI, Grounding and Wiring
Reactive Power Compensation

- Power Factor
- Conventional Compensation Techniques
- Power Factor Correction of Unsymmetrical Loads and Phase Balancing
- Static Compensation Systems
  - FACTS Devices
  - Reactive Power Compensation Solutions for Pulsed or Fast Varying Loads
  - Case Study for Reactive Power Compensation
  - Control System Design
  - STATCOM
• **Flexible AC Transmission Systems (FACTS)**
• Various technologies that enhance the security, capacity and flexibility of power transmission systems
Problems in Transmission Lines

![Graph showing problems in transmission lines with various voltage limits and thermal limits.](image-url)
FACTS

- NGH = Hingorani Damper T
- CSC = Thyristor Controlled Series Capacitor
- PAR = Phase-Angle-Regulator
- TCVL = Thyristor Controlled Voltage Limiter
- SCCL = Super-Conducting Current Limiter
- TSBR = Thyristor Switched Braking Resistor
- BESS = Battery Energy Storage System
- HVDC = High Voltage Direct Current
- LTC = Transformer-Load Tap Changer
- SVC = Static Var Compensator
- TSSC = Thyristor Switched Series Capacitor
- STATCOM = Static Compensator
- UPFC = Unified Power Flow Controller
- TCPAR = Thyristor Controlled Phase-Angle Regulator
- SCCL = Super-Conducting Current Limiter
- SMES = Super-Conducting Magnetic Energy Storage
# Steady State FACTS Solutions

<table>
<thead>
<tr>
<th>Issue</th>
<th>Problem</th>
<th>Corrective Action</th>
<th>Conventional solution</th>
<th>FACTS device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage limits</td>
<td>Low voltage at heavy load</td>
<td>Supply reactive power</td>
<td>Shunt capacitor, Series capacitor</td>
<td>SVC, TCSC, STATCOM</td>
</tr>
<tr>
<td></td>
<td>High voltage at light load</td>
<td>Remove reactive power supply</td>
<td>Switch EHV line and/or shunt capacitor</td>
<td>SVC, TCSC, STATCOM</td>
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<tr>
<td></td>
<td>Absorb reactive power</td>
<td>Switch shunt capacitor shunt reactor</td>
<td>SVC, STATCOM</td>
<td></td>
</tr>
<tr>
<td>High voltage following</td>
<td>Absorb reactive power</td>
<td>Add shunt reactor</td>
<td>SVC, STATCOM</td>
<td></td>
</tr>
<tr>
<td>outage</td>
<td>Protect equipment</td>
<td>Add arrestor</td>
<td>SVC</td>
<td></td>
</tr>
<tr>
<td>Low voltage following</td>
<td>Supply reactive power</td>
<td>Switch shunt capacitor, reactor, series capacitor</td>
<td>SVC, STATCOM</td>
<td></td>
</tr>
<tr>
<td>outage</td>
<td>Prevent overload</td>
<td>Series reactor, PAR</td>
<td>TCPAR, TCSC</td>
<td></td>
</tr>
<tr>
<td>Low voltage and</td>
<td>Supply reactive power and limit overload</td>
<td>Combination of two or more devices</td>
<td>TCSC, UPFC, STATCOM, SVC</td>
<td></td>
</tr>
<tr>
<td>overload</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal limits</td>
<td>Line or transformer overload</td>
<td>Reduce overload</td>
<td>Add line or transformer</td>
<td>TCSC, UPFC, TCPAR</td>
</tr>
<tr>
<td></td>
<td>Tripping of parallel circuit (line)</td>
<td>Limit circuit (line) loading</td>
<td>Add series reactor</td>
<td>SVC, TCSC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Add series reactor, capacitor</td>
<td>UPFC, TCSC</td>
</tr>
<tr>
<td>Loop flows</td>
<td>Parallel line load sharing</td>
<td>Adjust series reactance</td>
<td>Add series capacitor/reactor</td>
<td>UPFC, TCSC</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Adjust phase angle</td>
<td>TCPAR, UPFC</td>
</tr>
<tr>
<td></td>
<td>Post-fault sharing</td>
<td>Rearrange network or use “Thermal limit” actions</td>
<td>PAR, Series Capacitor/Reactor</td>
<td>TCSC, UPFC, SVC, TCPAR</td>
</tr>
<tr>
<td></td>
<td>Flow direction reversal</td>
<td>Adjust phase angle</td>
<td>PAR</td>
<td>TCPAR, UPFC</td>
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<tr>
<td>Short circuit levels</td>
<td>Excessive breaker fault current</td>
<td>Limit short circuit current</td>
<td>Add series reactor, new circuit breaker</td>
<td>SCCL, UPFC, TCSC</td>
</tr>
<tr>
<td></td>
<td>Change circuit breaker</td>
<td>Add new circuit breaker</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rearrange network</td>
<td>Split bus</td>
<td></td>
<td></td>
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<tr>
<td>Subsynchronous</td>
<td>Potential turbine/ generator shaft</td>
<td>Mitigate oscillations</td>
<td>series compensation</td>
<td>NGH, TCSC</td>
</tr>
<tr>
<td>resonance</td>
<td>damage</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Dynamic FACTS Solutions

<table>
<thead>
<tr>
<th>Issue</th>
<th>Type of System</th>
<th>Corrective Action</th>
<th>Conventional Solution</th>
<th>FACTS device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient Stability</td>
<td>A, B, D</td>
<td>Increase synchronizing torque</td>
<td>High-response exciter, series capacitor</td>
<td>TCSC, TSSC, UPFC</td>
</tr>
<tr>
<td></td>
<td>A, D</td>
<td>Absorb kinetic energy</td>
<td>Braking resistor, fast valving (turbine)</td>
<td>TCBR, SMES, BESS</td>
</tr>
<tr>
<td></td>
<td>B, C, D</td>
<td>Dynamic load flow control</td>
<td>HVDC</td>
<td>TCPAR, UPFC, TCSC</td>
</tr>
<tr>
<td>Dampening</td>
<td>A</td>
<td>Dampen 1 Hz oscillations</td>
<td>Exciter, Power system stabilizer (PSS)</td>
<td>SVC, TCSC, STATCOM</td>
</tr>
<tr>
<td></td>
<td>B, D</td>
<td>Dampen low frequency oscillations</td>
<td>- Power system stabilizer (PSS)</td>
<td>SVC, TCPAR, UPFC, NGH, TCSC, STATCOM</td>
</tr>
<tr>
<td>Post Contingency Voltage Control</td>
<td>A, B, D</td>
<td>Dynamic voltage support</td>
<td>-</td>
<td>SVC, STATCOM, UPFC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dynamic flow control</td>
<td>-</td>
<td>SVC, UPFC, TCPAR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dynamic voltage support and flow control</td>
<td>-</td>
<td>SVC, UPFC, TCSC</td>
</tr>
<tr>
<td></td>
<td>A, B, C, D</td>
<td>Reduce impact of contingency</td>
<td>parallel lines</td>
<td>SVC, TCSC, STATCOM, UPFC</td>
</tr>
<tr>
<td>Voltage Stability</td>
<td>B, C, D</td>
<td>Reactive Support</td>
<td>shunt capacitor, shunt reactor</td>
<td>SVC, STATCOM, UPFC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Network control actions</td>
<td>LTC, reclosing, HVDC controls</td>
<td>UPFC, TCSC, STATCOM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Generation control</td>
<td>High-response exciter</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Load control</td>
<td>Under-voltage load shedding Demand-Side</td>
<td>-</td>
</tr>
</tbody>
</table>

Source: FACTS For Cost Effective and Reliable Transmission of Electrical Energy by Klaus Habur and Donal O’Leary
Solution Cost Estimation

Source: Siemens AG Database
# Requirements in Transmission

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Transmission</th>
<th>Distribution (Industrial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady state voltage control;</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Voltage stability;</td>
<td>√</td>
<td>-</td>
</tr>
<tr>
<td>System stability;</td>
<td>√</td>
<td>-</td>
</tr>
<tr>
<td>Power Oscillation damping;</td>
<td>√</td>
<td>-</td>
</tr>
<tr>
<td>Coordination of VAr contributions from other equipment;</td>
<td>√</td>
<td>-</td>
</tr>
<tr>
<td>Fast VAr correction of variable loads;</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Fast correction of power factor;</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>The correction of (line current) unbalance;</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Harmonic filtering;</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
Reactive Power Compensation Solutions for Pulsed or Fast Varying Loads

FACTS, Distribution Level Solutions, LV Solutions
Saturated Reactor (SR)

• Shunt-connected iron core reactor. It is a variable (nonlinear) susceptance that is controlled by the terminal voltage. It is connected in parallel to filters or capacitor banks.

• SR is fixed in value and it is not a flexible solution
25MVAr 110kV shunt magnetically controlled (Saturated) reactor connected to 32MVAr Capacitor bank, installed in Kudymar Substain, Russia.

SR Installations in CERN

SVC1
Year 1974

SVC2
Year 2001

SVC3
(Year 1976)
Year 2006
Thyristor Switched Reactor (TSR)

- Thyristor Switched Reactor is a primitive TCR, which has the ability of controlling the reactive power in steps, with just on/off control.
- Only suitable for slowly varying loads with fixed capacity, i.e. underground cable compensation.
Thyristor Switched Reactor (TSR)

Reactors of a Y-connected TSR installed for Bursaray, Turkey for the compensation of underground cables installed for light railway
Thyristor Switched Capacitor (TSC)

- Connected as passive shunt filter that is switched by back to back connected thyristors.
- TSC control is also stepwise as in the case of TSR. When compared to the conventional contactor type filter banks, TSC can be turned on and off in a few operating cycles.
- In order to limit overvoltages and to balance the load, TSC must be used with other types of SVCs such as TCR or STATCOM
Thyristor Switched Capacitor (TSC)

Delta connected 500kVAR TSC system installed in TKİ BLİ Enterprises by TÜBİTAK UZAY
Synchronous Condenser

- It is the Former technology for adjustable compensation. It consists of a synchronous generator and a field control circuitry.
- Fully controllable and has low harmonic generation. In a synchronous compensator, reactive power is varied by changing field current.
- Major drawbacks are high maintenance cost, slow response and balanced VAr generation capability.
Synchronous Condenser

Armature Current versus Field Current for Synchronous Condenser
Thyristor Controlled Reactor

Single line diagram of a polyphase TCR with, and without series thyristor operation.
Main Objective: Cancellation of 5th and 7th harmonics (and some other higher harmonics)
TCR Currents

![Diagram showing TCR Phase AB Current and TCR Line AB Voltage graphs with markings α and σ.](image-url)
\[ B_L(\sigma) = \frac{\sigma - \sin \sigma}{\pi X_L} \]
TCR Harmonics

- 5th Harmonic
- 7th Harmonic
- 11th Harmonic
- 13th Harmonic

Graphs showing the variation of p.u. of rms reactor current with firing angle for different harmonics.
SVC Design
Design Methodology

Contracting

- Specification of Requirements
- Investigation of current loads and further investment plans
- Design by hand calculation and simulation tools
  - Unsatisfactory
  - Performance Satisfactory?
    - Yes: Integration
    - 0
      - Compare standards and specifications meets
        - Subsystem Manufacturing
        - Subsystem Lab Tests
Design Methodology (Cont’n)

Integration

Integrated System Lab Tests

Performance Satisfactory?

Yes

No

System Integration

Type of Corrective Action

Design Concept
Design Methodology (Cont’n)

1. Transportation
2. Installation to the site
   - Check wiring and installation
     - Ready
       - Comissioning
         - Field Tests
           - Evaluation of Tests
             - Satisfactory
             - Unsatisfactory
               - Type of Corrective Action
                 - System Integration

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Design Methodology (Cont’n)
Case Study

A unified and relocatable TCR based SVC system for open cast lignite mining
Case Study

A unified and relocatable TCR based SVC system for open cast lignite mining

- **Design Criteria**
  - Unified
  - Relocatable
  - Modular

- **Possible SVC Types**
  - TCR + F
  - TSC
  - TSR
  - STATCOM
Relocation for Open Cast Lignite Mines

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Load Identification

(a)
Load Identification

Data Acquisition system

NI DAQCard 6062E, SC-2040 S/H Card (0.5 Ms/s)
Load Identification

- Single line diagram
- Monthly electric bills
- Daily active and reactive power demands
- Detailed information about electric motor drives, transformers
- An investigation of previously installed shunt compensators, and capacitors
- Future production plans and machine stocks
Single Piece / Two Piece Reactor
# PSCAD Simulation Results

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum 5th Harmonic Filter Current (kA)</th>
<th>Maximum 5th Harmonic Filter Capacitor Voltage (kV)</th>
<th>Maximum 7th Harmonic Filter Current (kA)</th>
<th>Maximum 7th Harmonic Filter Capacitor Voltage (kV)</th>
<th>Maximum TCR Line current (kA)</th>
<th>Maximum TCR Thyristor current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4760</td>
<td>0.9582</td>
<td>0.4296</td>
<td>1.0245</td>
<td>26.7383</td>
<td>0.7590</td>
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<td>2</td>
<td>0.1383</td>
<td>0.5457</td>
<td>0.0927</td>
<td>0.5009</td>
<td>33.7312</td>
<td>0.9013</td>
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<td>3</td>
<td>0.1276</td>
<td>0.8337</td>
<td>0.0832</td>
<td>0.8152</td>
<td>27.5715</td>
<td>0.7833</td>
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<td>4</td>
<td>0.2920</td>
<td>0.4659</td>
<td>0.2629</td>
<td>0.4559</td>
<td>39.4042</td>
<td>0.6918</td>
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<td>5</td>
<td>0.1333</td>
<td>0.8257</td>
<td>0.0877</td>
<td>0.8005</td>
<td>1.4378</td>
<td>1.6126</td>
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<tr>
<td>6</td>
<td>0.1260</td>
<td>0.8171</td>
<td>0.0826</td>
<td>0.7959</td>
<td>1.7268</td>
<td>1.8834</td>
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<tr>
<td>7</td>
<td>0.1277</td>
<td>0.8336</td>
<td>0.0832</td>
<td>0.8151</td>
<td>1.0207</td>
<td>1.0602</td>
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<tr>
<td>8</td>
<td>0.1300</td>
<td>0.8090</td>
<td>0.0855</td>
<td>0.7799</td>
<td>2.5117</td>
<td>1.8673</td>
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<tr>
<td>9</td>
<td>0.1266</td>
<td>0.8253</td>
<td>0.0828</td>
<td>0.8054</td>
<td>1.1658</td>
<td>1.1886</td>
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<tr>
<td>10</td>
<td>0.1277</td>
<td>0.8336</td>
<td>0.0832</td>
<td>0.8151</td>
<td>1.0207</td>
<td>1.0602</td>
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<tr>
<td>11</td>
<td>0.1303</td>
<td>0.8294</td>
<td>0.0853</td>
<td>0.8070</td>
<td>1.0265</td>
<td>0.7659</td>
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<tr>
<td>12</td>
<td>0.1281</td>
<td>0.8252</td>
<td>0.0836</td>
<td>0.8029</td>
<td>1.2619</td>
<td>1.0690</td>
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</table>
Implmented System

- 15 or 34.5kV Busbar
- HV SF6 Breaker
- Coupling Transformer
- LV Air Ballast Breaker
- 1kV Bus
- L5, L7
- C5, C7
- 5th Harm. Filter
- 7th Harm. Filter
- TCR
Reactors

1 MVAr TCR
2 x 4.7mH, 376A, 1kV, BIL 20kV

1.5 MVAr TCR
2 x 3.17mH, 563A, 1kV, BIL 20kV

2 MVAr TCR
2 x 2.35mH, 752A, 1kV, BIL 20kV

Air core, outdoor reactor group
Thyristor Stack Design

1.5 MVAr TCR (Phase AB)

Phase A Line (1kV)

\[ R_{snb} = 270 \Omega \]

\[ C_{snb} = 0.33 \mu F \]

Phase B Line (1kV)

Single Switch

DCR1476SY3434

\[ \Omega = 270 \]

\[ \mu \Omega = 33.0 \]

\[ MVAr = 1476 \]

\[ SY3434 \]
Filters

1kV Busbar

L5 = 903uH
L7 = 674uH

C5 = 162uF
C7 = 108uF

Tuning Frequency: 240.25 Hz
Tuning Frequency: 340.58 Hz
Amplification due to Parallel Resonance

Harmonics injected from TCR (1A)
Measurement
Protection

36kV, 630A, 16kA SF6 Circuit Breaker

Protection Relays

Protection circuits in Control Panel
## Transformer Design

<table>
<thead>
<tr>
<th></th>
<th>Conventional Transformers</th>
<th>SVC Coupling Transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDD</td>
<td>Limits defined by [23,35,42]</td>
<td>High if filters are mostly at the primary side</td>
</tr>
<tr>
<td>Even Harmonics in the load (and SVC)</td>
<td>Limits defined by [23,35,42]</td>
<td>Higher than limits</td>
</tr>
<tr>
<td>DC Current</td>
<td>None</td>
<td>Depends on controller, may be excessive in misfiring conditions</td>
</tr>
<tr>
<td>Voltage Fluctuation</td>
<td>Limits defined in [22,23]</td>
<td>Depends on loadbus, mostly higher than regular</td>
</tr>
<tr>
<td>Transformer Design</td>
<td>IEC 76, ANSI C.57  [58,59]</td>
<td>IEC 76, ANSI C.57; with minor additions</td>
</tr>
<tr>
<td>Core Size and Physical Dimensions</td>
<td>Regular</td>
<td>Core and case dimensions are bigger for the same MVA</td>
</tr>
<tr>
<td>Overloads</td>
<td>Rare, depending on load busbar</td>
<td>Usual, depending on load busbar</td>
</tr>
<tr>
<td>Load Fluctuation</td>
<td>Low</td>
<td>High, especially in arc furnace applications</td>
</tr>
<tr>
<td>Saturation</td>
<td>IEC 76</td>
<td>Needs extra precautions</td>
</tr>
</tbody>
</table>
The ANSI/IEEE standard C57.110 [39] defines a K factor

\[
K = \sqrt{\frac{\sum_h (I_h^2 h^2)}{\sum_h I_h^2}}
\]

\[
I_{\text{max}} = I_R \sqrt{\frac{1 + P_{EC,R}}{1 + KP_{EC,R}}}
\]

\[
B_{op} \text{ can be selected below } 1.6 \text{ Wb/m}^2 \text{ instead of } 1.8 \text{ Wb/m}^2 \text{ used normally for distribution transformers}
\]

B-H Characteristics of an M3 type Steel Core
EMC Considerations

Avoiding Loops

Magnetic Clearances

1. Compensator Transformer
2. Switchgear Container
3. EMI Compatible Low-Voltage Equipment Container
4. Air-Cooled Thyristor Controlled Reactor
5. Guard Fence
6. Mounting Platform
Environmental Conditions

- Flashover due to extreme pollution
- Heavy Weather Conditions
Reactive Power Compensation

![Graph showing Reactive Power Compensation over time]

- Inductive
- Capacitive
- Load
- SVC

Data and graphs illustrate the compensation efforts over time, emphasizing load and SVC impacts on reactive power.
Harmonics

Transformer Primary Current Referred to 1kV

Filter Current

Field Data

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Harmonics

Reactor Line Current

Filter Current

Field Data
# Reactor Current

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>6-Pulse TCR Theoretical (%)</th>
<th>Field Data (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>1.52</td>
</tr>
<tr>
<td>5</td>
<td>5.05</td>
<td>5.02</td>
</tr>
<tr>
<td>7</td>
<td>2.59</td>
<td>2.56</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>0.35</td>
</tr>
<tr>
<td>11</td>
<td>1.05</td>
<td>0.95</td>
</tr>
<tr>
<td>13</td>
<td>0.75</td>
<td>0.72</td>
</tr>
</tbody>
</table>
Harmonics

TKI
BLI 34.5kV
Busbar

Transformer
Primary Current

Main
Transformer

Reactor Line
Current

5th Harm. Filter
Current (Rogovsky)

7th Harm. Filter
Current (Rogovsky)

C5 = 162uF
C7 = 108uF
L5 = 903uH
L7 = 674uH

250A / 5A
0.5Fs5 / 10VA

500A / 5A
0.5Fs5 / 10VA

1000A / 5A
0.5Fs5 / 10VA

Ground

3.17mH

3.17mH

3.17mH

3.17mH

3.17mH

100A / 5A
10P10 / 5VA
Harmonics

(a) SVC Current Referred to the 1kV side of the Coupling Transformer
(b) Reactor Line Current
(c) 5th Harmonic Filter Current
(d) 7th Harmonic Filter Current

No TCR firing
0.5 p.u. of full conduction current of TCR
### Compared to Design Parameters

<table>
<thead>
<tr>
<th>Filter element</th>
<th>5th HF</th>
<th>7th HF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max rms current, A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 Hz</td>
<td>4 / 3</td>
<td>13 / 9</td>
</tr>
<tr>
<td>50 Hz</td>
<td>26 / 16</td>
<td></td>
</tr>
<tr>
<td>350 Hz</td>
<td>1 / 0.8</td>
<td></td>
</tr>
<tr>
<td>Total current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>True rms, (A)</td>
<td>115 / 67</td>
<td>75 / 46</td>
</tr>
<tr>
<td></td>
<td>71 / 44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>110 / 65</td>
<td></td>
</tr>
</tbody>
</table>
Thyristor Valve (Phase) Voltage and Current
Thyristor Valve Voltage and Current Waveform, Reactor current 0.95 p.u. of full conduction current

- Max. 1.83kV Voltage
- Current

Time (ms)

Voltage (V) / Current (A)
Control System Design

For SVC Systems
Feed-back

Set Error -> PI -> Triggering -> Reactive Power

Measurement

- +
Feed-Forward

\[ I_{\text{line}} + I_{\text{load}} \rightarrow P \rightarrow \text{Triggering} \rightarrow \text{Reactive Power} \]

\[ I_{\text{SVC}} \]
Simple P-I Control

- Linearizing
- Trigger Circuits
- P-I Regulator
- Reactive Power Measurement
- TCR
- Harmonic Filter(s)
- Load
- Supply
Control with Load Balancing
Complete Control System Design

Flicker Compensation System with feed-forward and feed-back control
Response Time Simulation

- Proportional gain is 0.2,
- Integral gain is 0.45
- Feed-forward gain is 0.133
- PI time constant is selected 38ms
Control System Response

- 1. Measurement delay
- 2. Firing circuit delay
- 3. PI + FF regulator delay

Response

Time (mS)

- 0.1 - 10 mS
- 10 mS
- 30 - 100 mS

- • 1 - Measurement delay
  • 2 - Firing circuit delay
  • 3 - PI + FF regulator delay
Open Loop Response

Maximum Inductive Power Reached

Maximum Capacitive Power Reached

TCR Reactive Power (p.u.)

Time (ms)

TCR Response

TCR Reference

$T_r = 13\text{ms}$
PI Regulator Only (FF disabled)

PI Loop response of TCR, Feed-forward disabled

$T_r = 140\,\text{ms}$
PI + FF Regulators

- Proportional gain is 0.2,
- Integral gain is 0.45
- Feed-forward gain is 0.133
- PI time constant is selected 38ms
Reducing the Response Time

PI Time constant = 25ms

TCR Response (PI time constant = 25mS)

\[ T_r = 90\text{ms} \]