# Dynamic Reactive Power Control

By
V. R. Kanetkar
Full Time Consultant – Technical Services at
Veretiv Energy Private Limited
Thane (West)

## Acknowledgement

The author acknowledges with deep gratitude the experience he gathered while working with M/s L&T (1978-89), ABB Ltd India (1995-2009), Autometers Alliance Ltd (2009-12), Shreem Electric Limited (2012-16), and Vertiv Energy Private Limited (2016 onwards) and the opportunities offered by them towards drawing this long experience in power electronics, especially in R&D.

The author also acknowledges the contribution made to his professional life by all the engineers with whom he had an opportunity to work and his teachers from whom he learnt the value and impact the knowledge and experience can make.

Product photographs shown here are of the products on which he worked during his tenure with ABB Ltd India. He hopes that ABB Ltd India will not have any objection as these are shown here only to support the presentation subject and without any commercial angle attached. The author expresses his deep gratitude to ABB Ltd India and extends his apology to ABB Ltd India that these are shown without their written permission, though for a good engineering cause.

## Power Quality is related to any deviation from the normal voltage and frequency of the supply system.

## Power Quality Issues

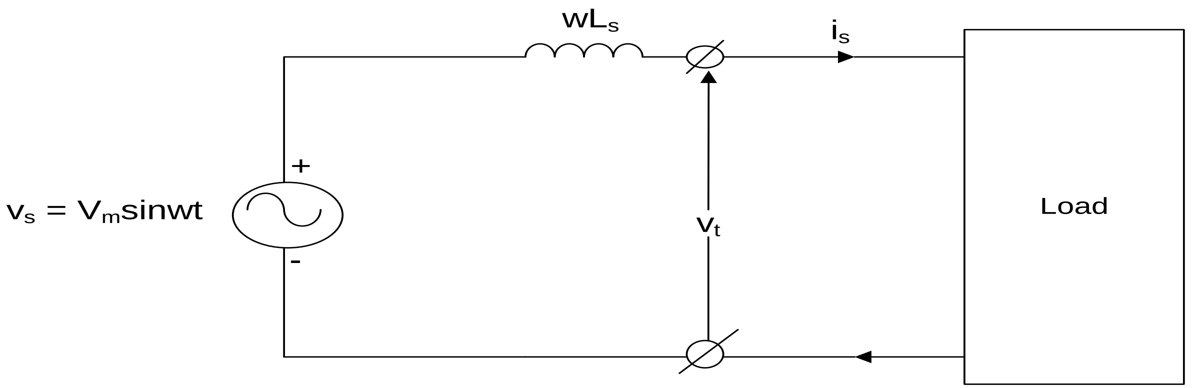
- **Varying reactive power causing terminal voltage and power factor variation, flicker, and additional losses in upstream system**

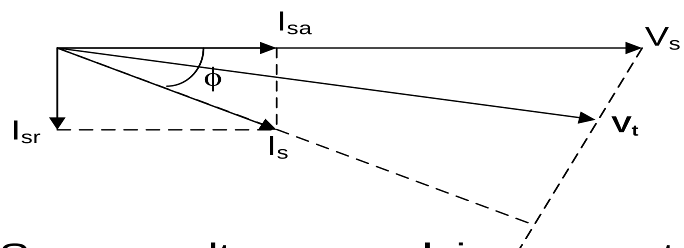
- **Current harmonics causing losses, voltage distortion, and system resonance**

- **Unbalanced currents giving rise to neutral currents and lifting the neutral potential dangerously with respect to earth**

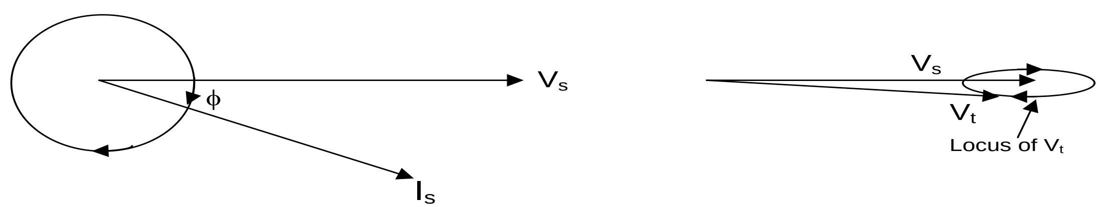
- **Sudden voltage dips / rises and frequency changes**

- **Voltage sags, swells, brownouts, and blackouts**



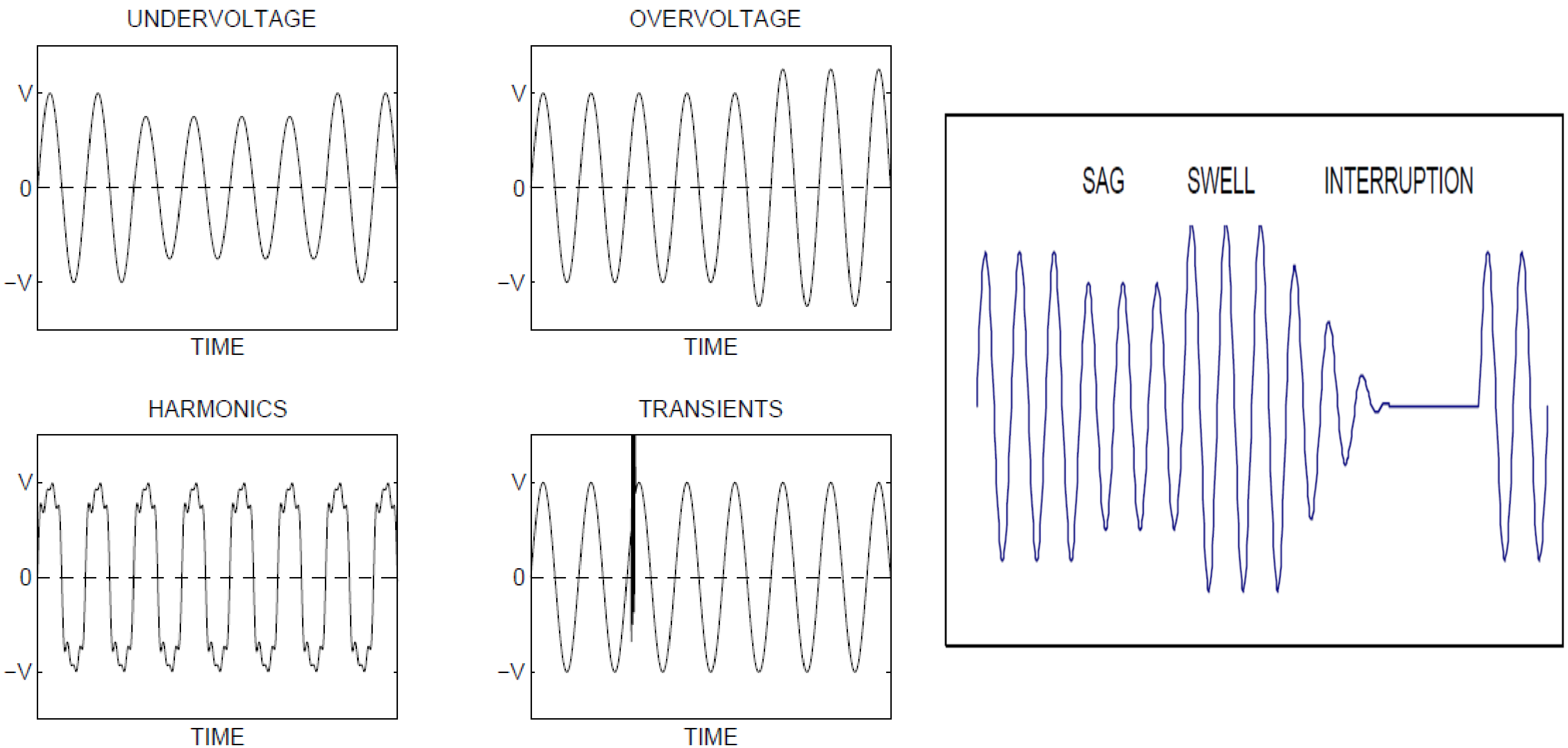




(a) Source voltage supplying current $i_s$ at lagging power factor $\phi$




(b) Locus of $V_t$

**Variation in terminal voltage $V_t$ with supply current $i_s$ at 360° powerangle range**


UNDERVOLTAGE
OVERVOLTAGE
HARMONICS
TRANSIENTS
V
0
−V
TIME
SAG
SWELL
INTERRUPTION

# Mitigation devices

## Reactive power control

• PF correction capacitors (very low response time)

• SVC (TCR, TSC) (Good response time, TCR odd harmonics, TSC / number of banks defining steps / resolution)

• STATCOM (Very fast response less than quarter cycle, stepless / smooth compensation)

## Harmonic control

• Current harmonics
Shunt passive and / or Active filters
(SVC light of ABB which also includes load balancing and reactive power control)

•Voltage harmonic (distortion)
Series active filters

## Voltage sag, swell, small interruptions / momentary voltage dips (0.6 to 1.5 secs)

• SVR (Low power levels, say few MVA / LV / part of MV)

•DVR (Medium to high power levels, say 50 to 60 MVA , MV and HV)
Response time 1 msecs to few msecs

## Other devices

• TCSC for damping power system oscillations, mitigating sub synchronous resonance, and improving stability of two power grids connected together

• Unified Power Flow Controller

• Surge arresters for voltage transients

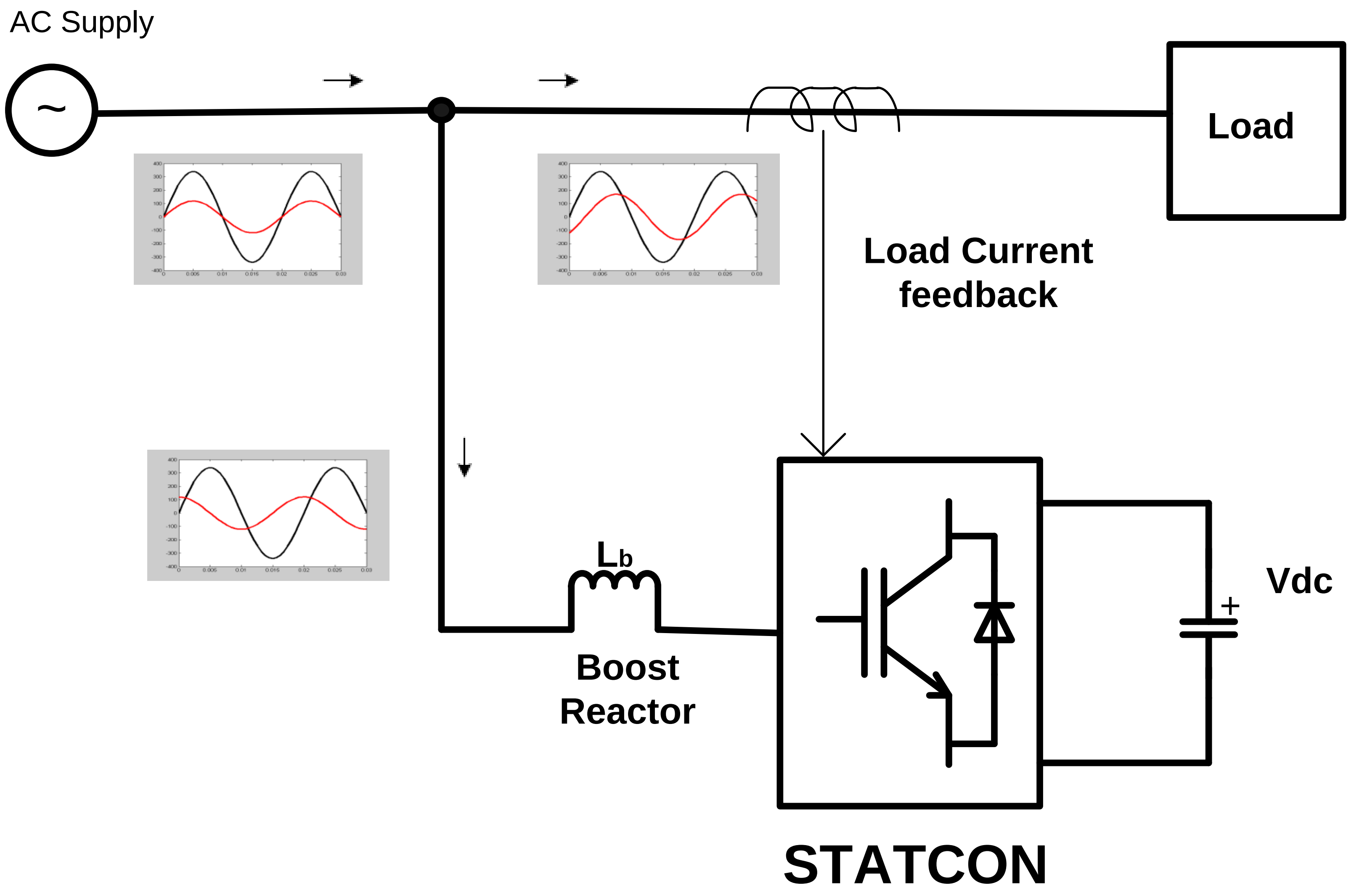
• Solid state transfer switch

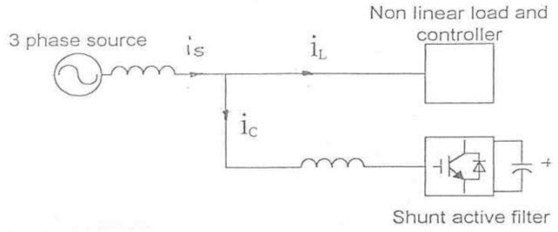
• UPS and BESS (Battery energy storage systems)

• Superconducting magnetic storage systems

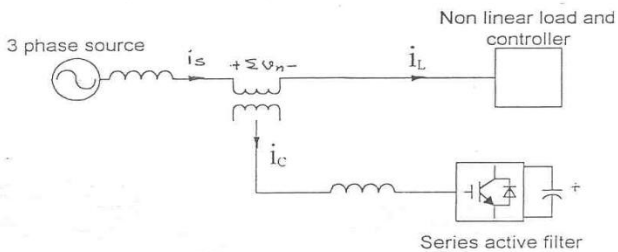
• Solid state circuit breakers

# 4Q Voltage Source Converters for DPRC

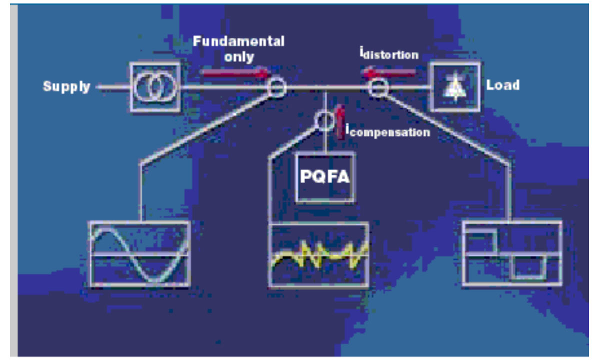


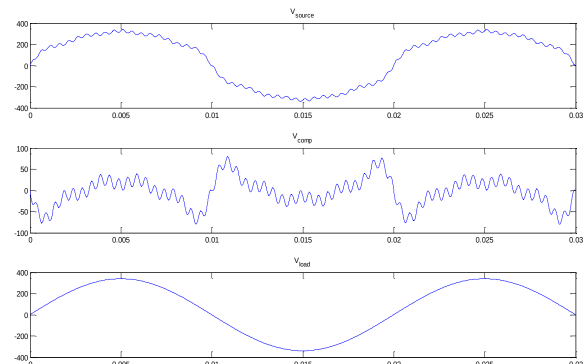



(a)



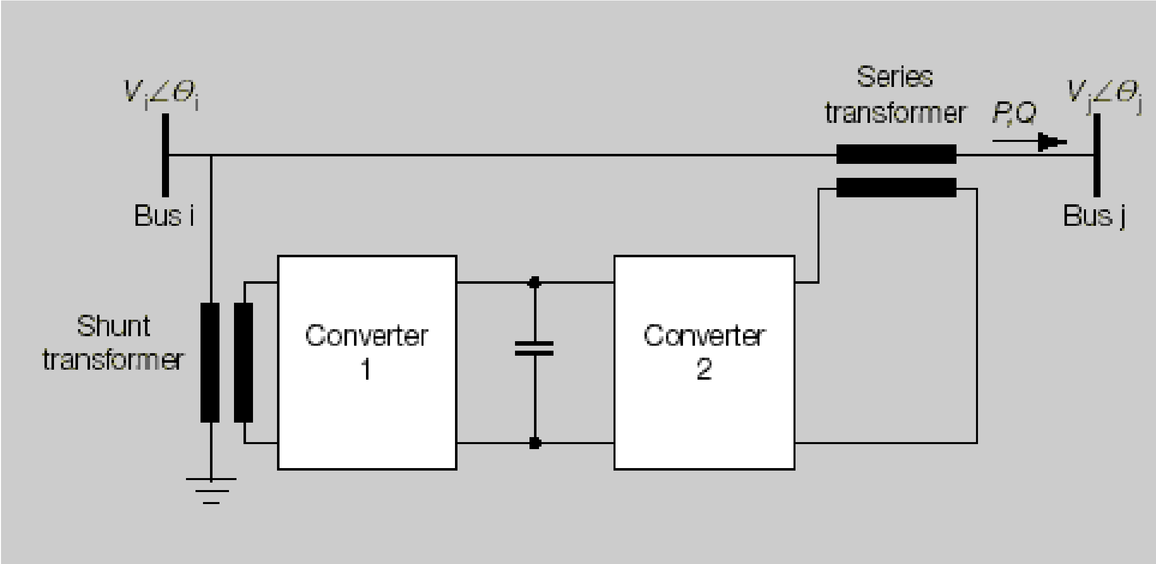

(b)



(a) Shunt active filter for harmonics

(b) Series active filter for voltage profile improvement




***Basic circuit arrangement of the unified power flow controller (UPFC)*** **23**

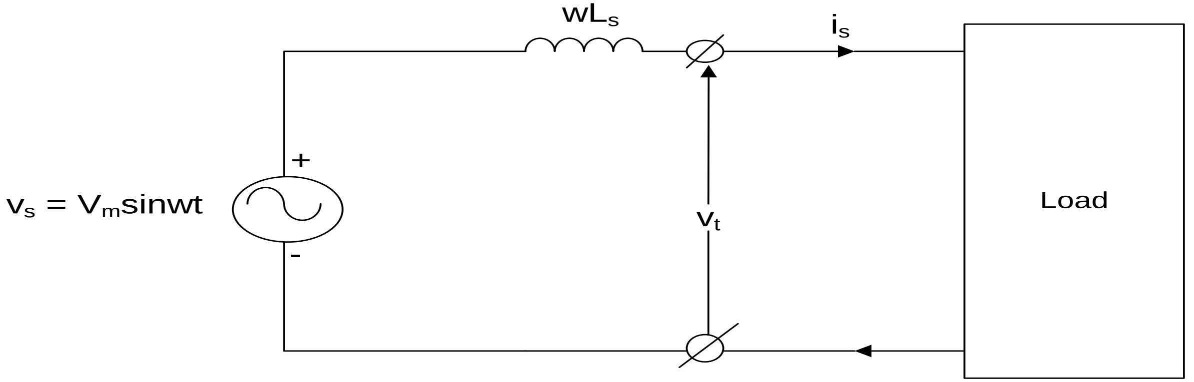
*P Active line power*
*Q Reactive line power*
*$V_{i,j}$ Voltage magnitudes, buses i and j*
*$\Theta_{i,j}$ Voltage angles, buses i and j.*

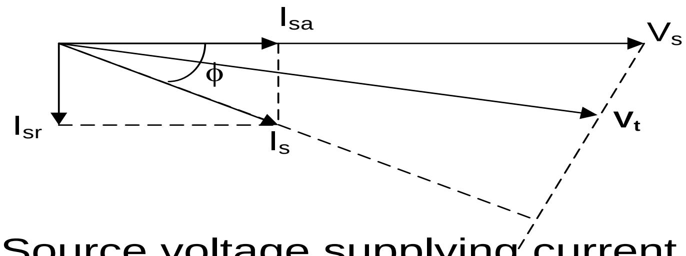
**Unified Power Flow Controller (UPFC)**

**Concentrate on Reactive Power Control (Dynamic), which is more important for us.**

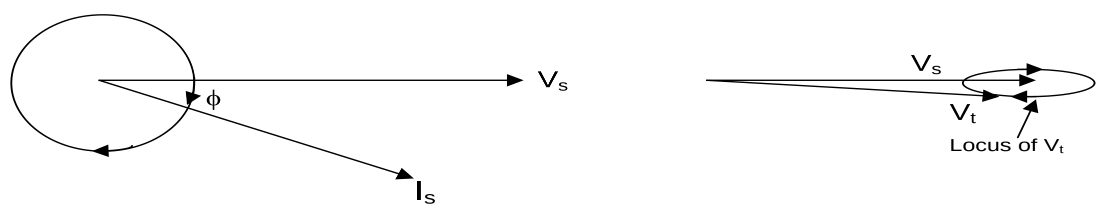
**This is called as "DRPC".**

Reactive Power equivalence to a glass of beer




(a) Source voltage supplying current $i_s$ at lagging power factor $\phi$




(b) Locus of $V_t$

**Variation in terminal voltage $V_t$ with supply current $i_s$ at 360° powerangle range**

## Why is Reactive Power Compensation required?

- Reduction in transformer or supply currents to improve power factor and reduce associated penalty

- Reduction in transformer or supply currents to reduce maximum kVA demand

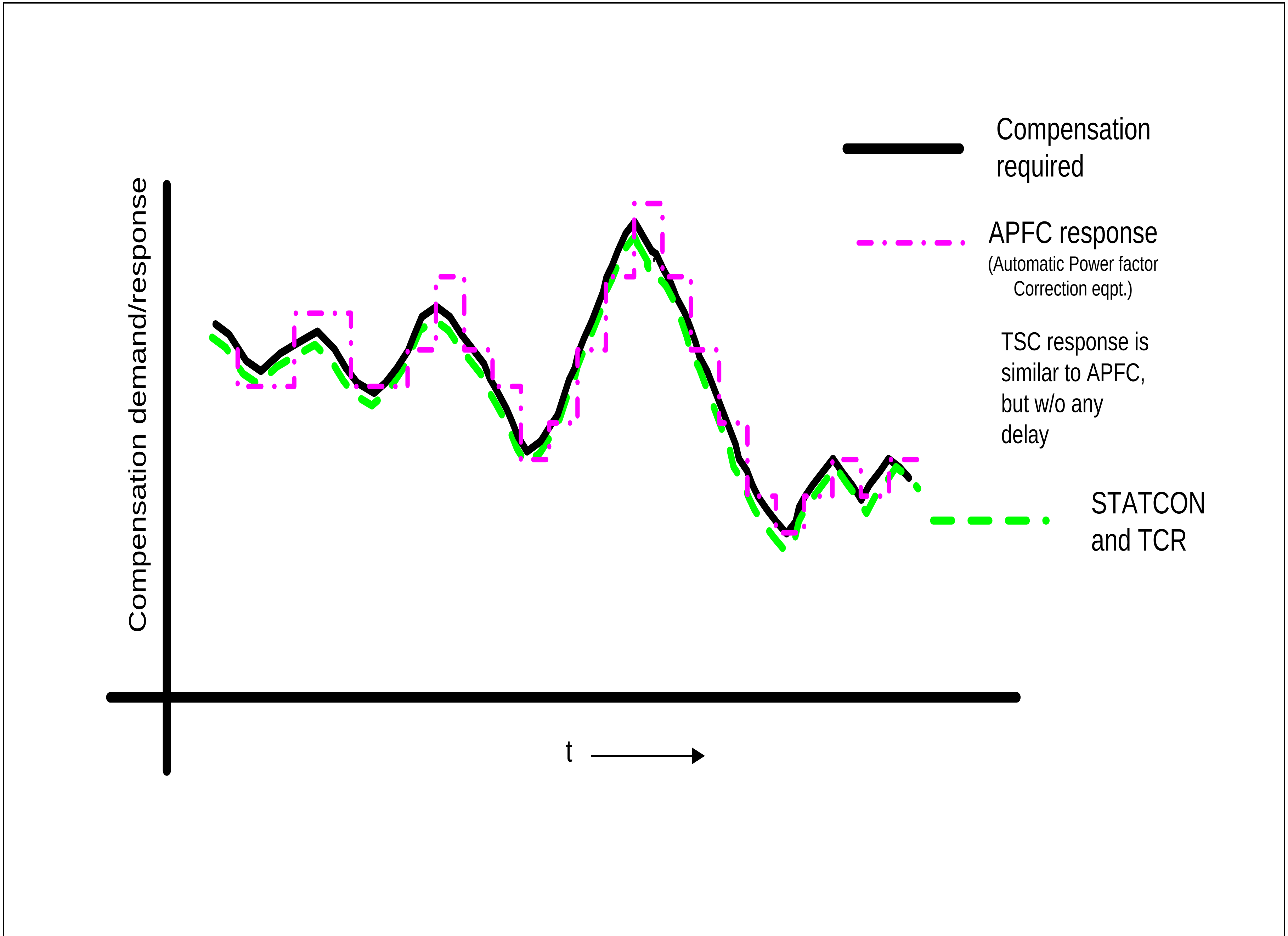
- Reduction in transformer or supply currents so that more load can be added

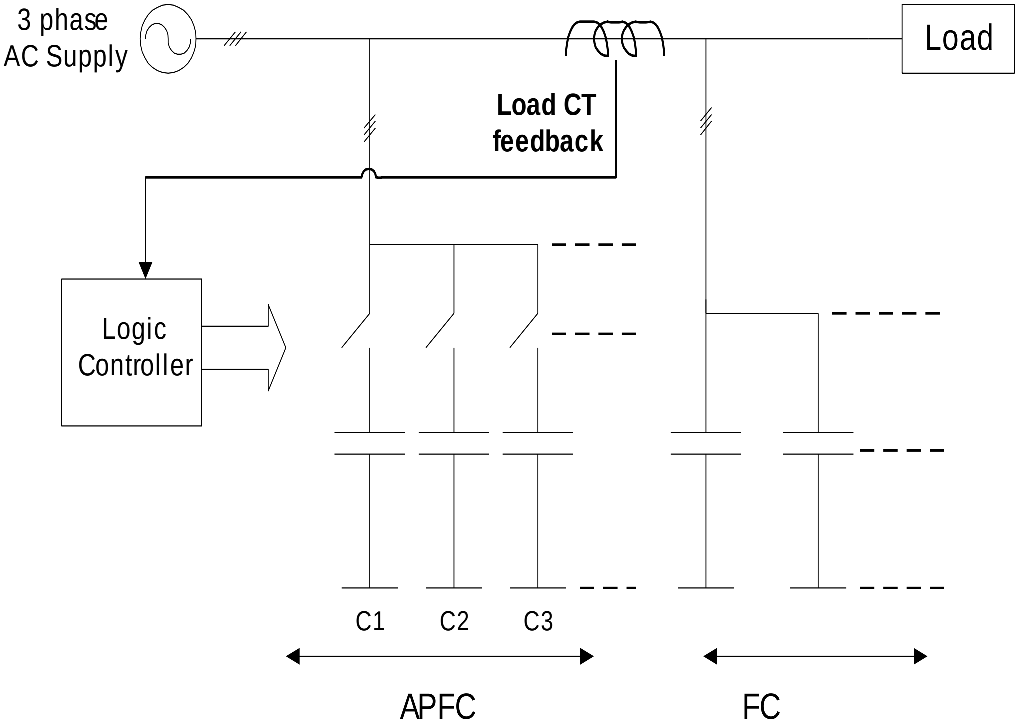
- Reduction in transformer and supply currents to reduce losses in the system

- Improvement of the voltage profile and reduction in flicker (better voltage stability)

**The reactive power compensation methods used earlier / even at present are as given below.**

- **Fixed HT / LT capacitors (FC)**
- **Switched HT capacitors as in 11 kV networks (SC-HT)**
- **Switched LT capacitors**
**(SC-LT or more commonly known as Automatic Power factor Correction or APFC)**
- **Thyristor Switched Capacitors (TSC)**
- **Thyristor Controlled Reactor (TCR)**


Compensation demand/response
t
Compensation required
APFC response
(Automatic Power factor Correction eqpt.)
TSC response is similar to APFC, but w/o any delay
STATCON and TCR




Fixed capacitor and APFC

## Fixed Capacitor / APFC based compensation

• **Low dynamics involved, hence suitable for slow varying loads**

• **High inrush currents and voltage transients due to contactor switchings affecting life of the capacitors as well as equipment connected on the same bus**

•**Considerable under and over-compensation for varying loads**

•**Resonance with supply short circuit impedance**

•**Harmonic amplification**

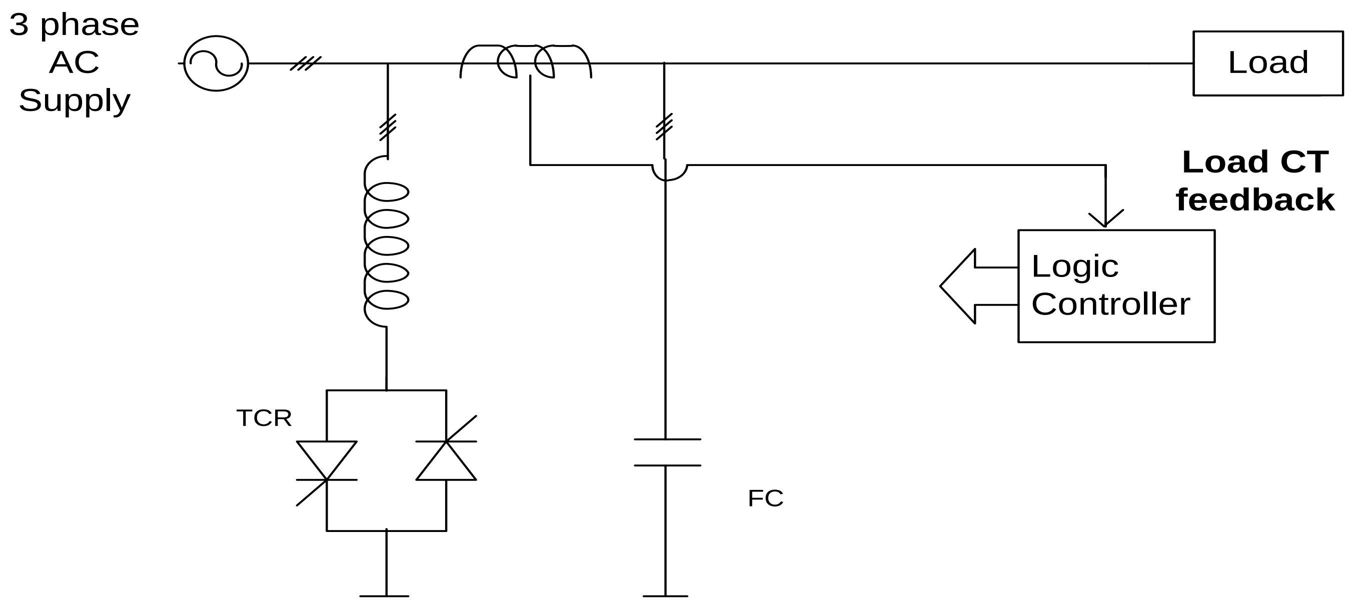
•**kVAR delivery is supply voltage dependent (proportional to square of the supply voltage) which produces inaccuracy in overall kVAR compensation**

•**Ageing problems of capacitors resulting in less kVAR**

•**Considerable maintenance**

**This method of reactive power compensation is, however, quite economical if there is not much of reactive power variation and if the disadvantages are not affecting the system.**

**The capacitors need to be sized based on the required base compensation, voltage variation, and current harmonics to be absorbed (using a series reactor with tuning frequency maintained below the lowest harmonic frequency).**




**TCR with FC (Also called as SVC)**

# TCR based compensation

- **Suitable for fast dynamically varying loads (arc furnace), but at the cost double kVAR installed capacity and lower order harmonics produced (normally, hence, preferred for very high compensation requirements such as 30 MVAR and beyond)**

- **Compensation kVAR to be installed is double the actual kVAR requirement**

- **Resonance with supply short circuit impedance**

- **Harmonic amplification**

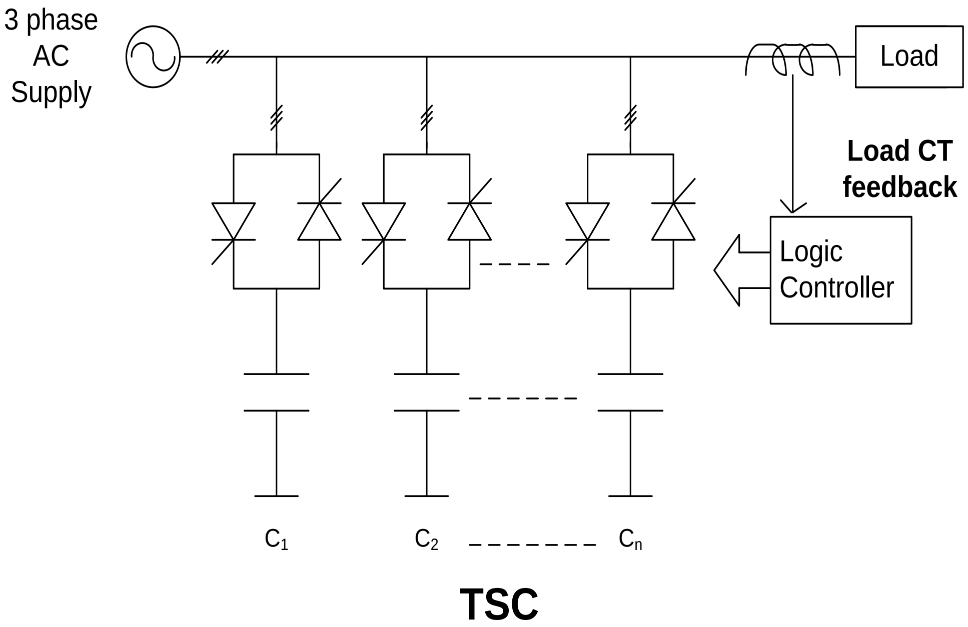
- **Not economical for low and medium power kVAR compensation**

- **Capacitor kVAR delivery is supply voltage dependent (proportional to square of the supply voltage) which produces inaccuracy in overall kVAR compensation**

- **Ageing problems of capacitors resulting in less kVAR and compensation inaccuracy**

- **Considerable maintenance**

**This method of reactive power compensation is definitely better than the first three methods, but also involves more installation cost. It offers good response time and is normally used for higher MVAR compensation (greater than 10 MVAR at least).**


3 phase
AC
Supply
Load
Load CT
feedback
Logic
Controller
C1
C2
Cn
TSC

## TSC based compensation

•Not suitable for load dynamics of the order of seconds (due to discharge time of capacitors for switching duty) unless control is designed for it.

•Can result in under and over-compensation for varying loads due to step response, unless steps are properly worked out.

•Resonance with supply short circuit impedance and harmonic amplification, if not designed properly.

• Can result in high inrush currents and voltage transients unless proper synchronization is not taken care of in the design

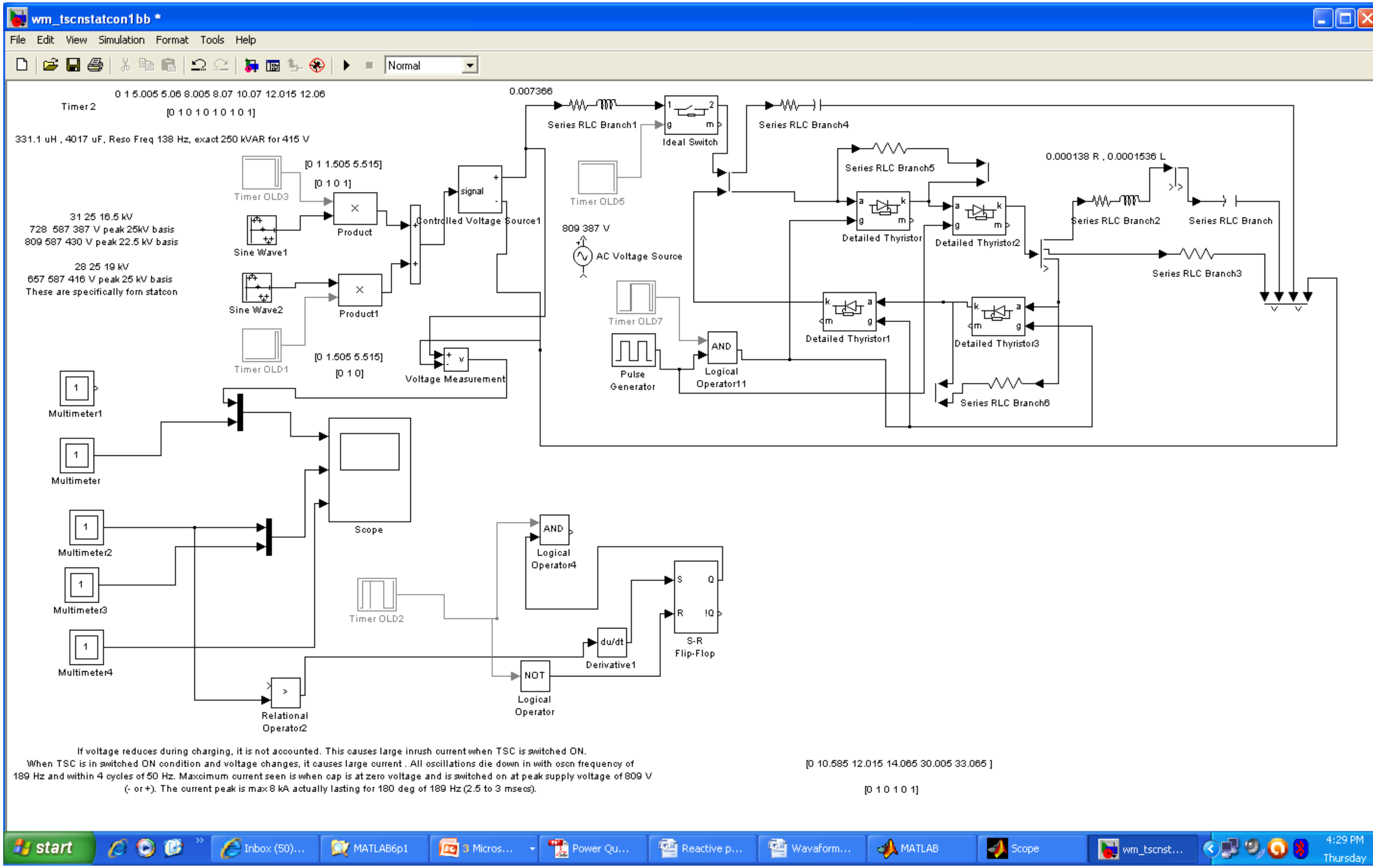
• kVAR delivery is supply voltage dependent (proportional to square of the supply voltage) which produces inaccuracy in overall kVAR compensation

• Ageing problems of capacitors resulting in less kVAR and compensation inaccuracy

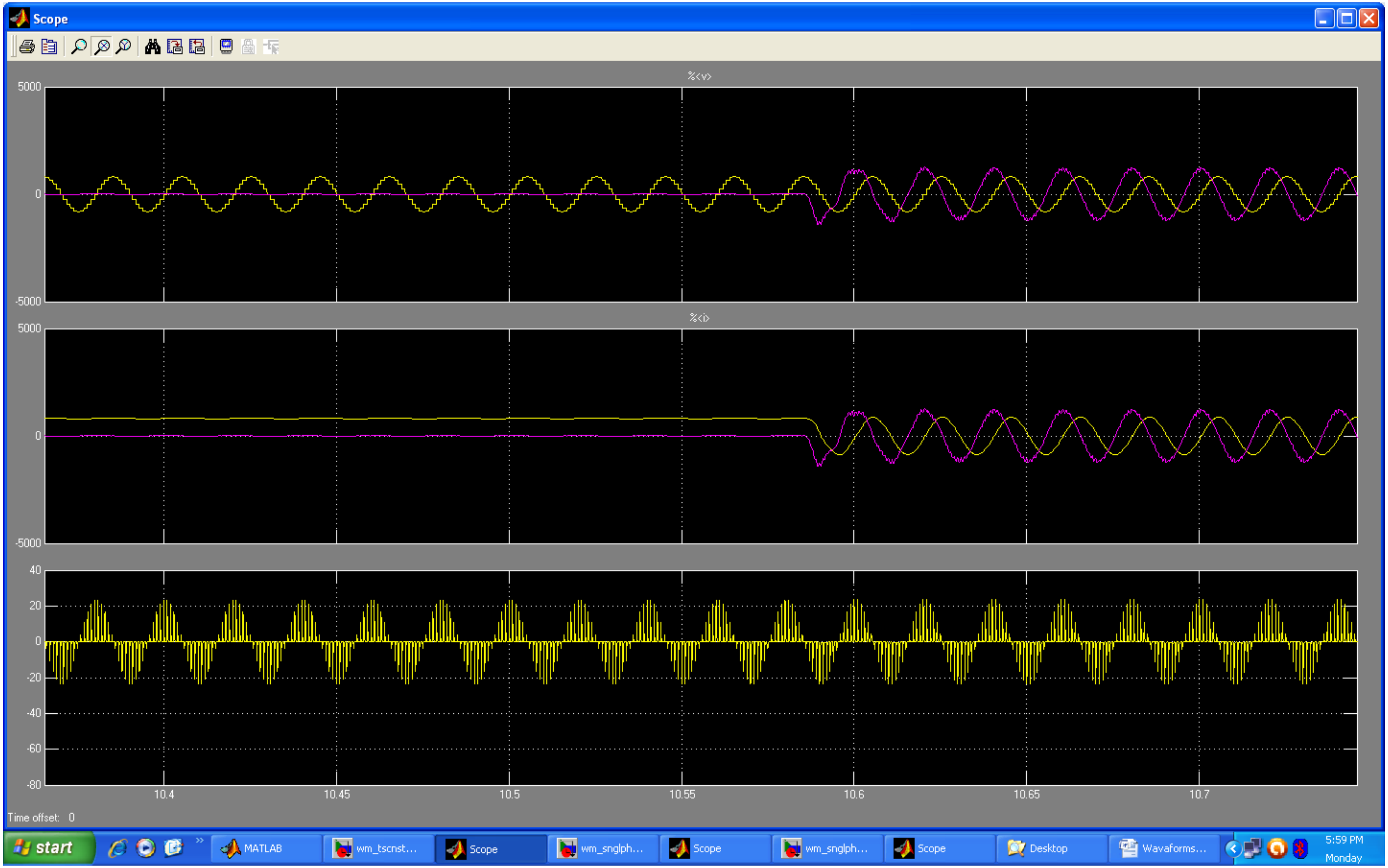
•Considerable maintenance unless capacitor designs / selection is properly done

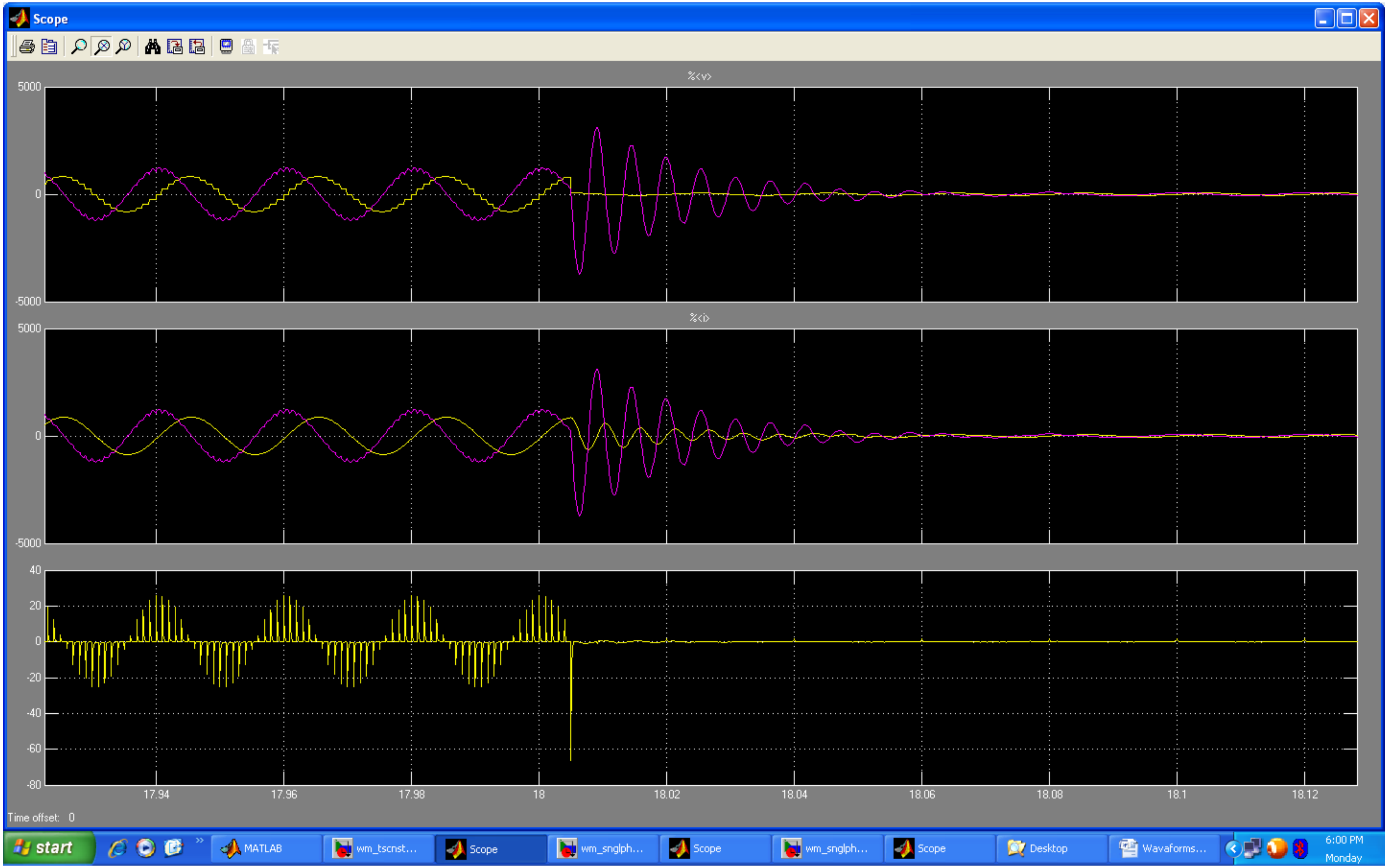
This method of reactive power compensation is definitely better than the first two methods, but also involves more installation cost.

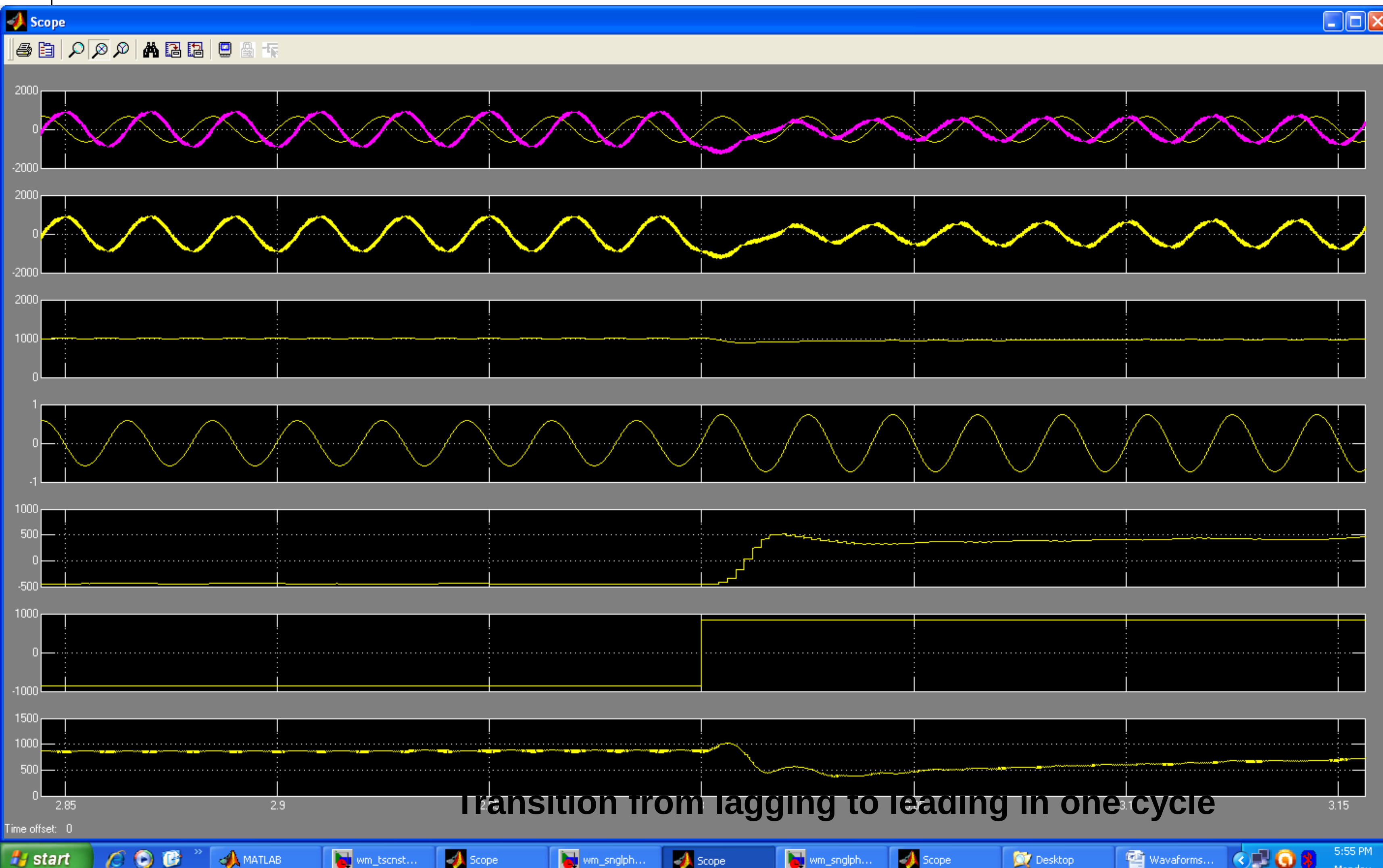
## 250 kVAR TSC simulation results


wm_tscnstatcon1bb *
File Edit View Simulation Format Tools Help
Normal
0 1 5.005 5.06 8.005 8.07 10.07 12.015 12.06
Timer 2
[0 1 0 1 0 1 0 1 0 1]
331.1 uH , 4017 uF, Reso Freq 138 Hz, exact 250 kVAR for 415 V
0.007366
Series RLC Branch1
Ideal Switch
Series RLC Branch4
Series RLC Branch5
0.000138 R , 0.0001536 L
[0 1 1.505 5.515]
[0 1 0 1]
Timer OLD3
Product
Sine Wave1
signal
Controlled Voltage Source1
Timer OLD5
809 387 V
AC Voltage Source
Detailed Thyristor
Detailed Thyristor2
Series RLC Branch2
Series RLC Branch
Series RLC Branch3
31 25 16.5 kV
728 587 387 V peak 25kV basis
809 587 430 V peak 22.5 kV basis
28 25 19 kV
657 587 416 V peak 25 kV basis
These are specifically forn statcon
Sine Wave2
Product1
Timer OLD7
AND
Pulse Generator
Logical Operator11
Detailed Thyristor1
Detailed Thyristor3
Series RLC Branch6
Timer OLD1
[0 1.505 5.515]
[0 1 0]
Voltage Measurement
Multimeter1
Multimeter
Scope
Multimeter2
Multimeter3
Multimeter4
AND
Logical Operator4
Timer OLD2
S-R Flip-Flop
du/dt
Derivative1
NOT
Logical Operator
Relational Operator2
If voltage reduces during charging, it is not accounted. This causes large inrush current when TSC is switched ON.
When TSC is in switched ON condition and voltage changes, it causes large current . All oscillations die down in with oscn frequency of
189 Hz and within 4 cycles of 50 Hz. Maximum current seen is when cap is at zero voltage and is switched on at peak supply voltage of 809 V
(- or +). The current peak is max 8 kA actually lasting for 180 deg of 189 Hz (2.5 to 3 msecs).
[0 10.585 12.015 14.065 30.005 33.065 ]
[0 1 0 1 0 1]
start
Inbox (50)...
MATLAB6p1
3 Micros...
Power Qu...
Reactive p...
Waveform...
MATLAB
Scope
wm_tscnst...
4:29 PM
Thursday

# TSC Control

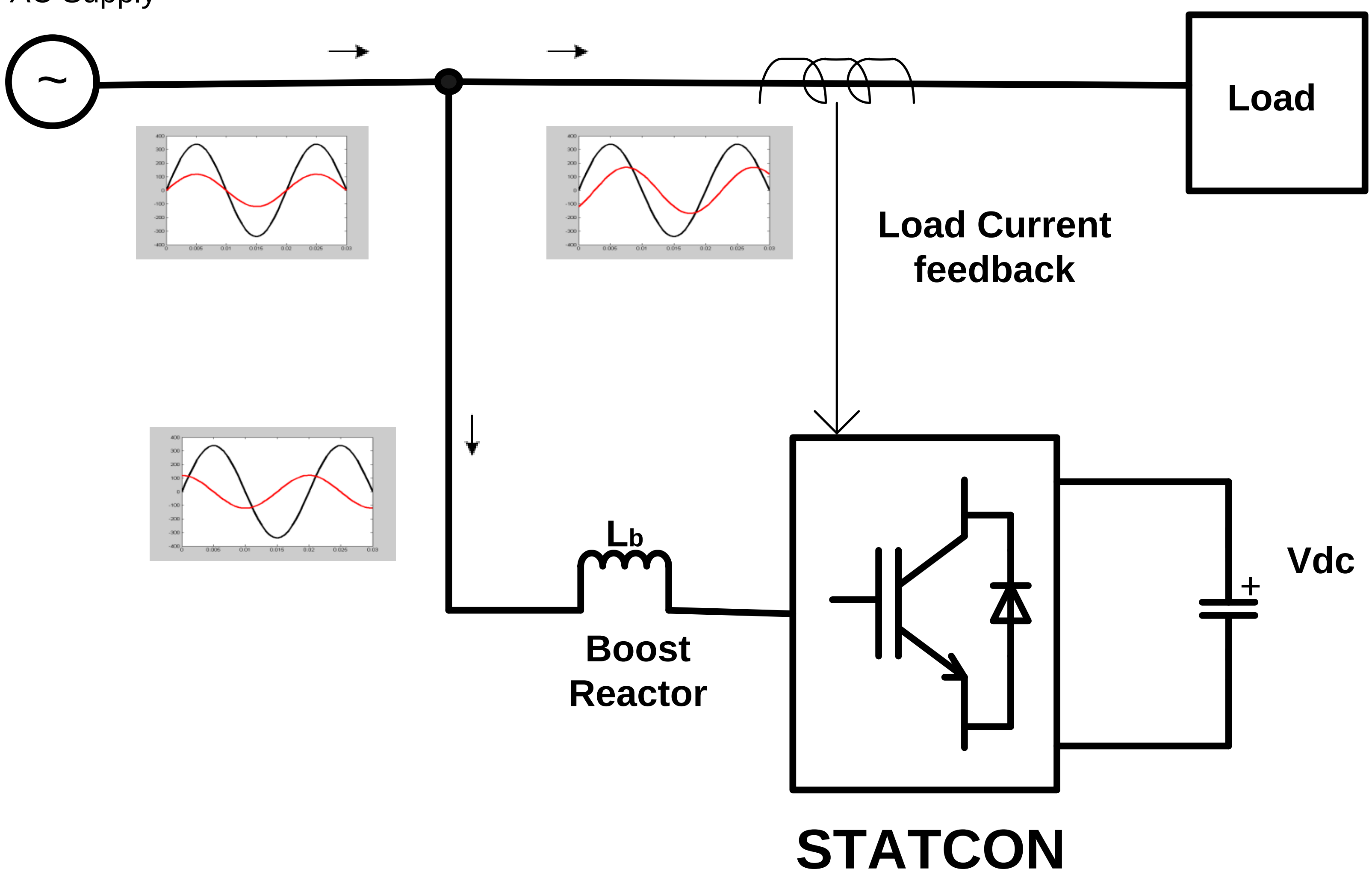

Scope
%<v>
5000
0
-5000
%<i>
5000
0
-5000
40
20
0
-20
-40
-60
-80
10.4
10.45
10.5
10.55
10.6
10.65
10.7
Time offset: 0
start
MATLAB
wm_tscnst...
Scope
wm_snglph...
Scope
wm_snglph...
Scope
Desktop
Wavaforms...
5:59 PM
Monday

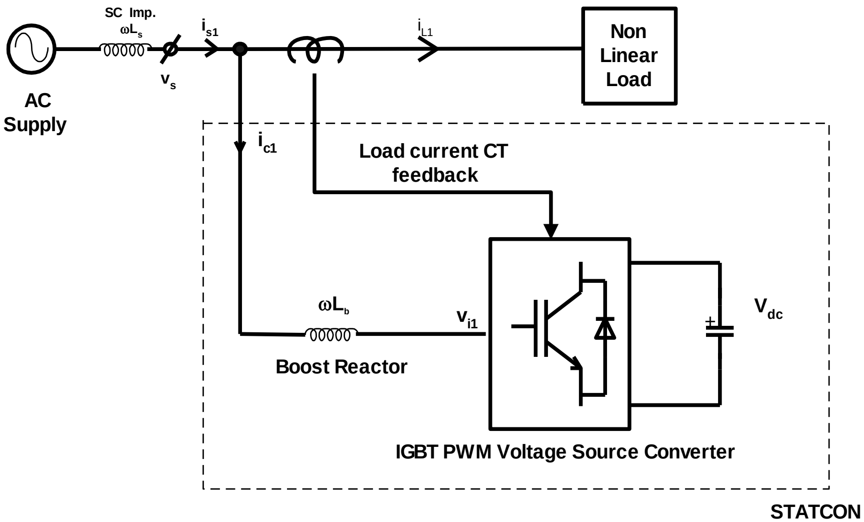

Scope
%<v>
5000
0
-5000
%<i>
5000
0
-5000
40
20
0
-20
-40
-60
-80
17.94
17.96
17.98
18
18.02
18.04
18.06
18.08
18.1
18.12
Time offset: 0
start
MATLAB
wm_tscnst...
Scope
wm_snglph...
Scope
wm_snglph...
Scope
Desktop
Wavaforms...
6:00 PM
Monday



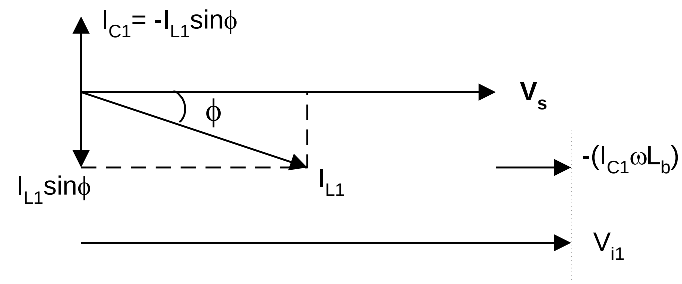

Transition from lagging to leading in one cycle

# 4Q Voltage Source Converters for DPRC

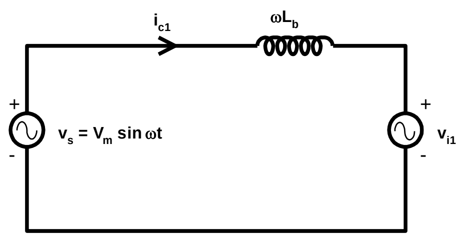




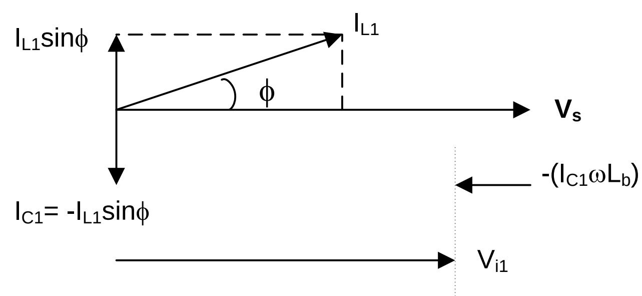

Single line diagram for a typical load using STATCON




Vector diagram for capacitive compensation
( Load demands inductive power
STATCON provides capactive compensation)



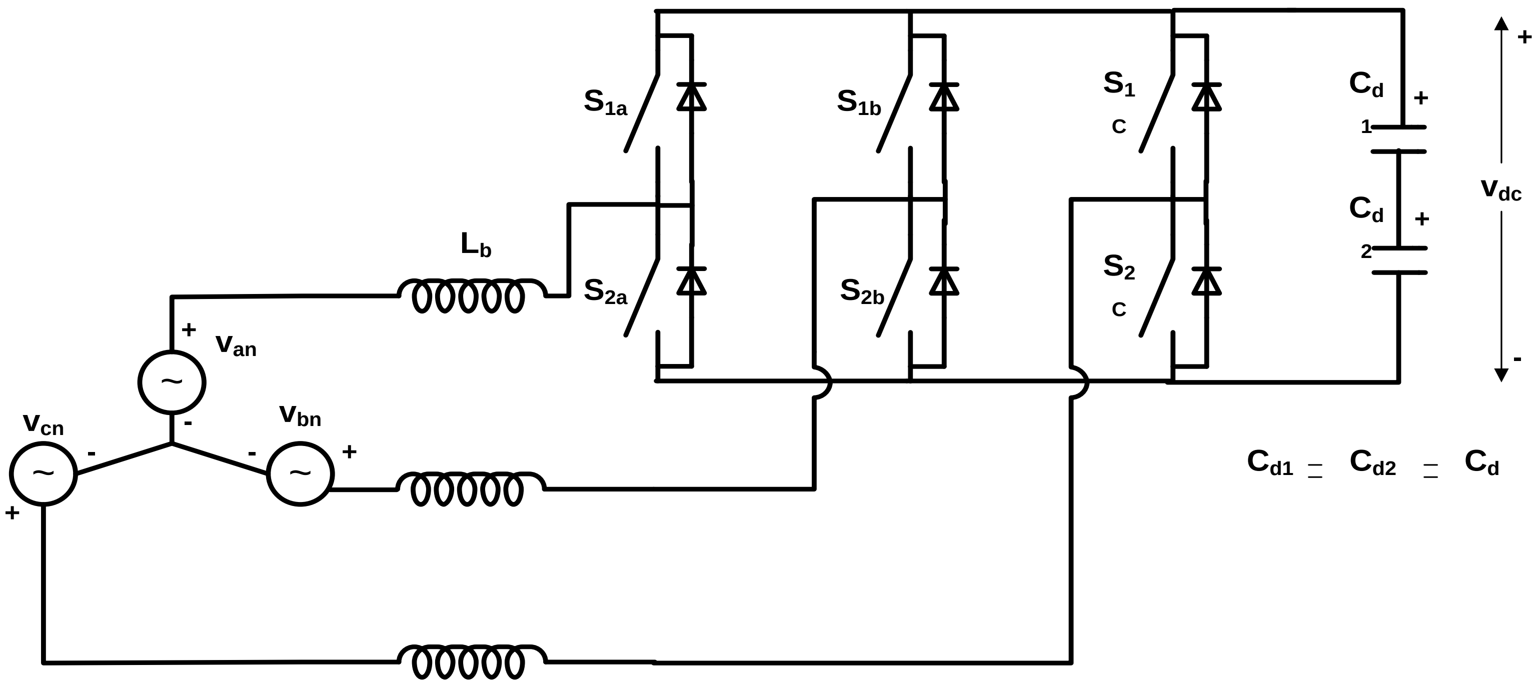

Equivalent circuit for the compensating reactive current drawn by STATCON



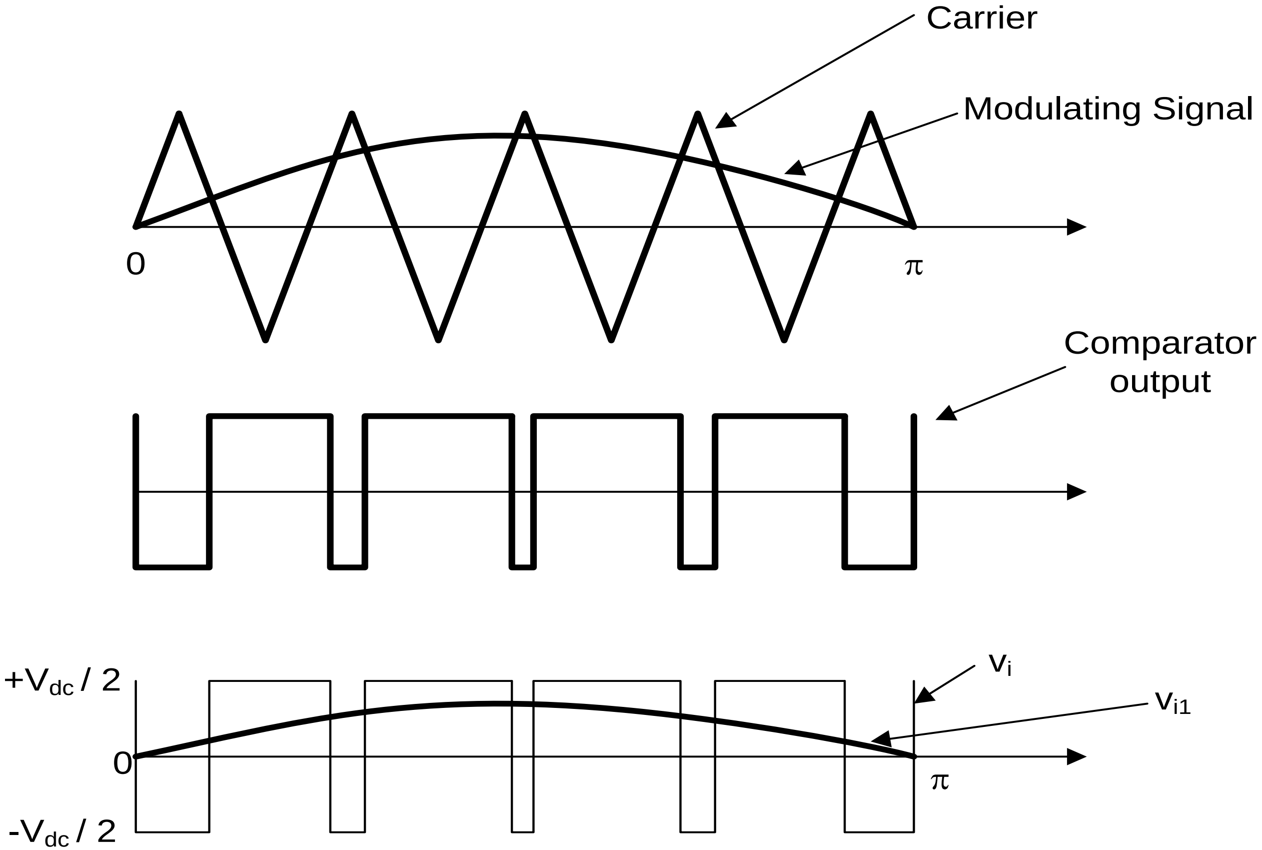

Vector diagram for inductive compensation
(Load demands capactive power
STATCON provides inductive compensation)

## Applications of Dynamic Reactive Power Control (DRPC) (TSC or Statcon or TSC+Statcon)

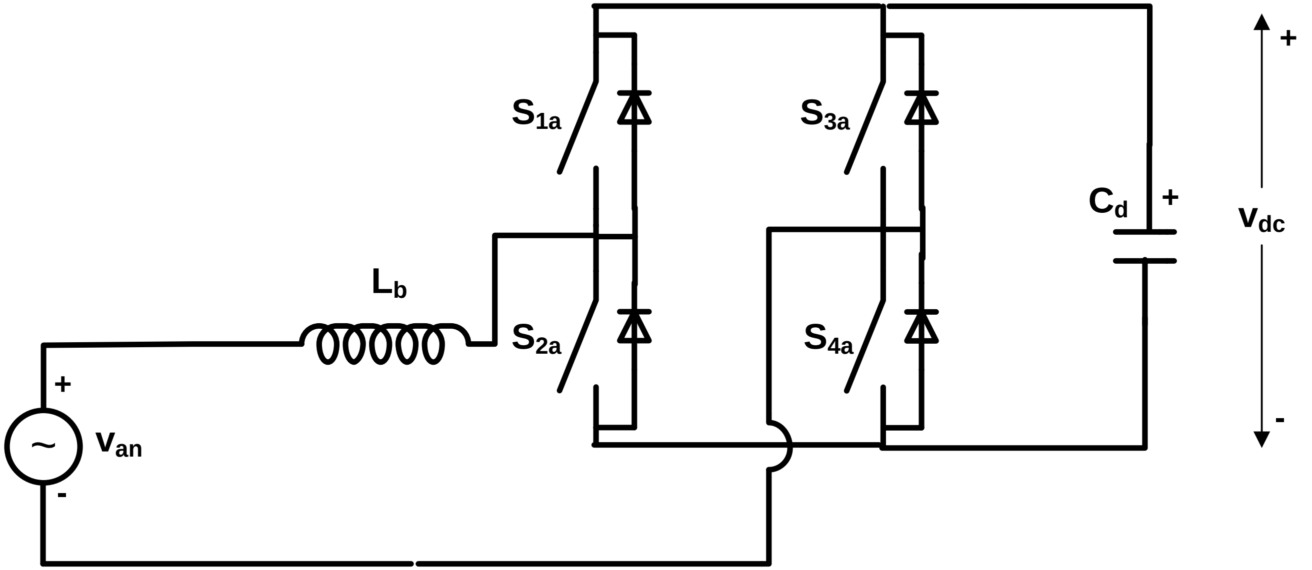
- **All core sector industries (paper, cement, steel)**
- **Refineries**
- **Arc furnace loads / furnace converters**
- **Wind Mills**
- **Distribution transformers**
- **Agricultural loads**
- **Railways**
- **Residential cum commercial complexes**
- **Public utility systems like escalators, conveyor belts, ropeways etc.**
- **Automobile industry loads like spot welding, tag welding, painting, robotic processes etc.**



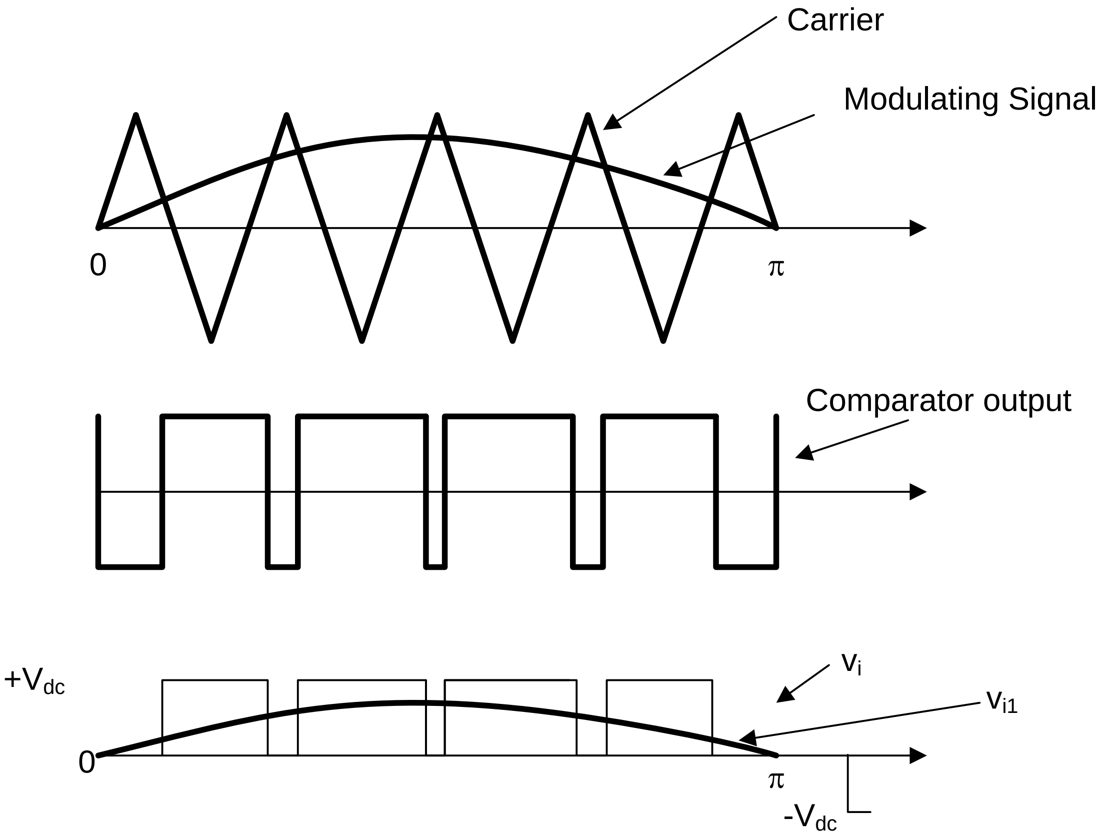

Three phase half bridge two level Voltage Source Converter




**Two level PWM generation based on SPWM method**

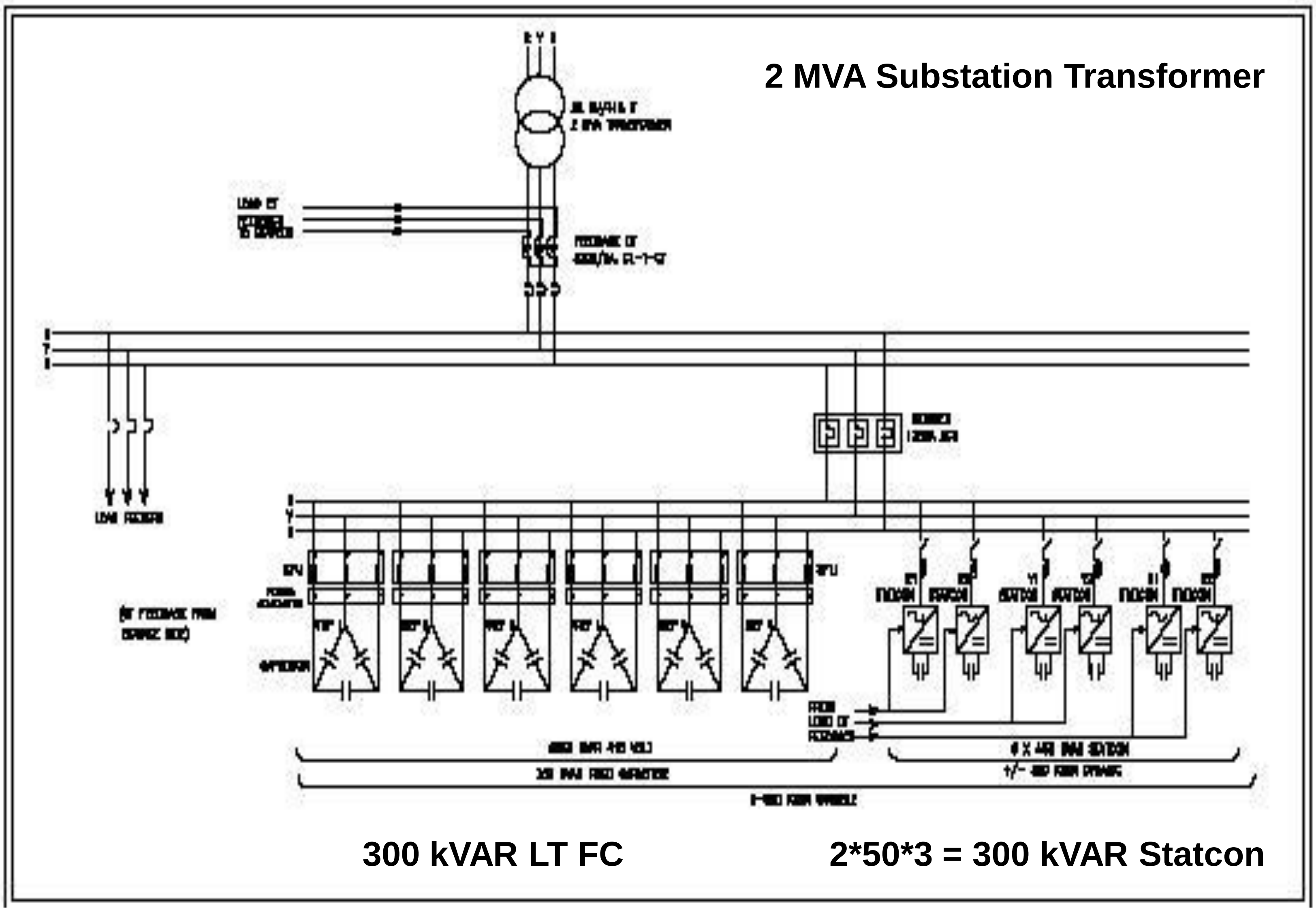



Single phase full bridge three level Voltage Source Converter

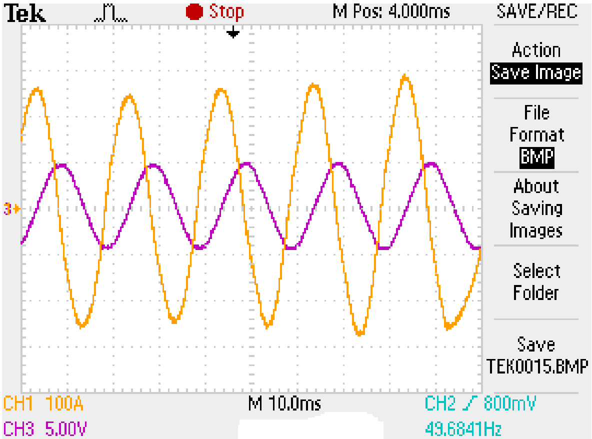



**Three level PWM generation based on SPWM method**

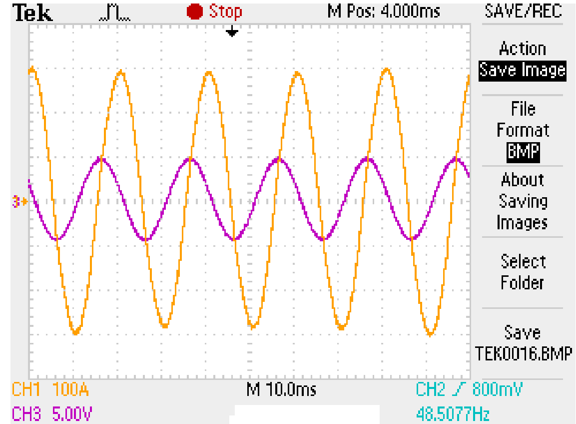
# 600 kVAR DRPC for spot welding



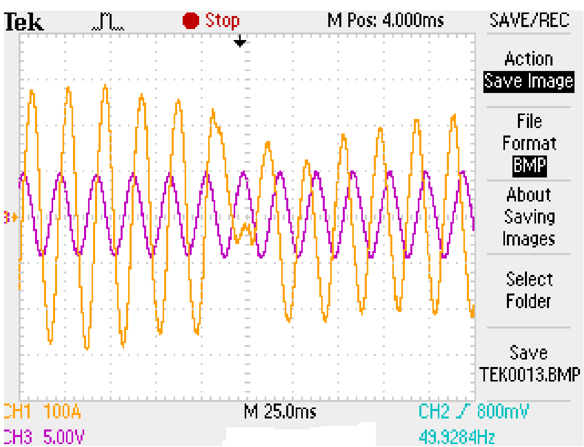
**ABB’s STATCON installation (3*600 kVAR = 1800kVAR) at TELCO, Pune,  for spot welding application**



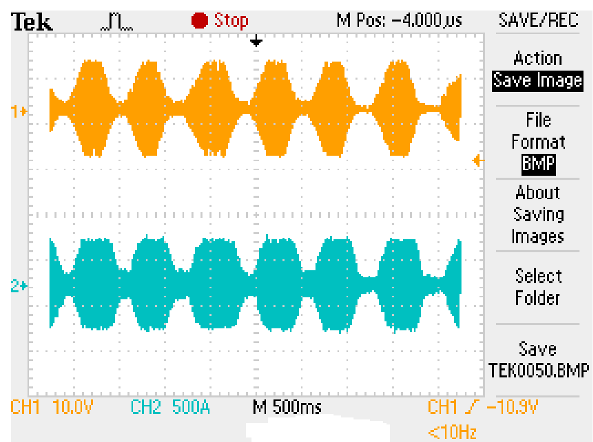

Lead (capacitive)



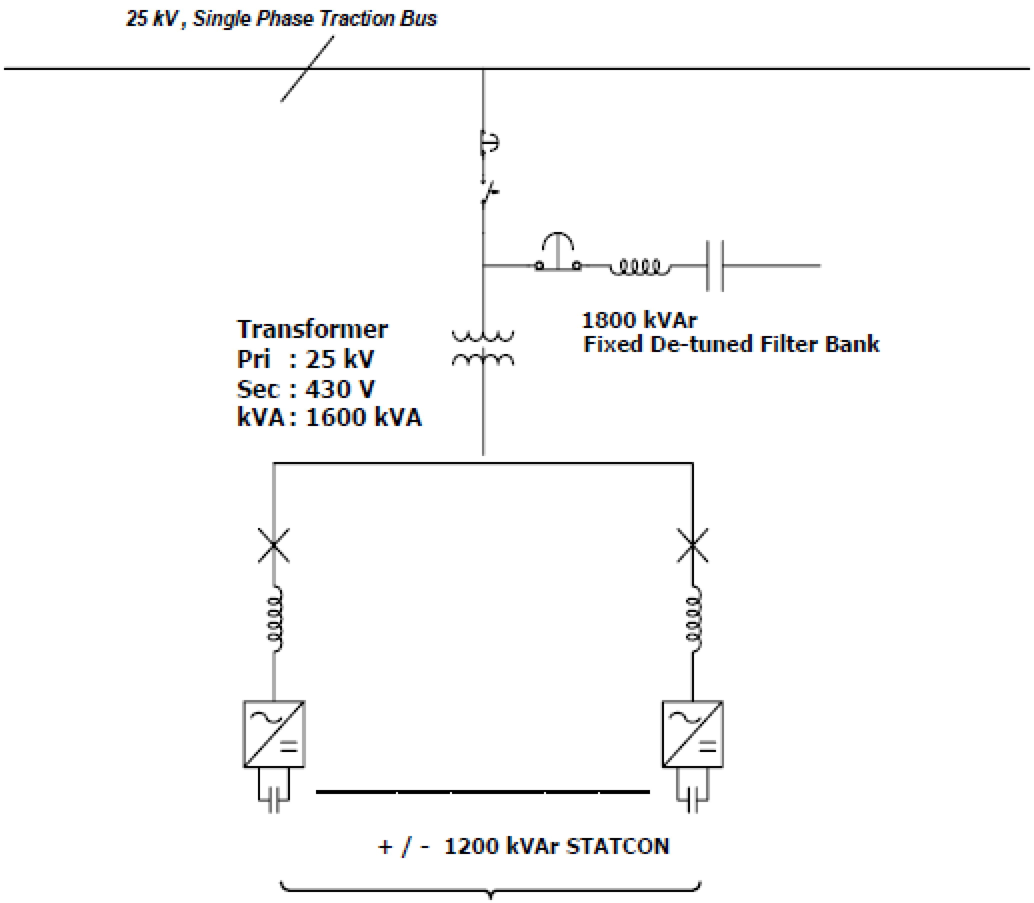

Lag (inductive)




Lag to Lead transient

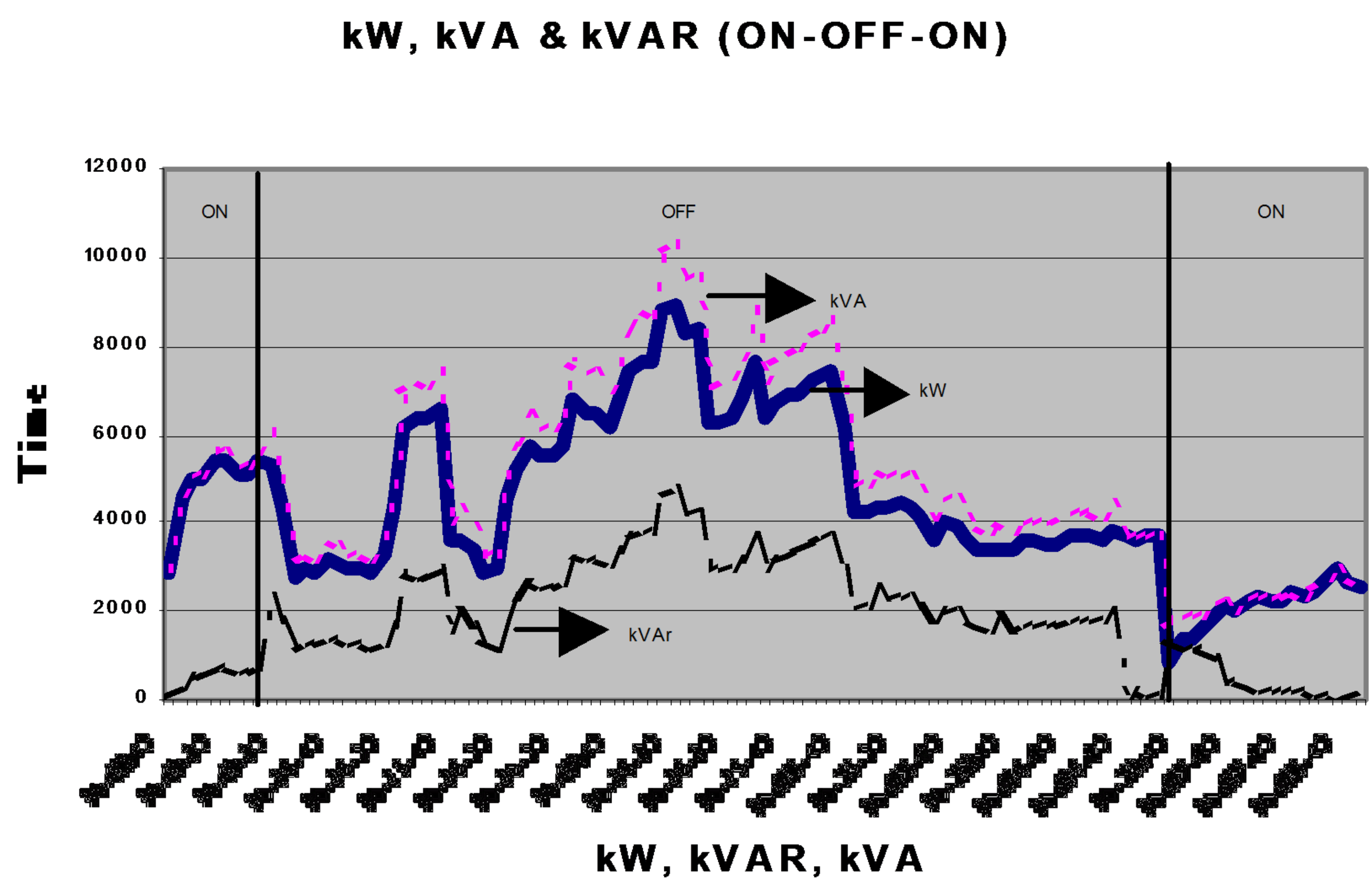


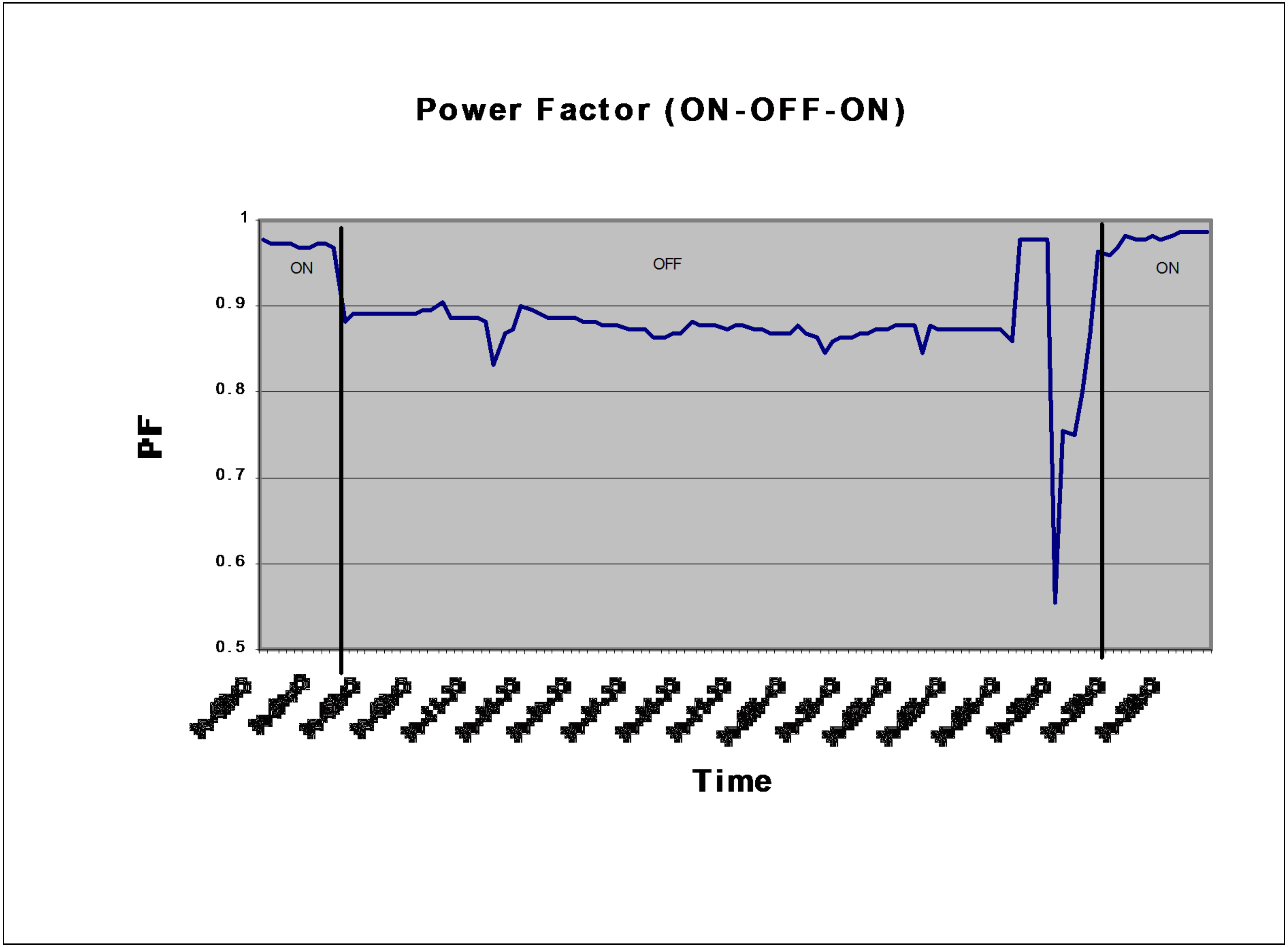

Spot welding dynamics

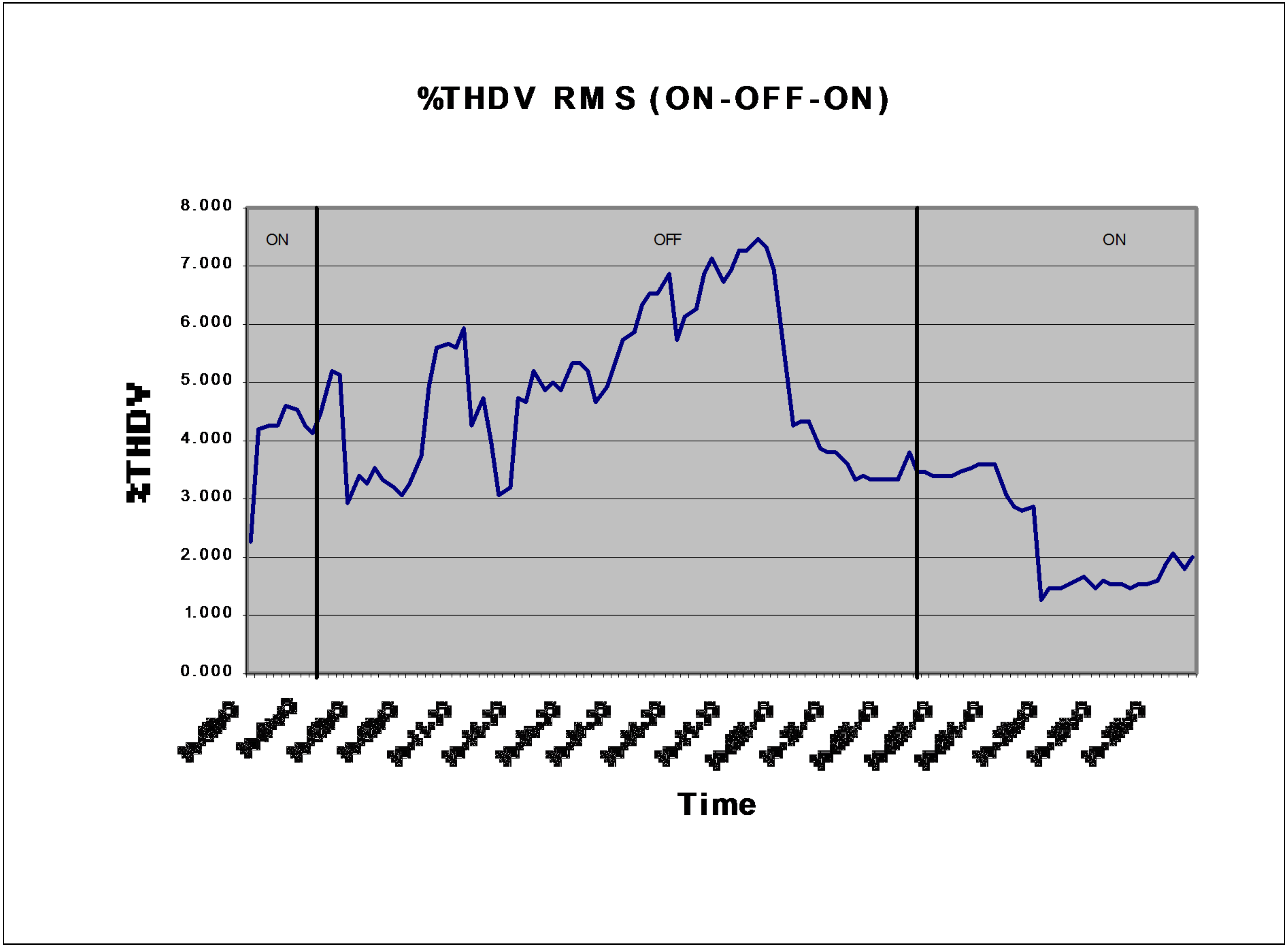



**Total Compensation 600 - 3000 kVAr**
**STATCON + / - 1200 kVAr**
**Fixed Capacitor (HT) 1800 kVAr**

**ABB’s 3 MVAR DRPC system at Lasalgaon CR substation**
**(1800 kVAR detuned HT FC + 150 KVAR*8 LV side 430 V Statcon)**


kW, kVA & kVAR (ON-OFF-ON)
12000
10000
8000
6000
4000
2000
0
ON
OFF
ON
kVA
kW
kVAr
Time
kW, kVAR, kVA


Power Factor (ON-OFF-ON)
1
0.9
0.8
0.7
0.6
0.5
PF
ON
OFF
ON
Time



%THDV RMS (ON-OFF-ON)
%THDV
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
ON
OFF
ON
Time

# Some statistics (Indian Scenario)

- **Need over 330000MW**
- **Installed capacity 155000 MW**
- **The shortfall cannot be covered even with 15000 MW / annum**
- **T&D losses 22-33%**
- **MoP (GoI): Focus hence on distribution**
- **At 125000MW average availability and 0.8 pf, RP= 93750 MVAR**
- **Even with 10% of this RPC considered as DRPC, the value is 9375 MVAR**

**•With Rs 4000/- kVAR for DRPC, the available DRPC market is 3750 Crores (pessimistic assumption)**

- **It will be growing market at the rate of $450^{+}$ Crores / annum**

## Approximate prices per kVAR

**FC :** Rs 300 – 800 / kVAR (LT)
and Rs 45 -70 / kVAR (HT)
**APFC:** Rs 900 – 1200 / kVAR
**TSC :** Rs 1400 – 1600 / kVAR
**Statcon:** Rs 3000 / kVAR

# DRPC in Indian Railway 25 kV TSS

**Specifications:**

25 kV (variation 28 to 19 kV) , 3000 – 4500 kVAR , required pf > 0.9 or 0.92

**Suppliers:**

**ABB** offers detuned HT side FC and Statcon with (25 kV / 430 V) transformer
**Shreem Capacitors** offers TSC with 2 * ( 25 kV / 415 V) transformers

**Analysis:**

**(1) TSS transformer 132 kV / 25 kV, 800 A, 20 MVA (Normal load reaches 600 A , sometimes crosses 600A)**

25 kV, 600 A, 0.7 pf, + 4500 kVAR => 0.86 pf

**25 kV, 600 A, 0.8 pf, + 4500 kVAR => 0.94 pf**

25 kV, 600 A, 0.7 pf, + 8075 kVAR => 0.97 pf

25 kV, 800 A, 0.7 pf, + 10775 kVAR => 0.97 pf

## (2) Typical comparison between "ABB Statcon based DRPC at 4500 kVAR" and "AAL TSC / TSC +Statcon"

**ABB system:** 2100 kVAR (=150 kVAR*14) Statcon + 2400 kVAR HT FC
Other major components: 3 MVAR transformer, 13% detuned reactor at HT, HT breakers for HT FC and transformer primary, and CT

**Equivalent AAL system: (1)** 5250 kVAR (=250 kVAR*21) TSC
**(2)** 5000 kVAR (=250 kVAR*20) TSC + 250 kVAR Statcon
Other major components: 5.5 MVAR transformer, HT breaker, and CT

**Option (2) is neglected as the Statcon affects pf in third digit and accuracy of pf is not important.**

# Typical comparison with "ABB DRPC at 4500 kVAR"

| | ABB | AAL / TSC |
|---|---|---|
| 19 kV, 800 A, 0.7 pf => | 0.805 | 0.805 |
| 28 kV, 600 A, 0.8 pf => | 0.944 | 0.9674 |
| FL loss at 25 kV in kW | 90-100 | 90-100 |
| NL loss at 25 kV in kW | 90-100 (Statcon in full inductive mode) | 12-18 |
| Cost Rs in Lakhs (inclusive of HT breaker, LT breaker, CT, Room Auxiliaries, controller(s), displays, miscellaneous) | 220+ | 200-220 |

**Thank You**

**For**

**Your Patience**