DEMOCRITUS UNIVERSITY OF THRACE
FACULTY OF ENGINEERING

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DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING, POWER SYSTEMS SECTOR

Project at the course: Special Applications of Power Electronics

Subject: Presentation of the combined series and shunt power conditioners

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We re going to talk about…

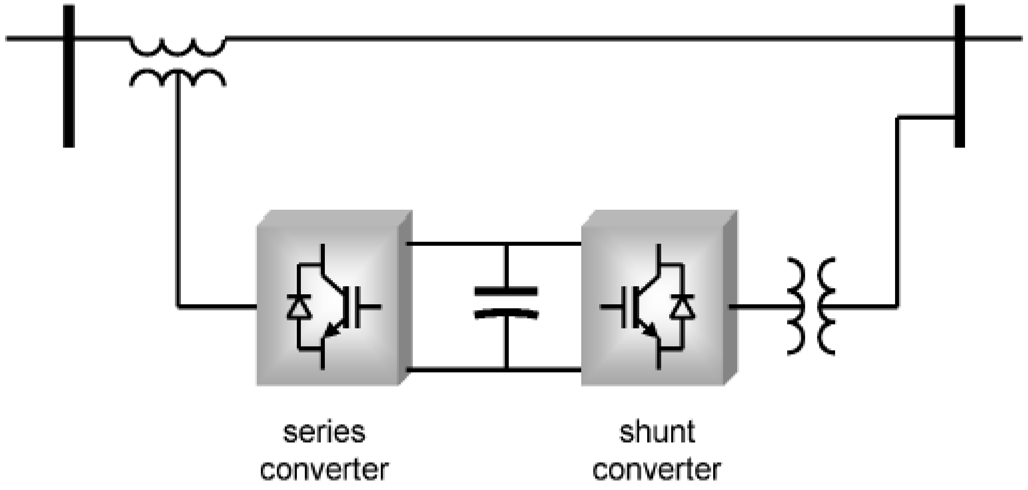
- The Unified Power Flow Controller (UPFC)
  - Power flow control
  - Reactive power compensation
  - Voltage regulation

- The Unified Power Quality Conditioner (UPQC)
  - Voltage and current harmonic compensation

- The Universal Active Power Line Conditioner (UPLC)
  - Does everything mentioned adove
  - It is based on the $p - q\ Theory$

The basic configuration of a generic series and shut conditioner

- The basic configuration consists of two power converters connected back to back through a common dc link
- A dc capacitor is used in the dc link as an energy storage element
- The ac output of the one converter is inserted in series with the power system
- The ac output of the other converter is connected in parallel
- The power flowing into the dc link through the series converter must be equal with the power flowing out through the shunt converter and vice versa
- The can be:
  - current – source converters (CSCs)
  - voltage – source converters (VSCS) (more widely used)



Combines series and shunt power conditioner

Switching Techniques

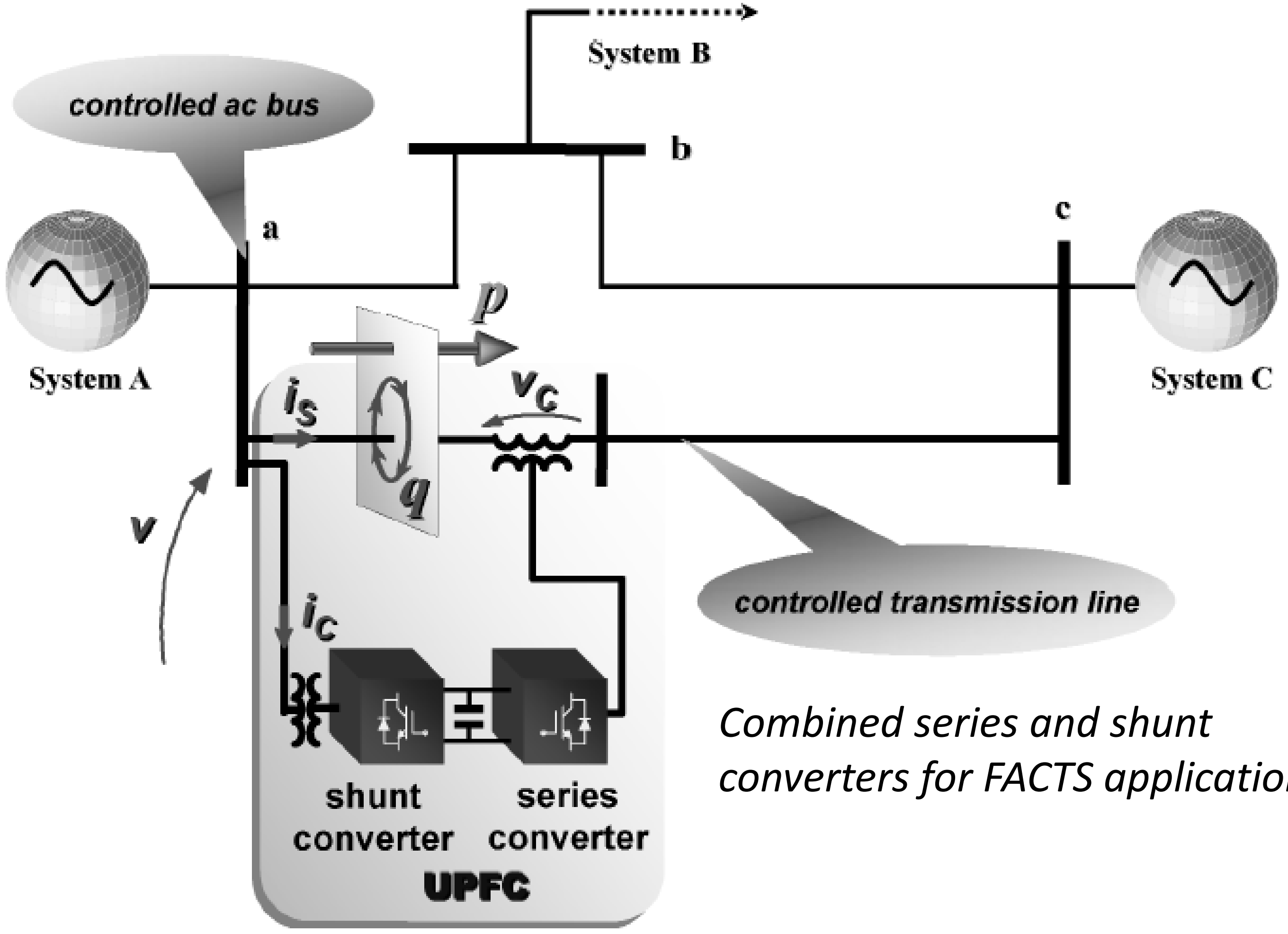
The Switching Techniques of the VSCs are an importuned aspect of them.

Some of them are:

- The multipulse converter approach
  - Switching at the fundamental frequency
  - Used in multipulse converters for very high power applications
  - Multipulse converters generate square – wave outputs
  - Their amplitude is directly proportional to the voltage of the dc link
  - Their phase angle can be quickly changed by adjusting the switching instants while the voltage can only change if the voltage of the dc link changes
- The Pulse – Width Modulation (PWM)
  - High – frequency switching
  - High – switching losses
  - Converters controlled by PWM can represent ideally controlled voltage or current sources
  - They can drain real (active) power and imaginary (reactive) power independently
  - The are preferred in specific applications

The Unified Power Flow Control (UPFC) /1

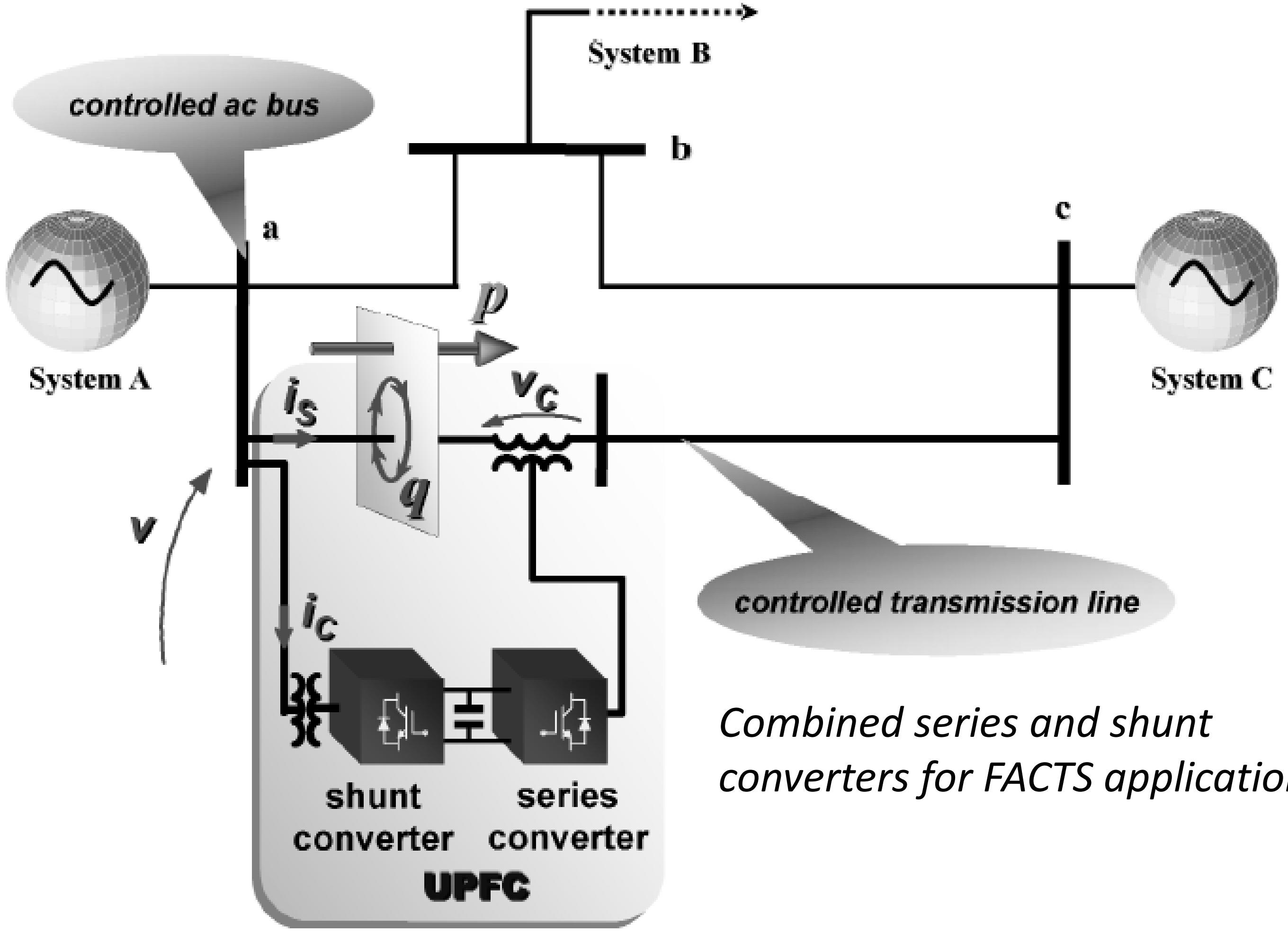
- The Unified Power Flow control is a FACT device (flexible ac transmission systems)
- Their 3 principal parameters are:
  - The terminal voltage
  - The series impedance
  - The phase angle displacement
    - All controlled in real time



Combined series and shunt converters for FACTS application

The Unified Power Flow Control (UPFC) /2

- The UPFC can control the active (real) and reactive (imaginary) power which flow through a transmission line
- The main goal is to increase the usable power transmission capacity up to its thermal limit (higher loading conditions)
- It is a very fast acting device with high performance and flexibility



Combined series and shunt converters for FACTS application

The Unified Power Flow Control (UPFC) /3

In contrast to thyristor – based compensators controlling only their firing angles, compensators based on self – commutated semiconductor devices can control switching patterns to behave as controlled current or voltage source. As a result, the VSC can drain real and imaginary powers which, as mentioned are controlled independently.

Thus, we have 2 degrees of freedom for each PWM converter and 1 restriction:

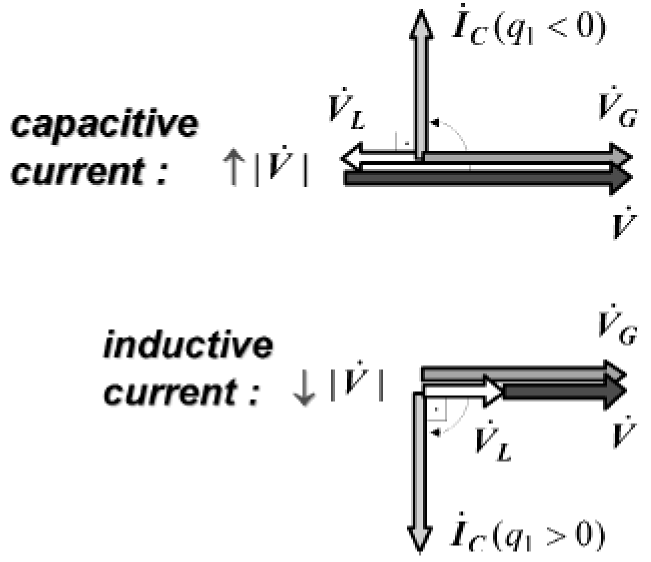
1. The compensating current i_c of the shunt converter produces real (p_1) and imaginary (q_1) powers with the controlled bus voltage v_s, independent of each other
2. The compensating voltage of the v_c of the series converter produces, with the controlled transmission line current i_s, real (p_2) and imaginary (q_2) powers, which are also independent of each other

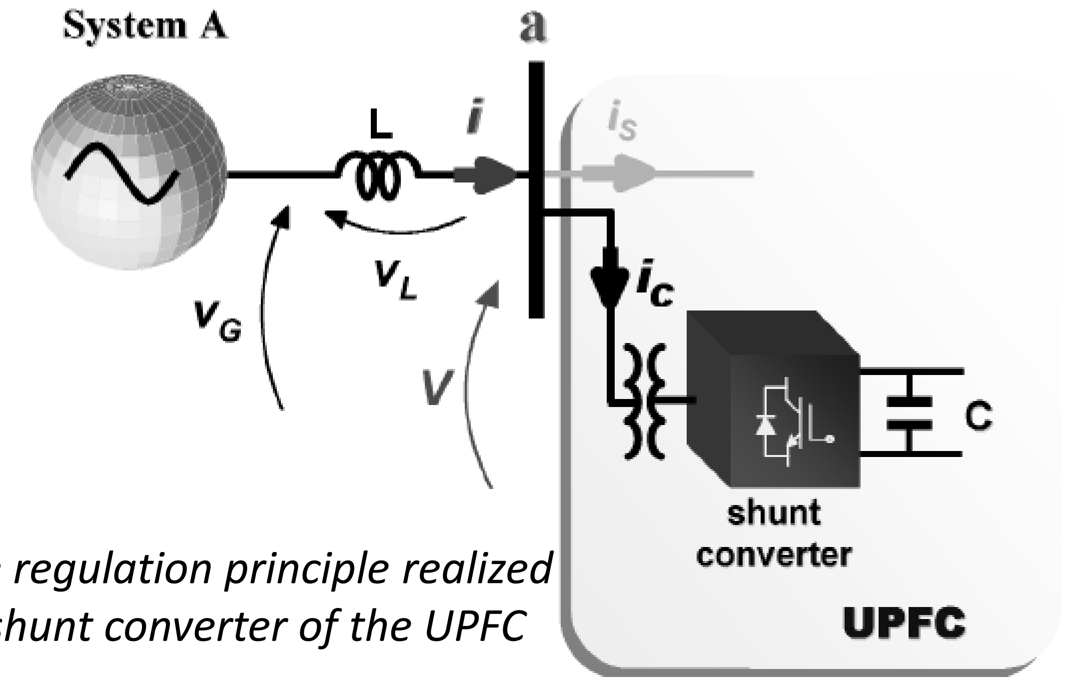
Restriction: The limited energy – storage of the capacitor in the dc link and the power rating of the converters restrict the four degrees of freedom (p_1, q_1, p_2, q_2).

Also, the power flowing into the dc link through the series converter must be equal with the power flowing out through the shunt converter and vice versa, so $p_1 = -p_2$ (not exactly if we take into account the losses in the converters).

Voltage Regulation Principle

- If the shunt converter injects inductive current i_c, the controlled bus “a” voltage decreases, because the inductive current produces imaginary power ($q_1 > 0$)
- If the shunt converter draws capacitive current i_c, the controlled bus “a” voltage increases, because the capacitive current consumes imaginary power ($q_1 < 0$)



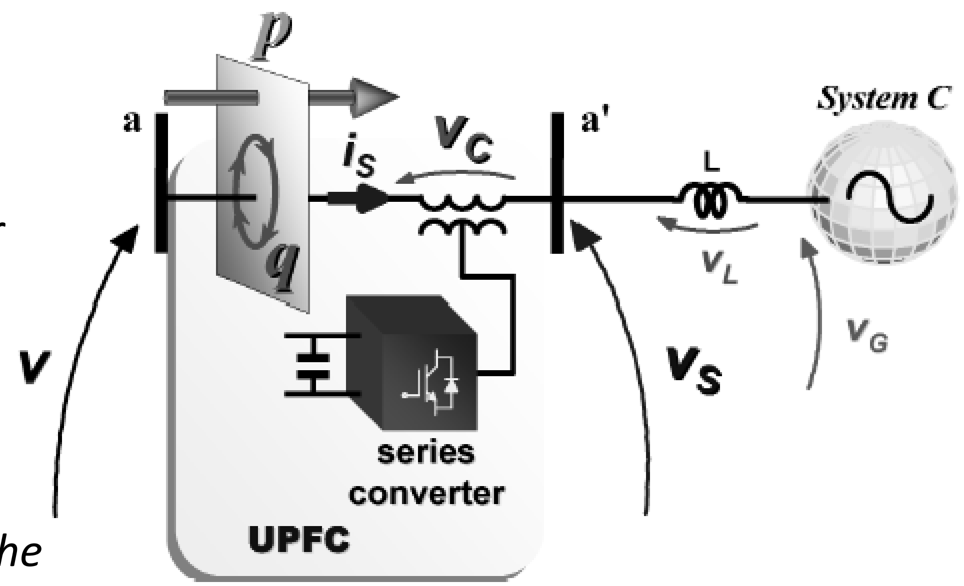


Voltage regulation principle realized by the shunt converter of the UPFC

Power Flow Control Principle 1/

- The series converter of a UPFC can control the instantaneous real and imaginary powers, which are produced by the voltage v of the controlled ac bus and the controlled current $i_s$of the transmission line
- The series converter inserts the compensating voltage v_c to change the voltage v_s at the right side of the UPFC, such that $v_s = v - v_c$
- It varies the terminal voltage v_s of the controlled transmission line and controls the current i_s to match the desired loading conditions for this line

- These desired conditions are a real power P_{REF} and an imaginary power Q_{REF}
- They could be locally fixed or commended remotely by a power dispatch control center
- The goal is to force the powers p and q to match the power orders P_{REF} and Q_{REF}

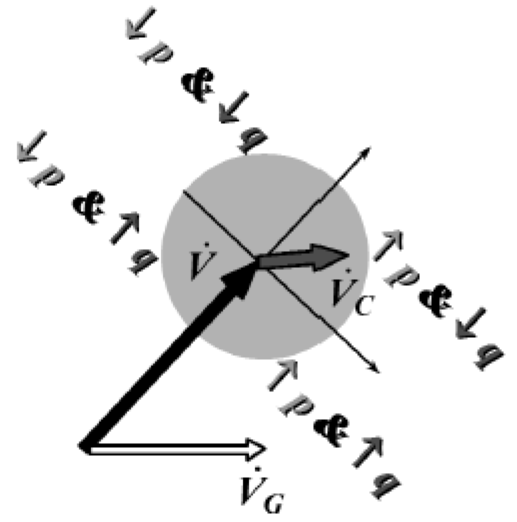


Power flow control by the series converter of the UPFC

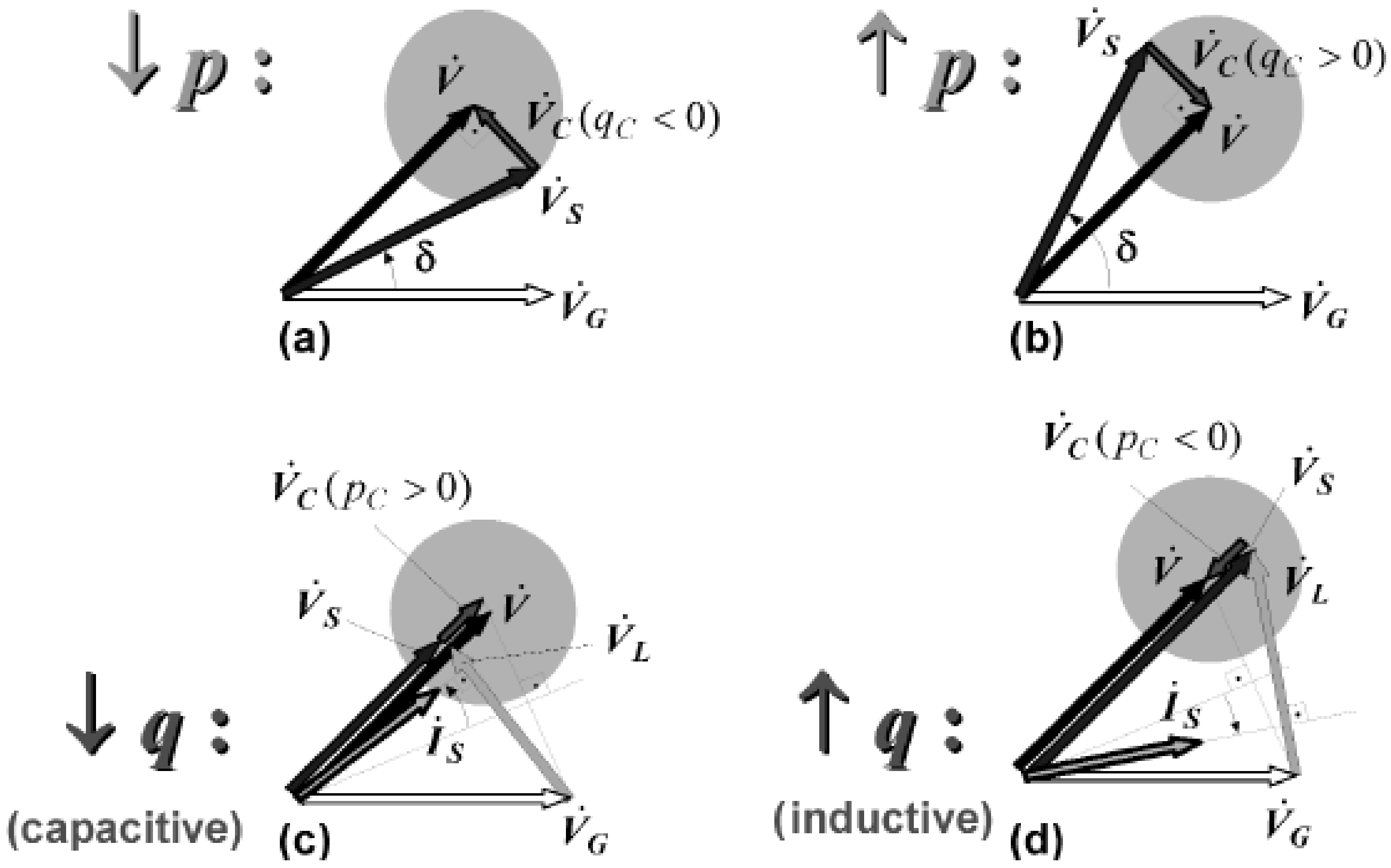
Power Flow Control Principle 2/

The idea consists in inserting a fundamental voltage component $\dot{V}_c$ to change the phase angle and the amplitude of the terminal voltage $\dot{V}_s$

- The reference is the phasor $\dot{V}$ of the controlled ac bus voltage
- The compensating voltage phasor $\dot{V}_c$ consists of two components $\dot{V}_c(p_c)$ (parallel to the phasor $\dot{V}$) and $\dot{V}_c(q_c)$ (orthogonal to the phasor $\dot{V}$)
- Note: p_c and q_c are just control signals with no relation to real p and imaginary q powers of the controlled transmission line
- The parallel component $\dot{V}_c(p_c)$ controls the imaginary power q
- The orthogonal component $\dot{V}_c(q_c)$ controls the real power p
- The control of the the imaginary power q and the real power p it not fully decoupled due to cross effects
- The compensating voltage $\dot{V}_c$ can vary inside a limited circle restricted by the rated voltage of the series converter



Power Flow Control Principle 3/



$$v_s = v - v_c$$

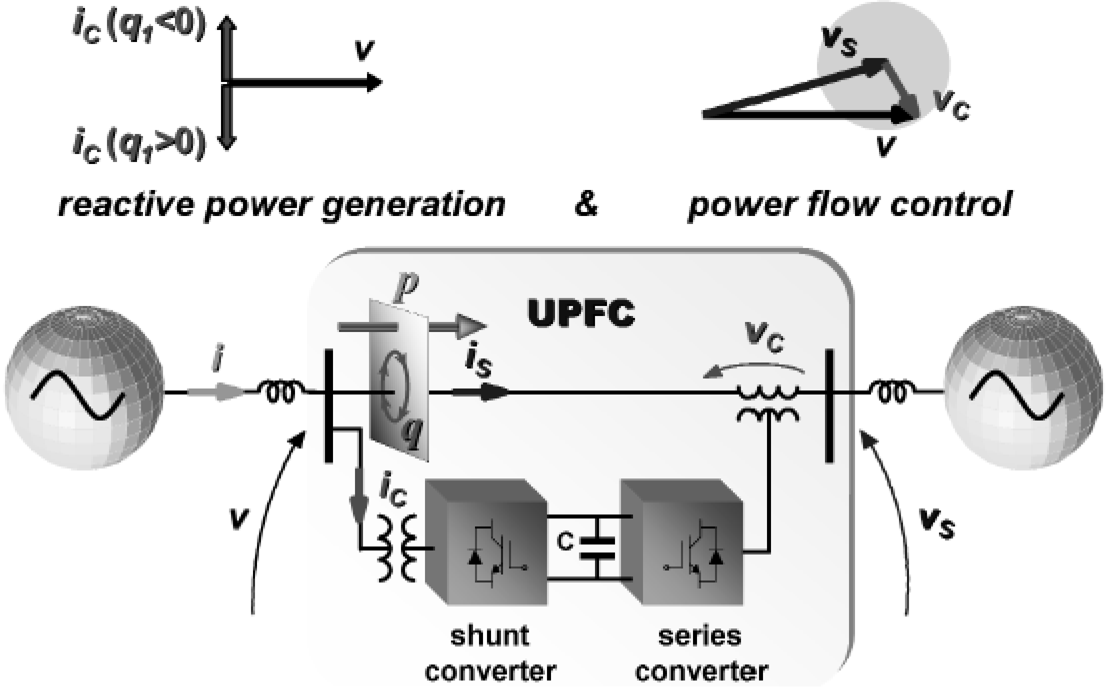
A controller design for the UPFC 1/

A controller for the UPFC that realizes voltage regulation and power flow control can be designed based on the $p - q$ $Theory$ and the concept of instantaneous aggregate voltage.

- The shunt converter acts as a controlled current source and produces compensating current i_c
- The series converters acts as a controlled voltage source and produces compensating voltage v_c

A controller design for the UPFC 2/

- By generating controllable reactive current i_c, the magnitude of voltage v of the controlled bus is kept constant around its reference point
- The product of controlled current i_s and controlled voltage v produces the real power p and imaginary power q which are also continuously compared with their reference values to determine properly the compensating voltage of the UPFC series converter
- The voltage v at the left – hand side of the UPFC and the current i_s through the controlled transmission line are the principal measurements for designing a UPFC controller



Functionality of the UPFC

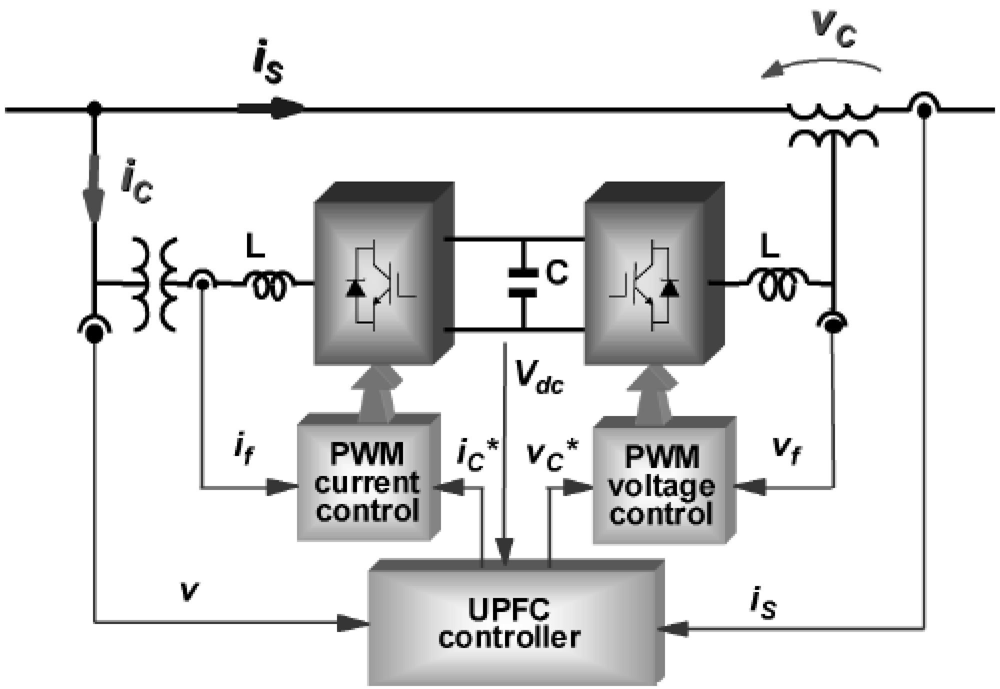
A controller design for the UPFC 3/

The converter is also responsible for keeping the dc link voltage constant which is accomplished by adding a controlled active current component to i_c, produces energy flow into (from) the dc link, to counteract the energy flow going out of (into) the UPFC series converter and to do this it needs a measurement of the dc link voltage

The measured compensating current i_f and compensating voltage v_f are used as minor feedback loops in the PWM control circuits

The PWM current and voltage control circuits are considered as part of the power converters, instead of part of the UPFC controller

The power flow control functionality is performed by the series converter



Basic control block diagram of the UPFC and converters

UPFC controller and $p - q\ Theory$

A UPFC controller can be designed using only the concepts learned from the $p\ - q\ Theory$ and the concept of the instantaneous aggregate voltage

- Only three measurements are need as inputs to the UPFC controller:
    1. The phase voltages of the controlled ac bus (v_a, v_b, v_c)
    2. The voltage of the common dc link (V_{dc})
    3. The currents of the controlled transmission line (i_{Sa}, i_{Sb}, i_{Sc})
- Four reference values are needed:
    1. The real power order of the controlled transmission line (P_{REF})
    2. The imaginary power order of the controlled transmission line (Q_{REF})
    3. The voltage magnitude of the controlled ac bus (V_{REF})
    4. The rated voltage of the common dc link (V_{dcREF})

When designing controllers for power conditioners, it is valuable to achieve simplifications in order to reduce computation efforts and since a three – phase system without a neutral wire is being considered, all calculations related to zero – sequence components are eliminated and only two measurements instead of three are for each three – phase point of measurement

Control block diagram of the series converter /1

With the zero - sequence components neglected, this relations are valid:

$$v_a + v_b + v_c = 0 \qquad (1)$$

$$i_a + i_b + i_c = 0$$

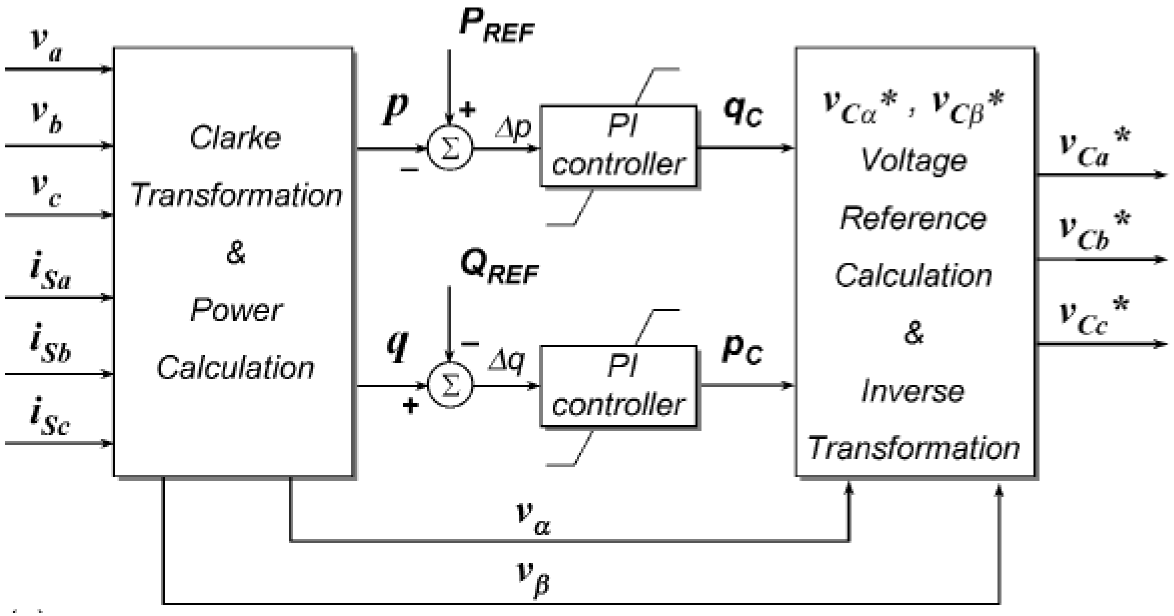
So, the line voltages do not contain any zero - sequence components:

$$v_{ab} + v_{bc} + v_{ca} = 0 \qquad (2)$$

$$v_{ab} = v_a - v_b$$
$$v_{bc} = v_b - v_c$$
$$v_{ca} = v_c - v_a$$

From (1), it is possible to determine voltages as functions of line voltages:

$$v_a = (v_{ab} - v_{ca})/3$$
$$v_b = (v_{bc} - v_{ab})/3 \qquad (3)$$
$$v_c = (v_{ca} - v_{bc})/3$$



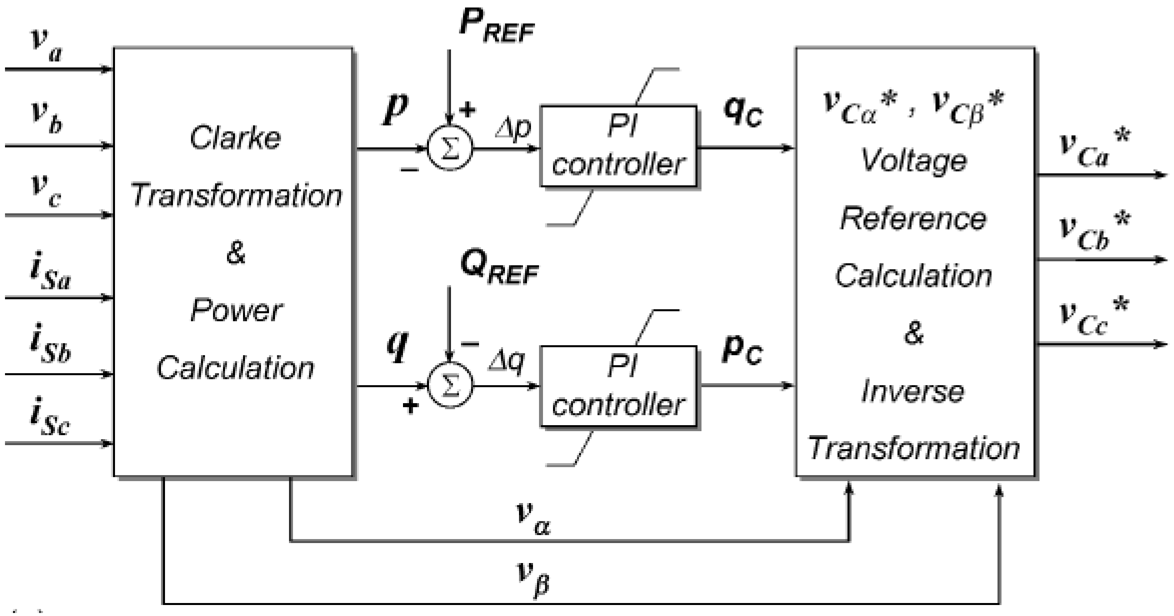
Control block diagram of the series converter /2

Since $v_{ca} = -v_{ab} - v_{bc}$, from (2), phase voltages can be determined from the measurements of only two line voltage:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix}\begin{bmatrix} v_{ab} \\ v_{bc} \end{bmatrix} \quad (4)$$

Neglecting zero – sequence components, the Clarke transformation is given by

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (5)$$

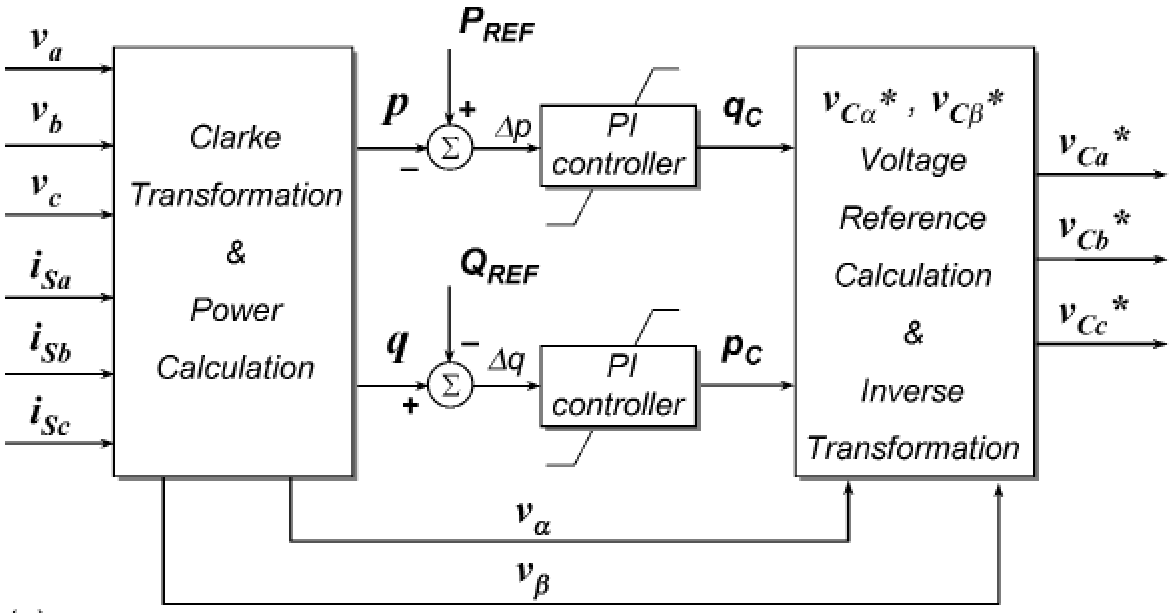


Control block diagram of the series converter /3

From (4) and (5), the αβ – voltage components can be determined directly from the two measured line voltage:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{ab} \\ v_{bc} \end{bmatrix} \qquad (6)$$

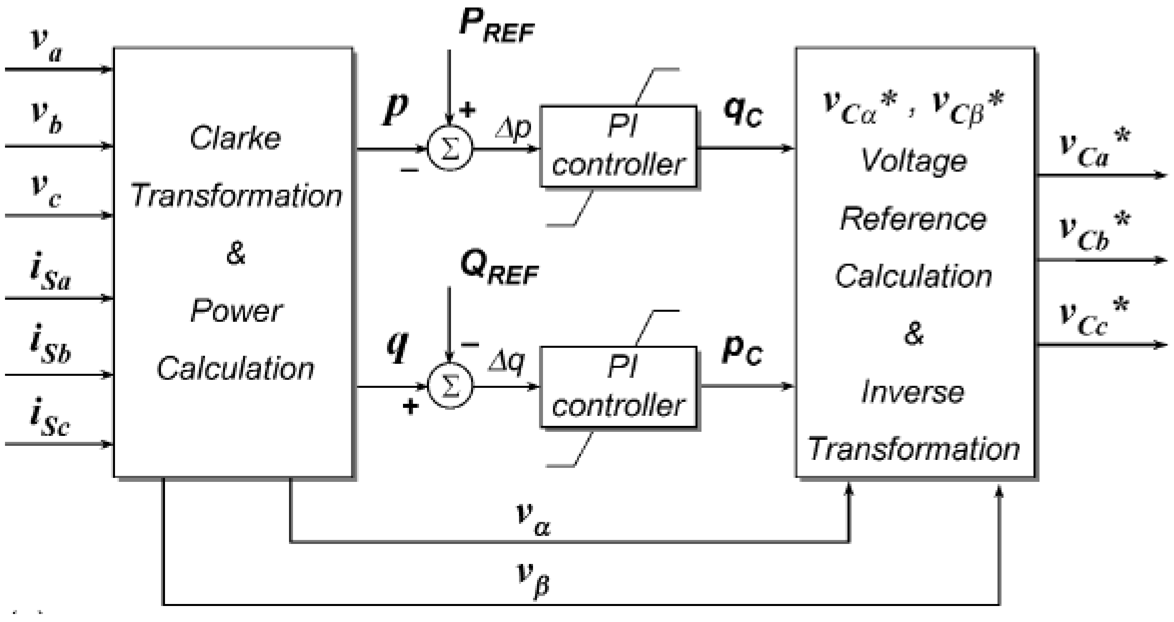
Therefore, two line voltages can replace those three phase – to – neutral voltages inputs v_a, v_b and v_c in the UPFC controller shown here.



Control block diagram of the series converter /4

If (1) is valid, the number of current measurements from the controlled transmission line can also be reduce. Only two measurements of line currents are necessary, provided that $i_c = -i_a - i_b$. In this case, the $\alpha\beta$ – current components are given by:

$$\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{3}{2} & 0 \\ \frac{\sqrt{3}}{2} & \sqrt{3} \end{bmatrix} \begin{bmatrix} i_{Sa} \\ i_{Sb} \end{bmatrix} \quad (7)$$



But, the convenience of reducing measurements and computation efforts in the Clarke transformation should take into account performance requirements for the UPFC, when it is operating under fault conditions in the ac system, where in this case zero – sequence components may not be negligible

Control block diagram of the series converter /5

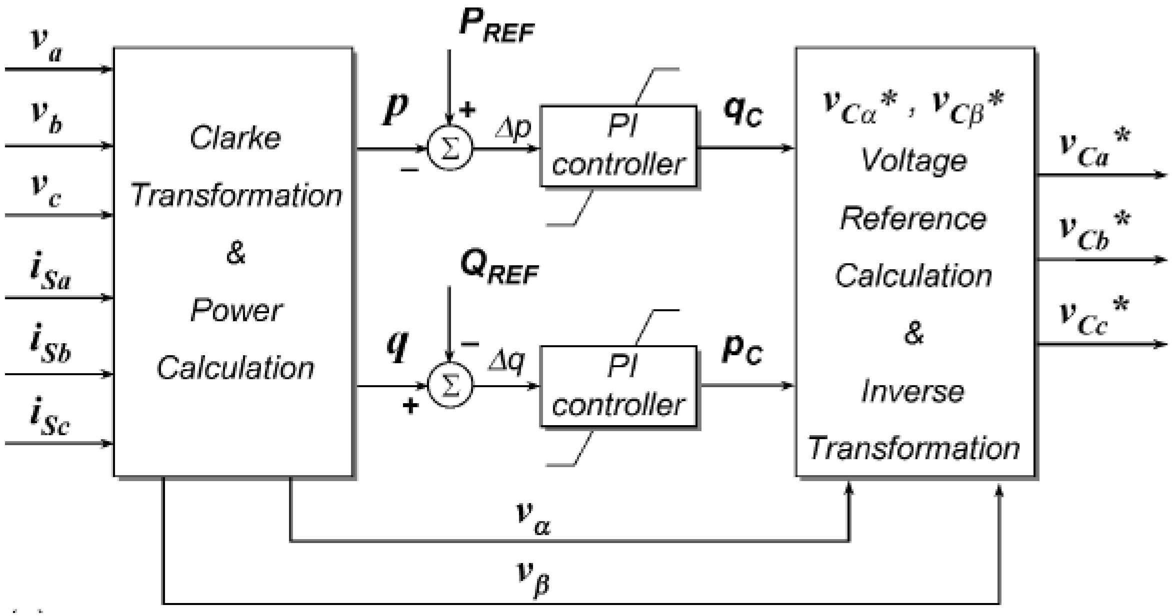
The real and imaginary powers of the controlled transmission line are given by:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} \qquad (8)$$

The instantaneous powers from above are continuously compared with their reference (real and imaginary power order, P_{REF} and Q_{REF} respectively). The calculated error signals Δp and Δq serve as input variables to PI controllers that generate an "imaginary control power" signal q_c and a "real control power" signal p_c. The signals are auxiliary variables based on the $p - q\ Theory$. Their dimension is V^2.

The compensating voltage components of the αβ axes are determined as:

$$\begin{bmatrix} v^*_{C\alpha} \\ v^*_{C\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p_C \\ q_C \end{bmatrix} \qquad (9)$$

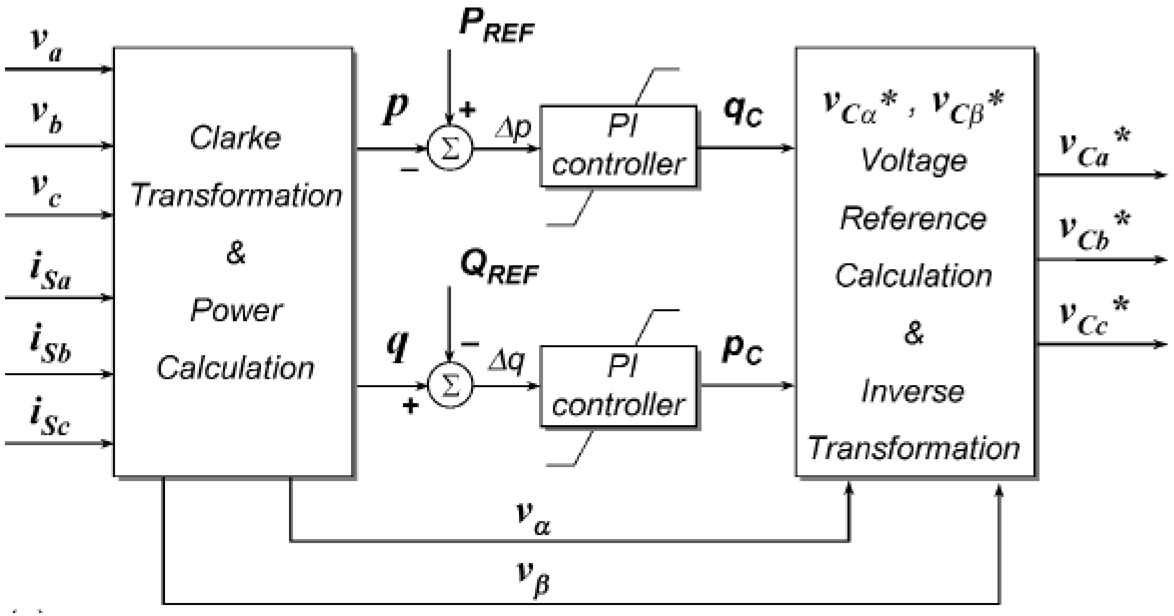


Control block diagram of the series converter /6

The inverse Clark transformation of (9) is:

$$\begin{bmatrix} v_{Ca}^* \\ v_{Cb}^* \\ v_{Cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{C\alpha}^* \\ v_{C\beta}^* \end{bmatrix} \quad (10)$$

All the mentioned equations constitutes the entire control algorithm of the controller for the series converter of the UPFC.



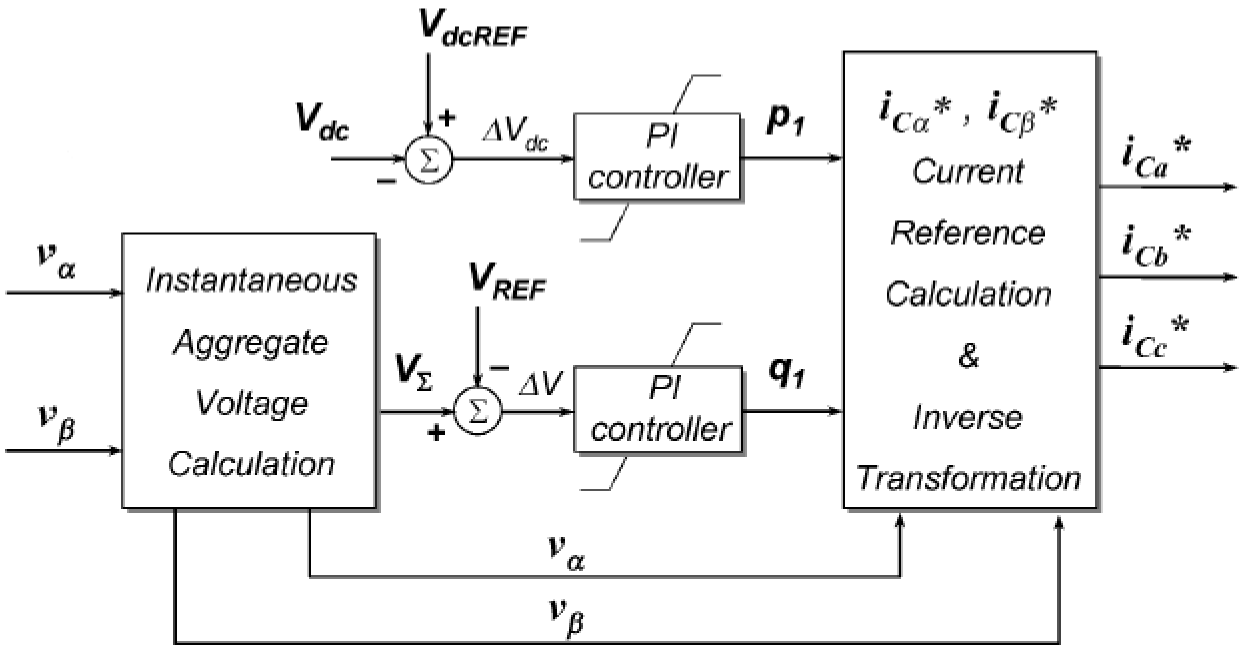
Control block diagram of the shunt converter /1

The measured voltage of the controlled ac bus, already used and transformed into $\alpha\beta$ axes in the series converter controller is provided to the shunt converter controller.

The instantaneous aggregate values in phase mode and in $\alpha\beta0$ variables:

$$v_{\Sigma} = \sqrt{v_a^2 + v_b^2 + v_c^2} = \sqrt{v_\alpha^2 + v_\beta^2 + v_0^2} \quad (11)$$

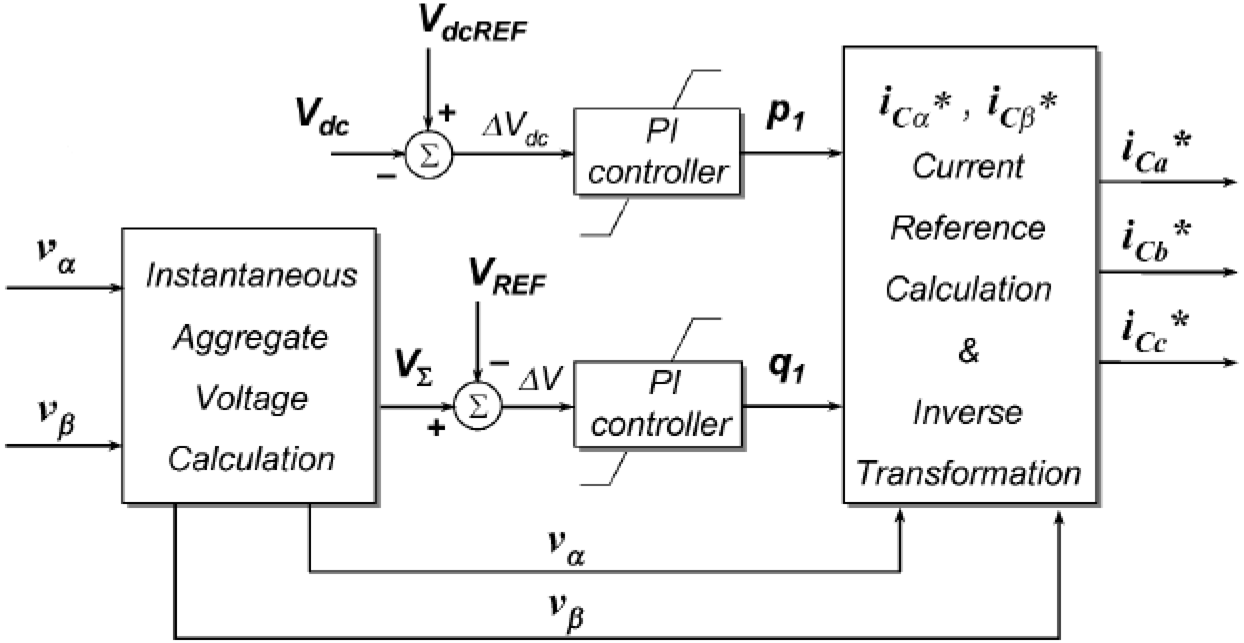
Zero – sequence components are being neglected and v_0 can be eliminated. This is the ideal case where the phase voltages are balanced and they do not have any zero – sequence and negative – sequence components.



Control block diagram of the shunt converter /2

A function of the shunt converter of the UPFC is to provide energy balance inside the common dc link.

- The shunt converter must absorb (inject) an nearly equal amount of average real power as the injected (absorbed) by the UPFC series converter
- Instead of using direct calculation of power p_2 that is given by the product of v_c and i_s, a measurement of the dc link voltage v_{dc} is used to generate the compensating real power p_1 for the shunt converter.
- By doing so, and extra real power need to supply losses in the power circuit of the UPFC is conveniently included in control signal p_1.



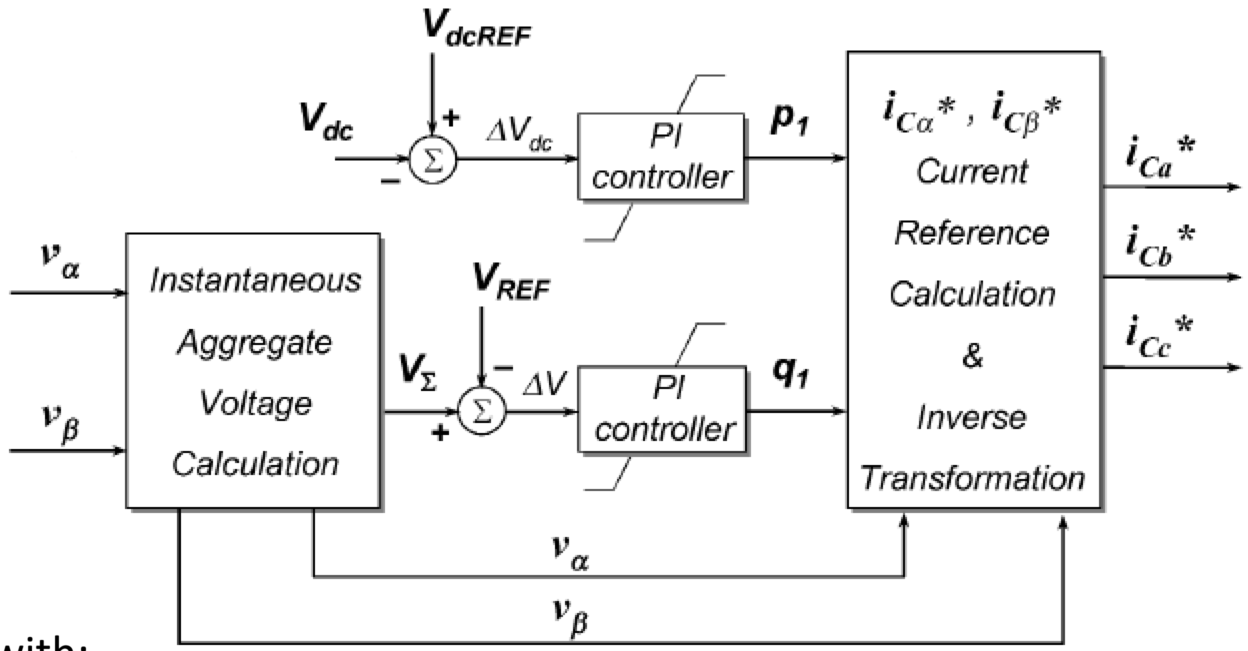
Control block diagram of the shunt converter /3

The compensating current on the $\alpha\beta$ axes are determines as:

$$\begin{bmatrix} i^*_{C\alpha} \\ i^*_{C\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p_1 \\ q_1 \end{bmatrix} \quad (12)$$

The inverse Clarke transformation gives the instantaneous reference currents:

$$\begin{bmatrix} i^*_{Ca} \\ i^*_{Cb} \\ i^*_{Cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_{C\alpha} \\ i^*_{C\beta} \end{bmatrix}$$



The PWM is provided by the control algorithms with:

- Instantaneous current reference values from the shunt converter
- Instantaneous voltage reference values from the series converter

UPFC Approach Using a Shunt Multipulse Converter

Multipulse converters are composed of voltage – source converters that can be conventional bridge converters or multilevel converters

- They are used in high power applications
- They use:
  - Gate – turn – off thyristors (GTOs)
  - Insulated – gate bipolar transistors (IGBTs)
  - Integrated – gate commutated thyristors (IGCTs)

High – power converters with high efficiency are built by using several series and/or shunt connections of three – phase converters modules, each one formed with a reduced number of power semiconductor devices in series and/or parallel in each converter valve

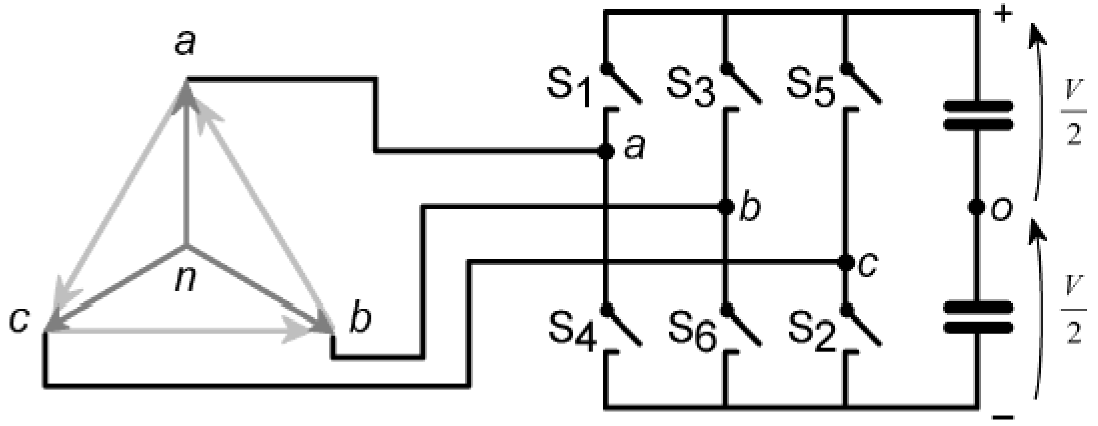
For high power applications the PWM converters are not suitable because they operate in high frequencies and due to them they have high switching losses and a reduced bang of operational frequencies

On the other hand, multipulse converters switch at the fundamental frequency and they have reduced switching losses

Six – Pulse Converter 1/

Three – phase voltage – source converters can be understood as a bridges composed of six switches.

- The switches operate with unidirectional voltage blocking capability and bidirectional current flow
- The can be realized by associating power semiconductor devices, such as GTOs, IGBTs and antiparallel diodes
- In order to avoid short circuits on the dc bus, there may be only one conducting switch per leg
    - Phase a leg: S_1 and S_4
    - Phase b leg: S_3 and S_6
    - Phase c leg: S_5 and S_2
- The dc bus capacitance was divided into 2 equal parts to create the dc midpoint “o” that is uses as the reference to the output voltages of the converter (v_{ao}, v_{bo}, v_{co})



Idealized three – phase, voltage – source converter

Six – Pulse Converter 2/

Each switch of the leg conducts 180^o per cycle and the switching pulses of the legs are shifted by 120^o from each other.

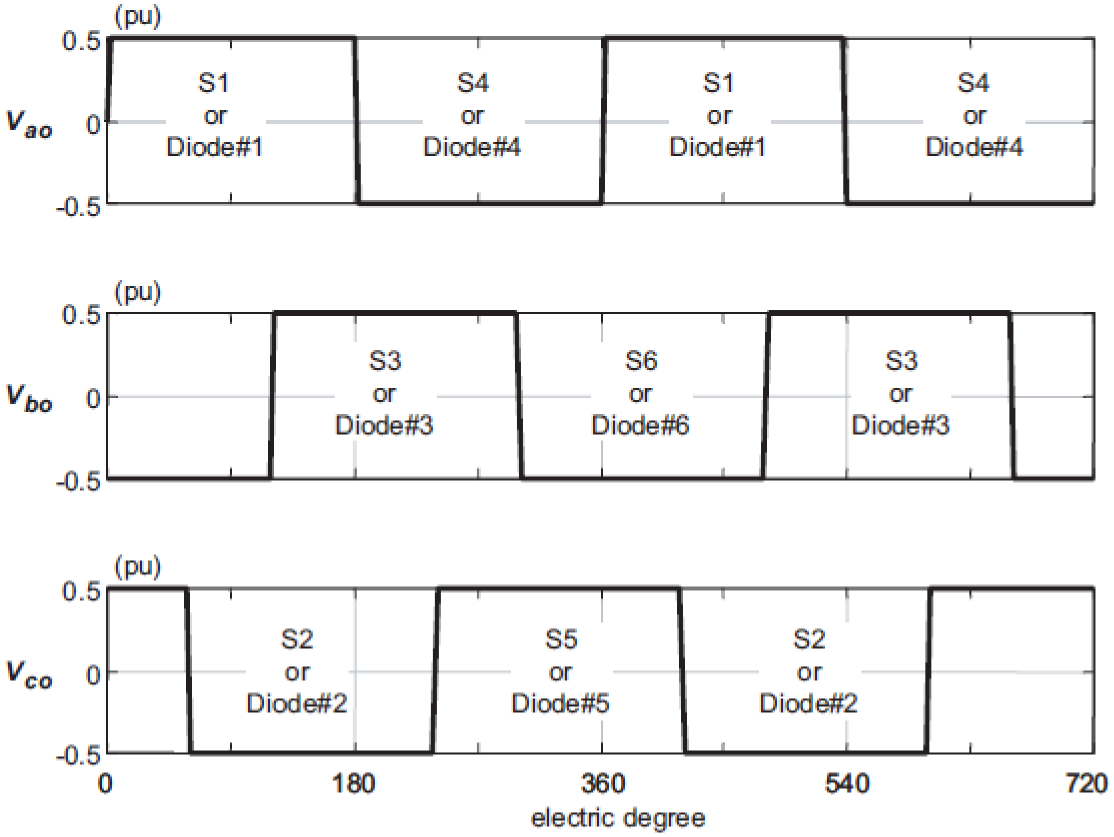


Fig.1 Output voltages of the converter referred to the dc midpoint "o"

Six – Pulse Converter 3/

The out put line voltage (v_{ab}, v_{bc}, v_{ca}) and phase voltages (v_{an}, v_{bn}, v_{ca}) can be easily derived from the voltages of the figure 1.

The line voltage outputs are:

$$v_{ab} = v_{ao} - v_{bo}$$
$$v_{bc} = v_{bo} - v_{co}$$
$$v_{ca} = v_{co} - v_{ao}$$

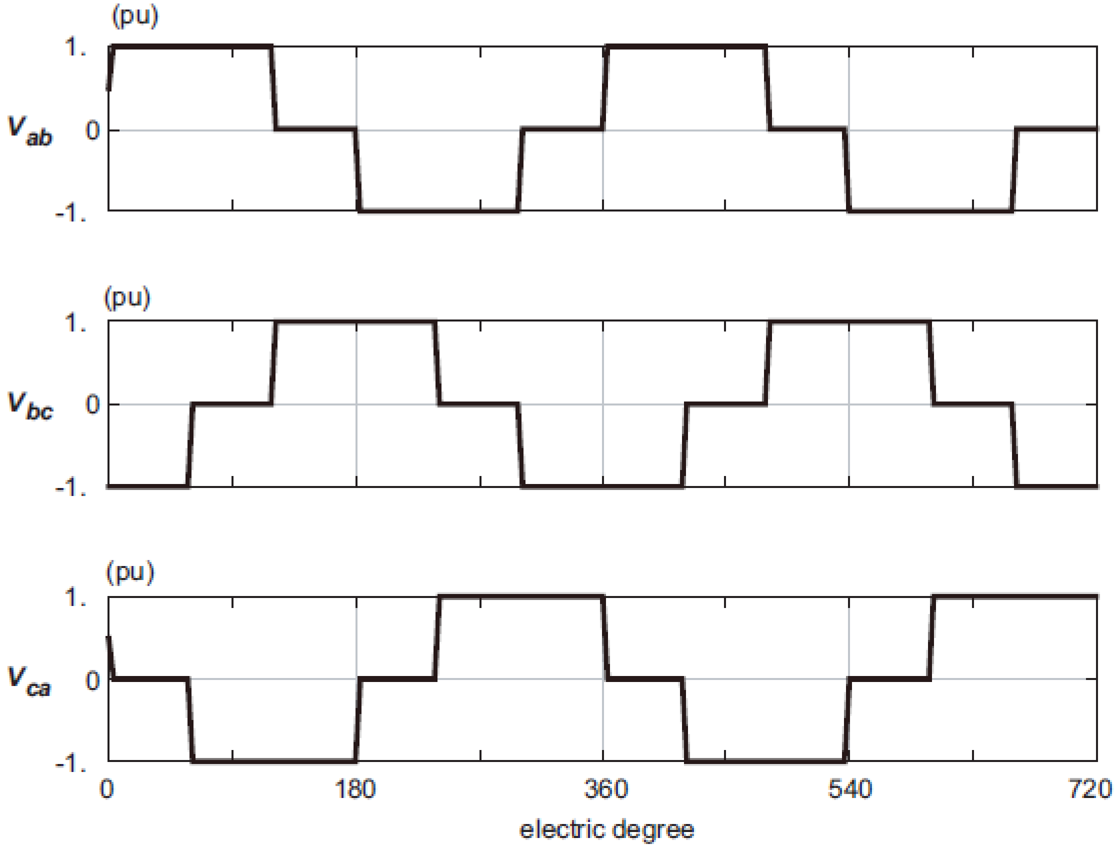


Fig.2 Line voltage output of the voltage – source converter

Six – Pulse Converter 4/

The phase voltages that would appear at a fictitious, balanced Y – connected, three – phase load can determined as:

$$v_{an} = \frac{v_{ab} - v_{ca}}{3}$$

$$v_{bn} = \frac{v_{bc} - v_{ab}}{3}$$

$$v_{cn} = \frac{v_{ca} - v_{bc}}{3}$$

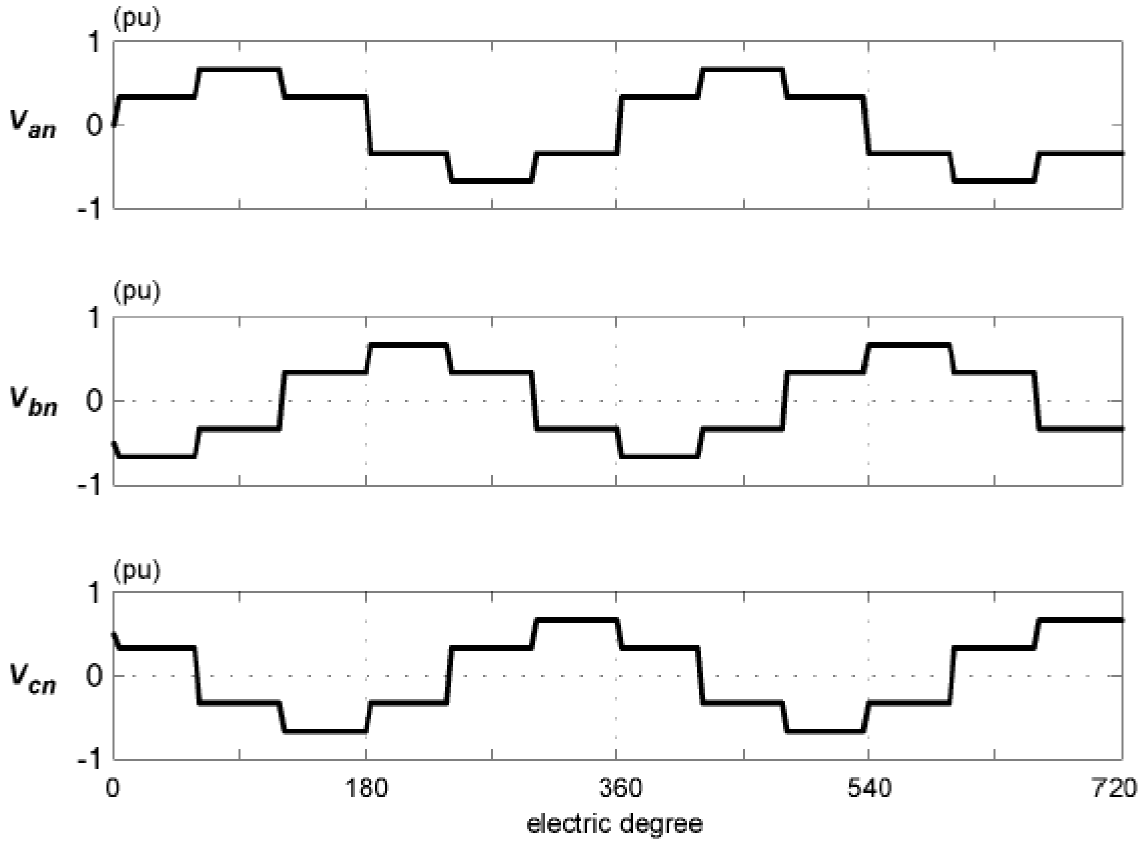


Fig.3 Phase voltage at a balanced three – phase load connected to the six – pulse converter

Six – Pulse Converter 5/

- The fundamental components of the phase voltages v_{an}, v_{bn} and v_{cn} (figure 3) are in phase with the output voltages v_{ao}, v_{bo} and v_{co} (figure 1)
- The pulse time sequence in the switching control must be synchronized with the controlled ac bus voltage
- 3n $(n = 1,3,5 \dots)$ harmonic voltage components appear between the neutral point of the load and the midpoint of the dc side of the six – pulse converter
- It has not fundamental component

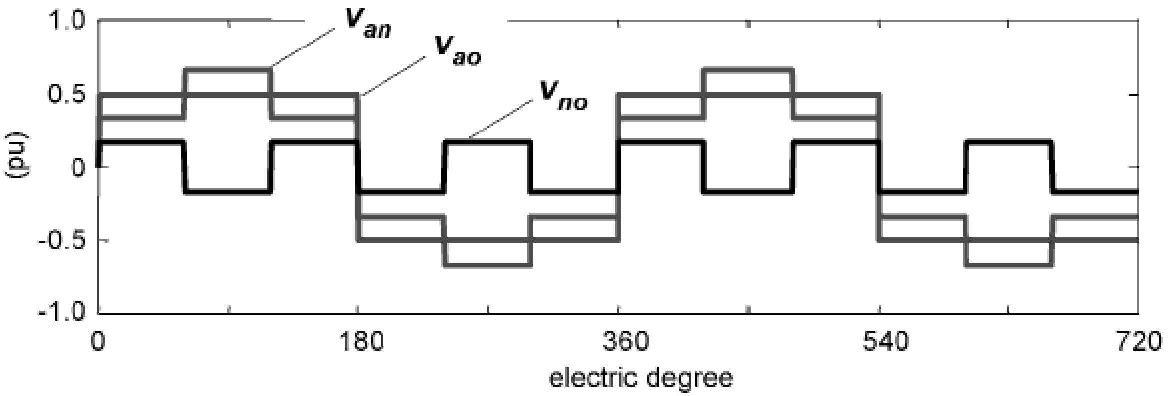


Fig.4 Voltage v_{no} between the load neutral and dc midpoint

Six – Pulse Converter 6/

- The output voltages waveform of the elementary six – pulse converter (figure 2 and 3) contains harmonic components with frequencies on the order of $[(6k \pm 1) \cdot f_o]$, where the f_0 is the fundamental frequency and $k = 1,2,3 \ldots$
- The current in the dc side has harmonic components at frequencies on the order of $[6k \cdot f_0]$ and as a result the simple converter is impractical for direct us in high – power applications
- Instead of using filters, several six – pulse converter modules can be arranged, using transformers as magnetic interfaces, to form a multipulse converter, which is a useful technique to perform harmonic neutralization
- The higher the number of six – pulse converter modules, the lower the distortion of the resultant output voltage
- For example eight six – pulse converters can be combined by means of magnetic interface (special transformers) to form an equivalent 48 – pulse converter
    - The first harmonic order is the 47^{th} in the ac voltage and the 48^{th} in the dc current
    - The amplitude of the harmonics decrease as the harmonic order increases
    - It has nearly sinusoidal voltage
    - It can be applied without any additional filtering system
    - Despite the resultant output voltage which is nearly sinusoidal, each six – pulse converter still generates the quasisquare output voltage

Quasi 24 – Pulse Converter 1/

The basic configuration of a quasi 24 – pulse converter that can be used as a shunt converter in a UPFC approach has:

- 4 six – pulse converters connected in parallel to the dc capacitor
- 4 ordinary three – phase transformers to compose the magnetic interface

The ordinary transformers are preferred for the magnetic interface due to their simplicity compared to zig – zag transformers, but complex interfaces can allow theoretically the complete cancelation of the low order harmonics.

- For example, in a 24 – pulse arrangement all low – order harmonics up to 23rd order, except for the fundamental one, are fully cancelled
- The arrangement of figure 5 cannot cancel fully the 11th and 13th harmonics, although is reduces the significantly

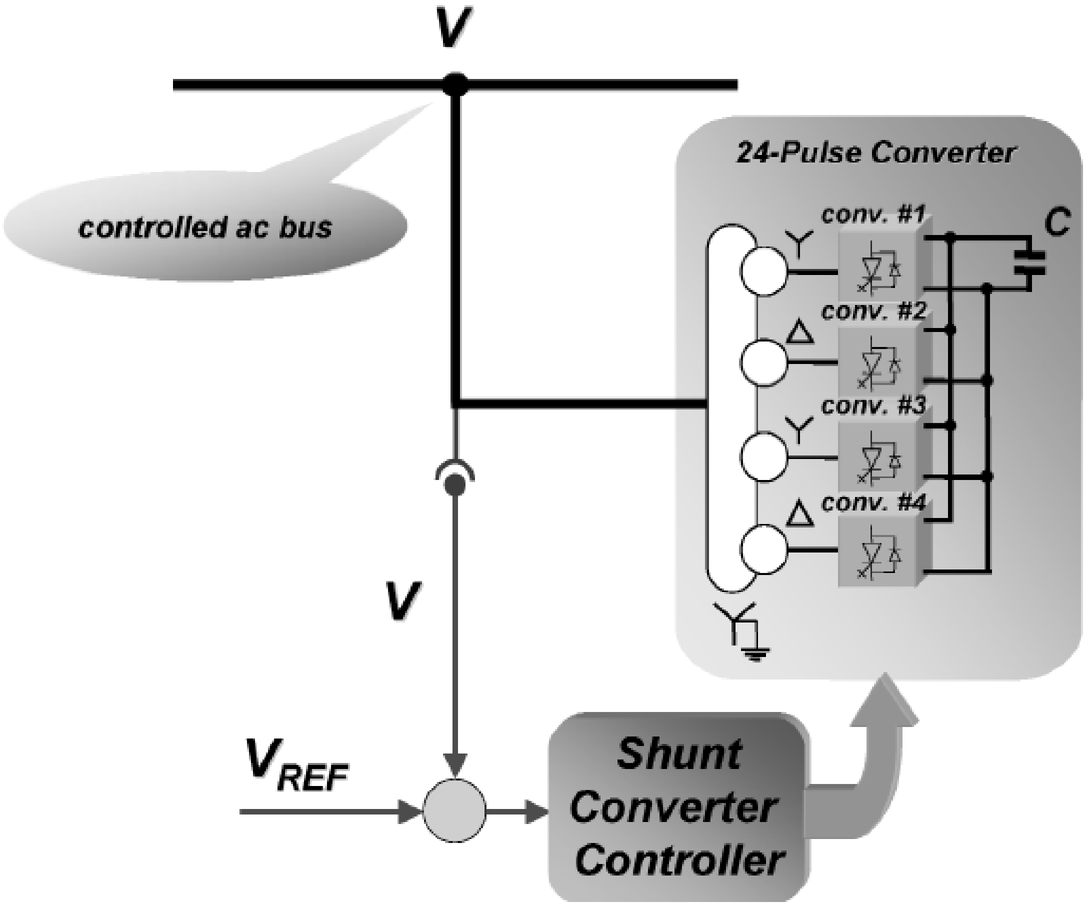


Fig.5 Basic configuration of a quasi 24 – pulse shunt converter for the UPFC

Quasi 24 – Pulse Converter 2/

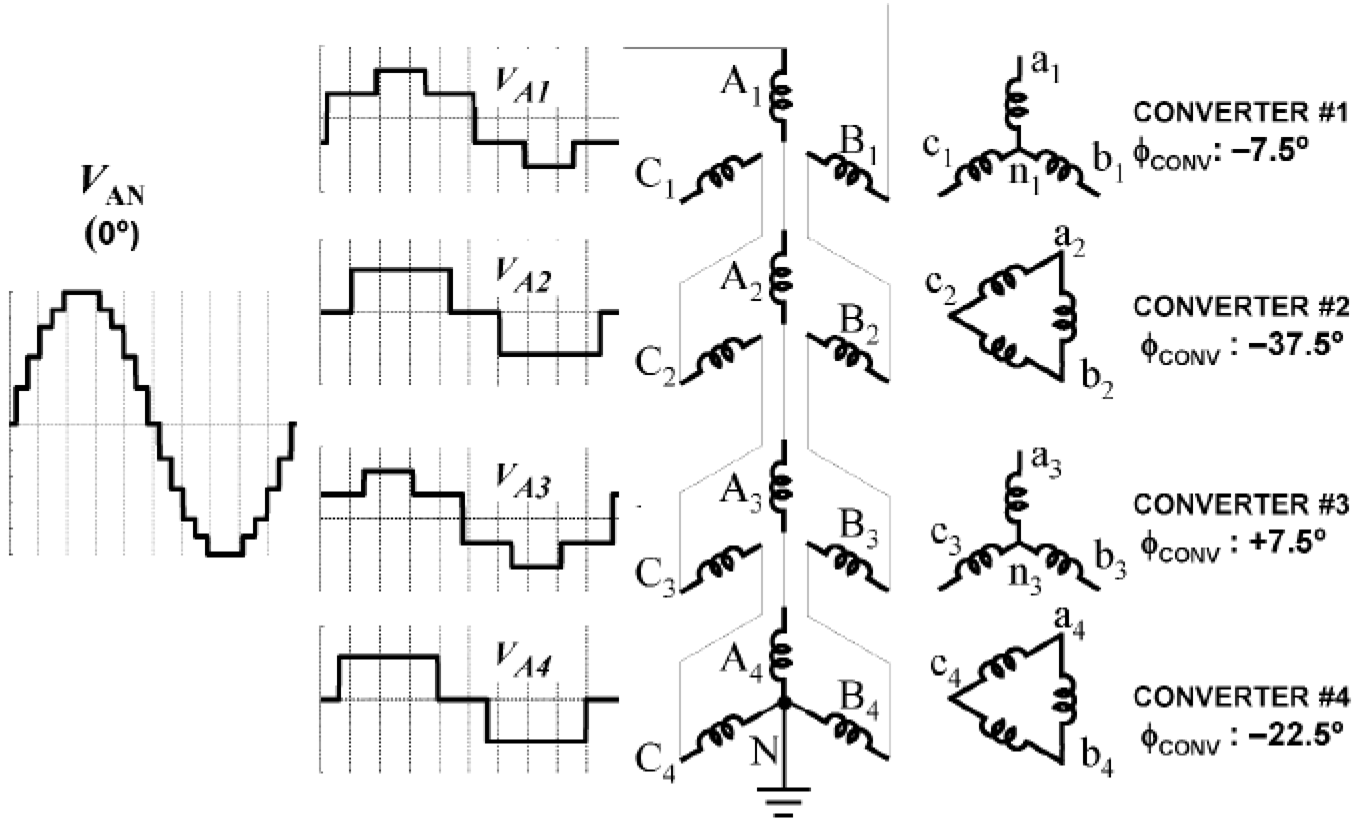


Fig.6 Transformer connections for the quasi 24 – pulse converter

Quasi 24 – Pulse Converter 3/

The quasi 24 – pulse magnetic interface exploits the well – know technology of three – phase Y – Y and Y – Δ transformers and takes advantages of the different voltage waveforms, which excite the windings of those transformers

- The phase – to – neutral voltages of the figure 3 (v_{an}, v_{bn}, v_{cn}) are applied to the windings of the Y – Y transformer
- The line – to – line voltages of the figure 2 (v_{ab}, v_{bc}, v_{ca}) are applied to the secondary windings of the Y – Δ transformer

In figure 6, negative values for the switching sequence $(\varphi_{conv} < 0)$ of the converters mean that the first pulse (turn – on) of the sequence for the switch in figure 1 is delayed by the corresponding negative angle $\varphi_{conv} = \omega t_d$ with respect to the reference given by a synchronized phase angle reference of the primary side of the transformer which is the control ac bus

- For example if the system frequency is $50\ Hz$, in figure 6, the time delay given for the converter #1 is $t_d = \frac{7.5 \cdot \pi}{180 \cdot 2\pi \cdot 50}$ =416.67 µs, while the switching sequence of the converter #3 is in advance by 416.67 µs

The switching sequence of the converters must keep the fixed phase shifts φ_{conv} in order to preserve the quasi 24 – pulse waveform

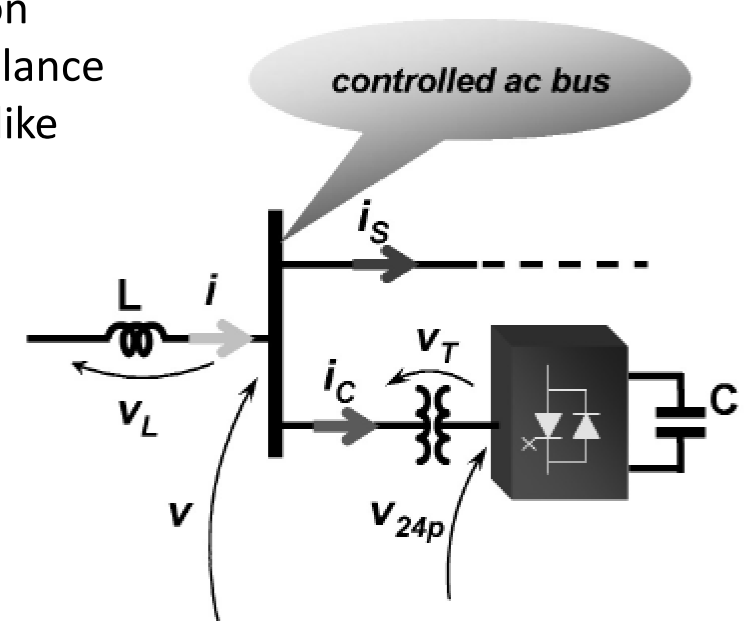
Control of Active and Reactive Power Multipulse Converters 1/

Let's assume that a multipulse converter is used as the shunt converter of a UPFC and is connected to the controlled ac bus

The main elements of the power circuit involved with the variation of active and reactive power are:

- the dc capacitor of the common dc link
- a single block representing the converters
- a single transformer representing the magnetic interface

The UPFC shunt converter should be able to control active – power generation independently of the reactive power generation, so it can perform energy balance in the common dc link as well as voltage regulation on the controlled ac bus like the UPFC approach with PWM converters



Control of Active and Reactive Power Multipulse Converters 2/

The 24 – pulse voltage has a fundamental component with the amplitude directly proportional to the dc voltage on the common link

- The phasor associated with the fundamental component is represented by v_{24p}
- The phasor associated with the ac bus voltage is represented by v
- The transmission line current i_s is not directly affected by i_c, because i_s is controlled by series converter of the UPFC
- The generated reactive current of the shunt multipulse converter flows to the system at the left – hand side of the UPFC and causes an additional voltage drop v_L on the equivalent series impedance
- This voltage drop will cause an increment on the magnitude of the controlled ac bus voltage if the sunt converter is drawing capacitive current

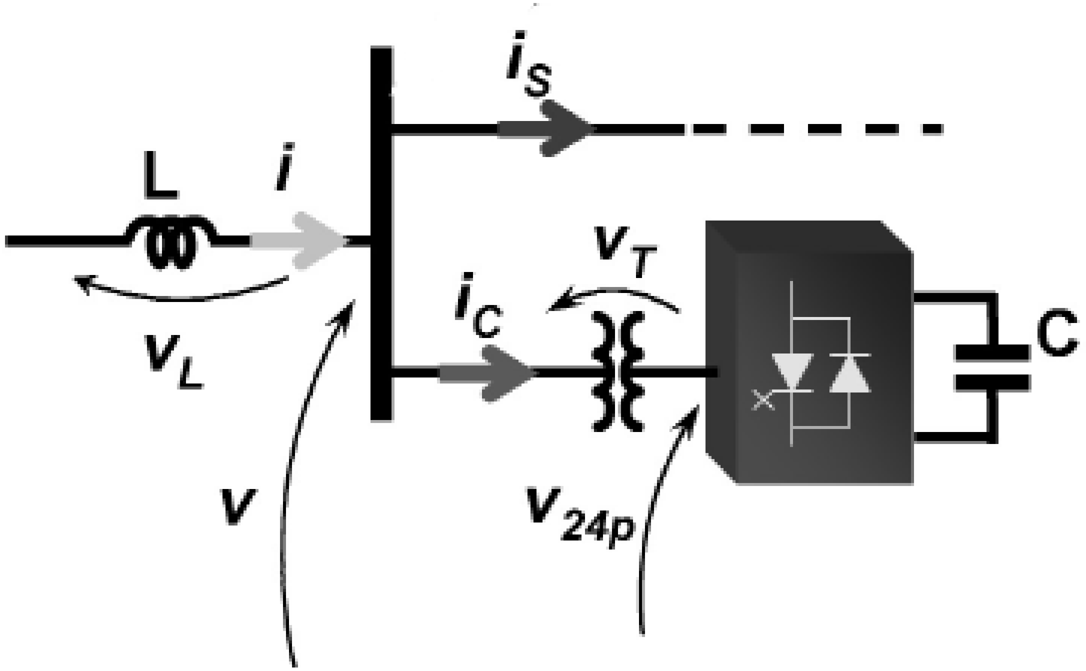


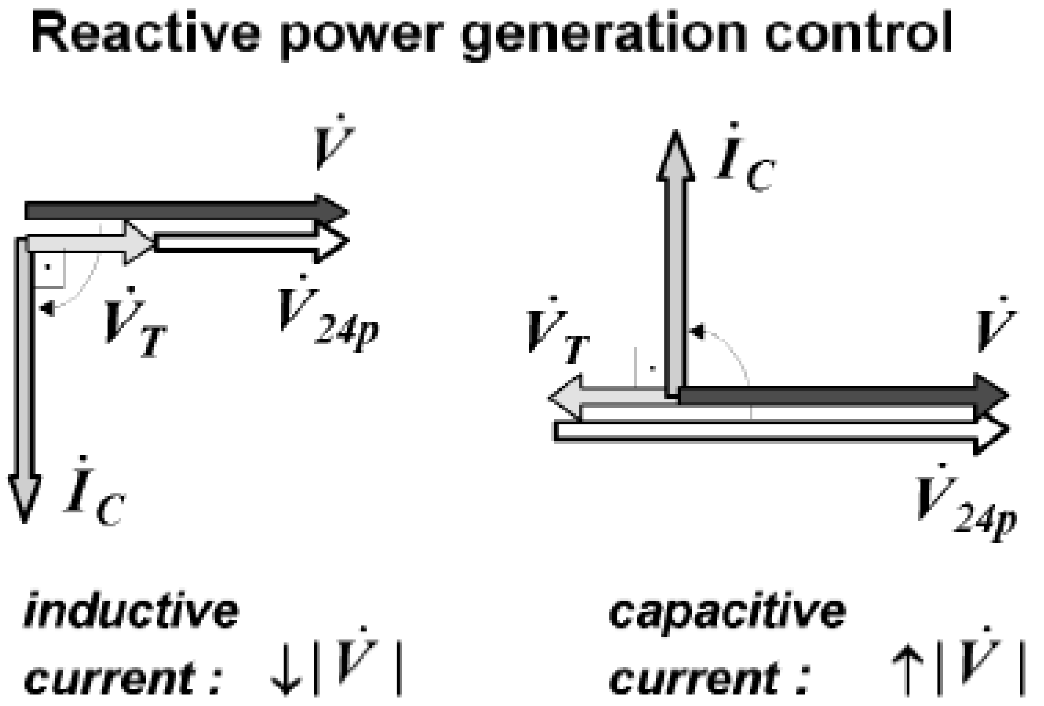
Fig.7 Shunt connected multipulse converter

Control of Active and Reactive Power Multipulse Converters 3/

- If $\dot{V}_{24p}$ and $\dot{V}$ have the same frequency, the same amplitude and the same phase angle, no current flows through the converter transformer and $\dot{V}_T$ is zero
- If $\dot{V}_{24p}$ is in phase with $\dot{V}$, but they have different amplitudes, pure reactive current $\dot{I}_c$ flows through the converter transformer
- If $\dot{V}_{24p}$ has a lower amplitude than $\dot{V}$, $\dot{I}_c$ is inductive (lagging current)
- If $\dot{V}_{24p}$ has an amplitude greater than that of $\dot{V}$, $\dot{I}_c$ is capacitive (leading current)

The dc voltage must vary in order to control the generated reactive power of the multipulse converter

Active power is controlled by phase shifting of the output voltage $\dot{V}_{24p}$ with respect to $\dot{V}$

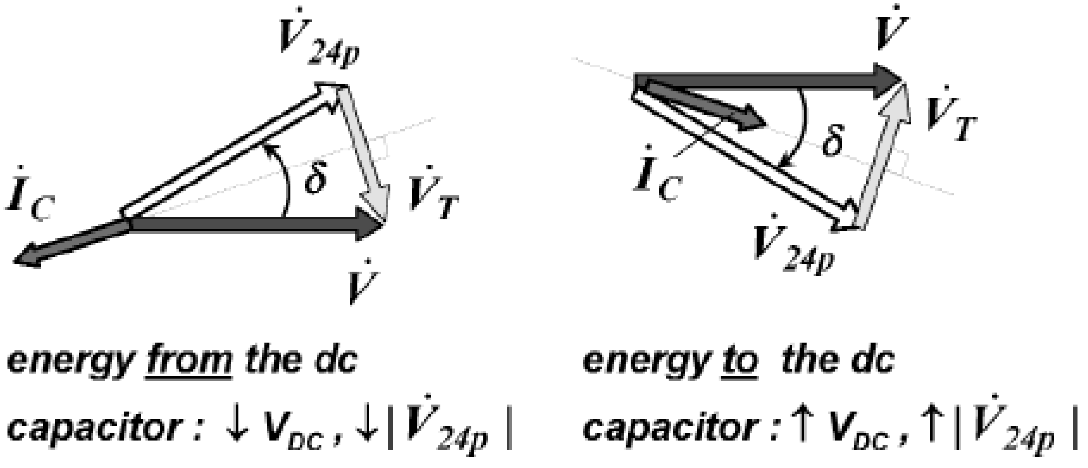


Control of Active and Reactive Power Multipulse Converters 4/

Active power is controlled by phase shifting of the output voltage $\dot{V}_{24p}$ with respect to $\dot{V}$

This allow the realization of the energy balance in the dc link and an extraction or injection of an extra amount of energy, besides the necessary energy for the energy balance in order to adjust the dc – link voltage to control also the reactive power generation needed for the ac – bus voltage regulation

Active power flow control

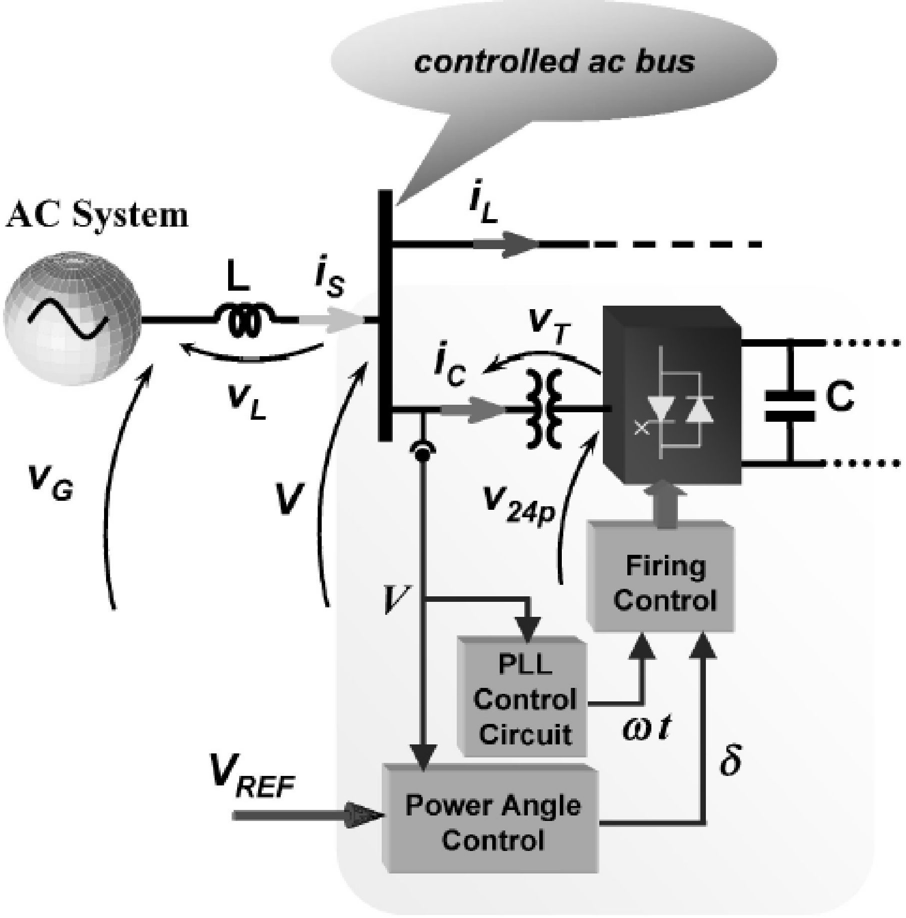


Shunt Multipulse converter 1/

Instead of producing instantaneous values of compensating current references, as we do in the UPFC shunt PWM converter, the switching logic of the shunt multipulse converter must receive the following information:

- The phase angle $\theta = \omega t$, synchronized with the controlled ac bus voltage, which can be calculated by a phase – locked – loop (PLL) circuit
- A shifting angle δ, determined by the UPFC shunt converter controller

The main shunt converter controller need only a measurement from the controlled ac bus voltage



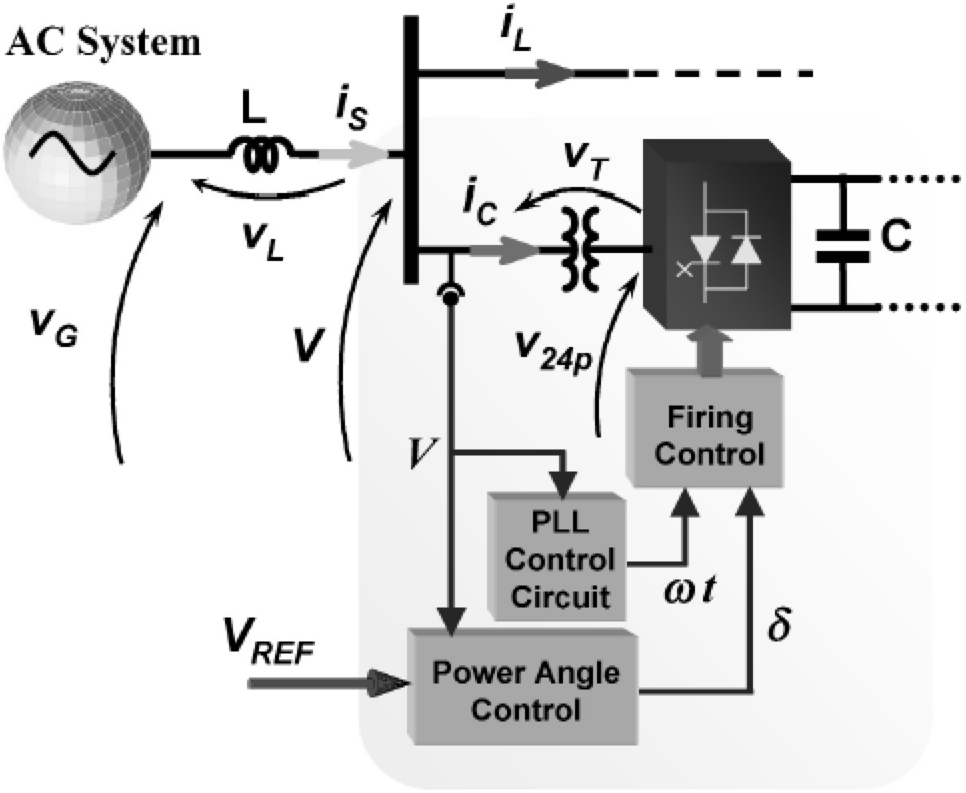
Controller for the UPFC multipulse shunt converter

Shunt Multipulse converter 2/

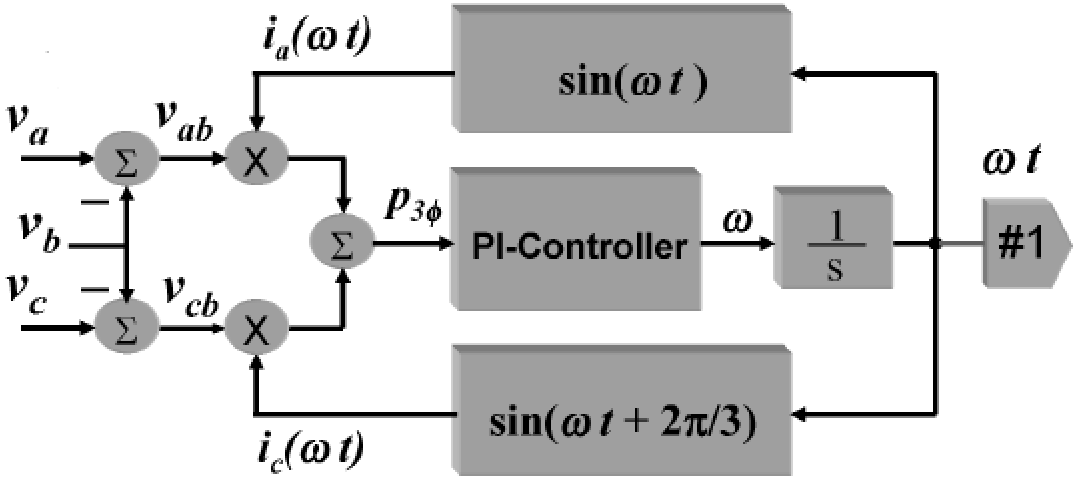
The PLL control circuit is an excellent alternative to generate the synchronized phase angle $\theta = \omega t$.

- It locks the phase angle of the fundamental positive – sequence component of the measured system voltage instead of locking the phase angle of the phase – to neutral voltage in α phase, as commonly calculated by other PLL circuits

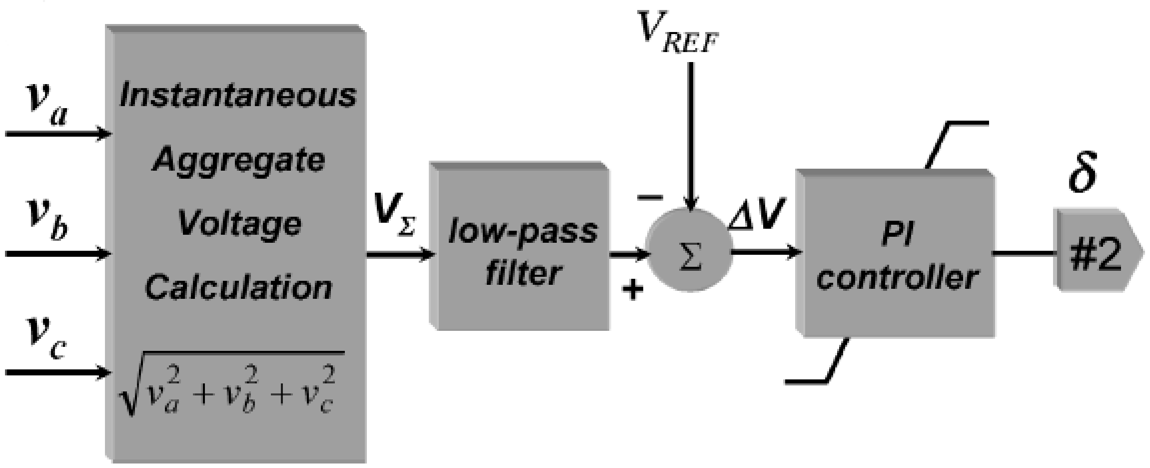
The power angle control block is basically composed of a PI controller that integrates the error between the instantaneous aggregate value of the controlled ac bus voltage and its reference value



Shunt Multipulse converter 3/



Synchronizing circuit – the PLL circuit



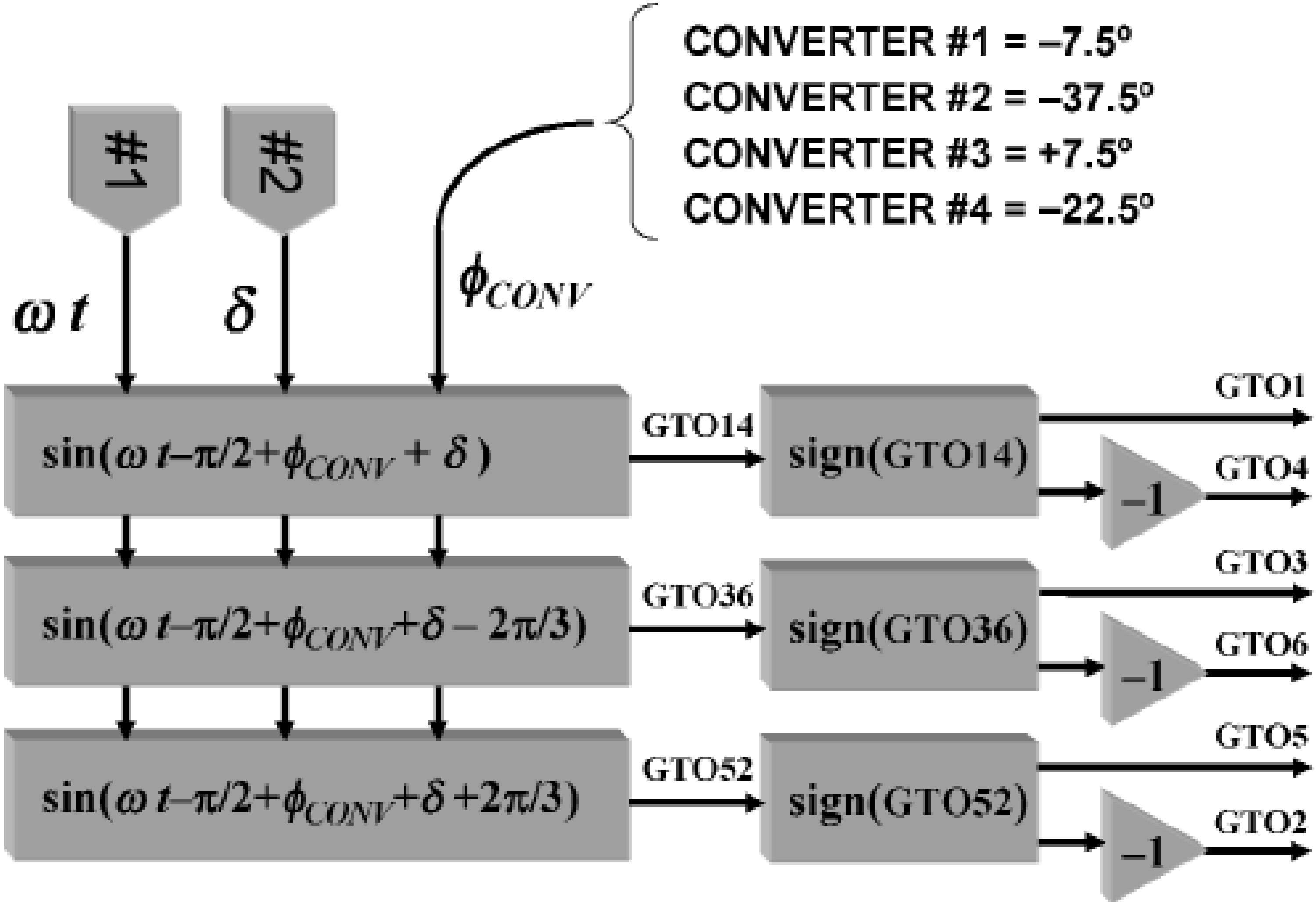
Complete power angle control circuit

Shunt Multipulse converter 4/

Example:

- If the UPFC series converter, when controlling the reactive and active power flow through the controlled transmission line, need to inject energy into the ac network (the active power determined by the product of v_c and i_s) this energy leaves the dc capacitor discharging it
- This reduces the dc voltage and causes a reduction in the output voltage v_{24p}
- It is possible to say that the compensating current i_c becomes more inductive, which will cause less shunt (capacitive) reactive compensation and the voltage magnitude of the controlled bus decreases
- This produces an increasing negative voltage error ΔV and the power angle δ becomes more negative forcing the UPFC shunt converter to draw more energy from the network
- As a result, the dc capacitor will be charged again until the shunt reactive compensation (capacitive component of i_c) becomes effective enough to bring the controlled ac bus voltage to its reference value
- Indirect changes in the shunt capacitive compensation makes the PI controller of the power angle control circuit to perform both compensation functions of the shunt converter:
    - AC voltage regulation
    - Energy balance inside the common dc link

Firing logic of the quasi 24 – pulse shunt converter



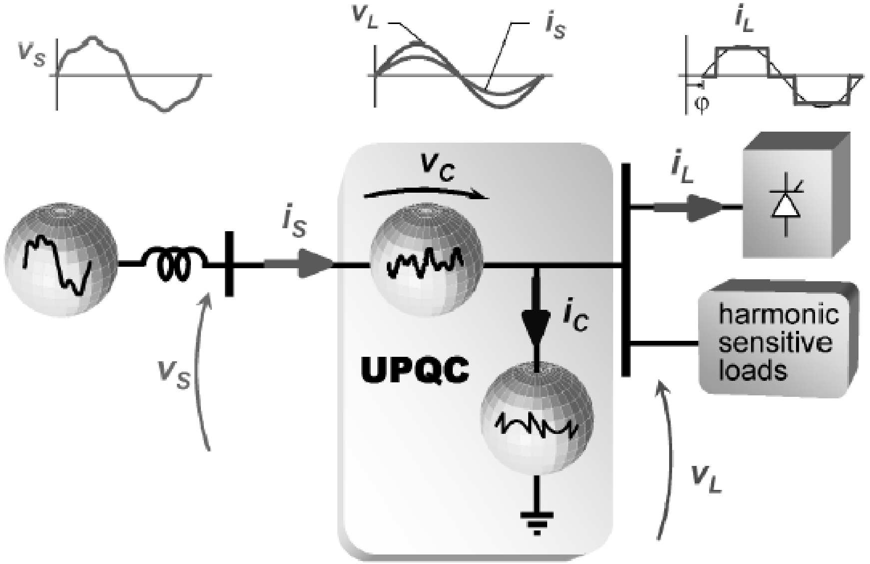
The Unified Power Quality Conditioner (UPQC) 1/

The Unified Power Quality Conditioners (UPQCs) consists of combined series and shunt active power filter for simultaneous compensation of voltage and current.

- They are connected close to loads that generate harmonic currents in power distribution systems
  - The harmonic – producing loads may affect other sensitive load connected at the same ac bus terminal
- A UPQC is one of the most flexible devices for harmonic compensation
- It compensates:
  - Harmonic currents
  - Imbalances of nonlinear load
  - Harmonic voltages
  - Imbalances of the power supply

It improves the power quality delivered for

harmonic – sensitive loads



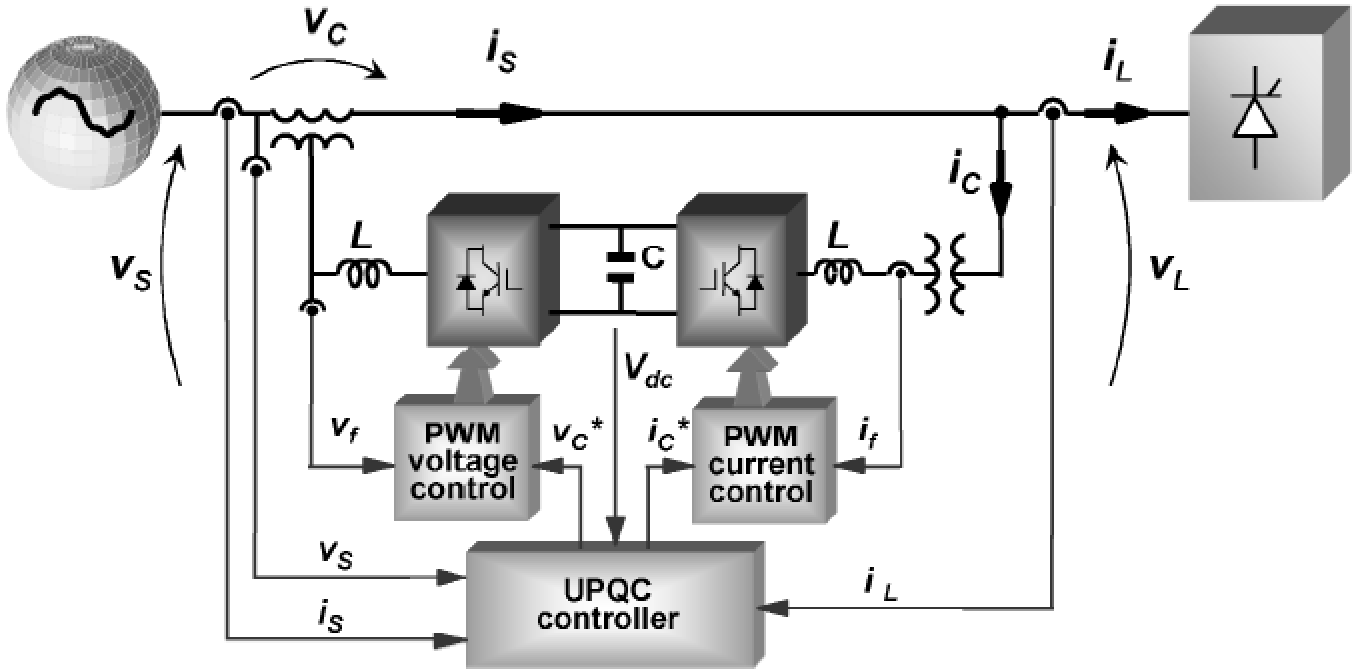
Combined series and shunt compensation (UPQC device)

The Unified Quality Power Conditioner (UPQC) 2/

The UPQC is realized by employing two PWM converters, coupled back – to – back through a common dc link and an integrated controller that provides both voltage and current references for the series and shunt PWM converters

The integration provides compensators:

- which are compact
- With improved overall performance



Basic configuration of the unified power quality conditioner (UPQC)

General description of the UPQC 1/

The unified power quality conditioner has two distinct parts:

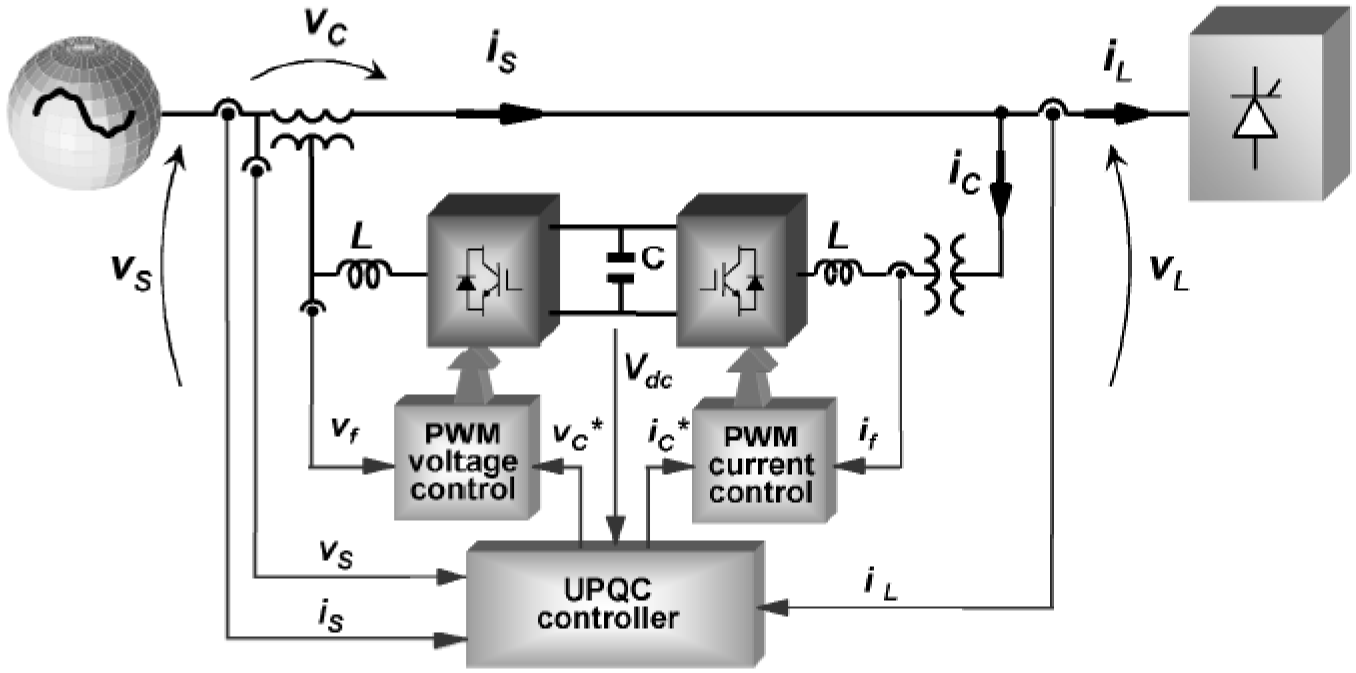
1. Power circuit formed by the series and shunt PWM converters
2. UPQC controller

Unlike the other configurations UPQC:

- UPQC needs an additional current measurement of the nonlinear load
- The shunt converter of the UPQC must be connected as close as possible to the non – linear load instead of the network side

General description of the UPQC 2/

- The series PWM converter of the UPQC behaves as a controlled voltage source (series active filter)
- The shunt PWM converter behaves as a controlled current source (shunt active filter)
- No power supply is connected at the dc link, only small dc capacitor as small energy storage element
- The integrated controller of the series and shunt active filter of the UPQC realizes an "instantaneous" algorithm to provide the compensating voltage reference v_c^*, as well as the compensation current reference i_c^* to be synthesized by the PWM converters



Assignments for combined series and shunt active power filter, the UPQC 1/

Series Active Filter

- Compensates source voltage harmonics, including negative and zero sequence components at the fundamental frequency
- Blocks harmonic currents flowing to the source (harmonic isolation)
- Improves the system stability (damping)

Shunt Active Filter

- Compensates load current harmonics, including negative and zero sequence components at the fundamental frequency
- Compensates reactive power of the load
- Regulates the capacitor voltage of the dc link

The functions mentioned above are the raisons why the UPQC approach is the most powerful compensator for scenarios where the supply voltage is itself unbalanced and/or distorted and is applied to a critical load that requires high power quality

Assignments for combined series and shunt active power filter, the UPQC 2/

In order to reduce the power rating of the shunt active filter, it might be interesting to exclude load reactive – power compensation from the UPQC approach, and to leave this function to other conventional or less expensive compensators

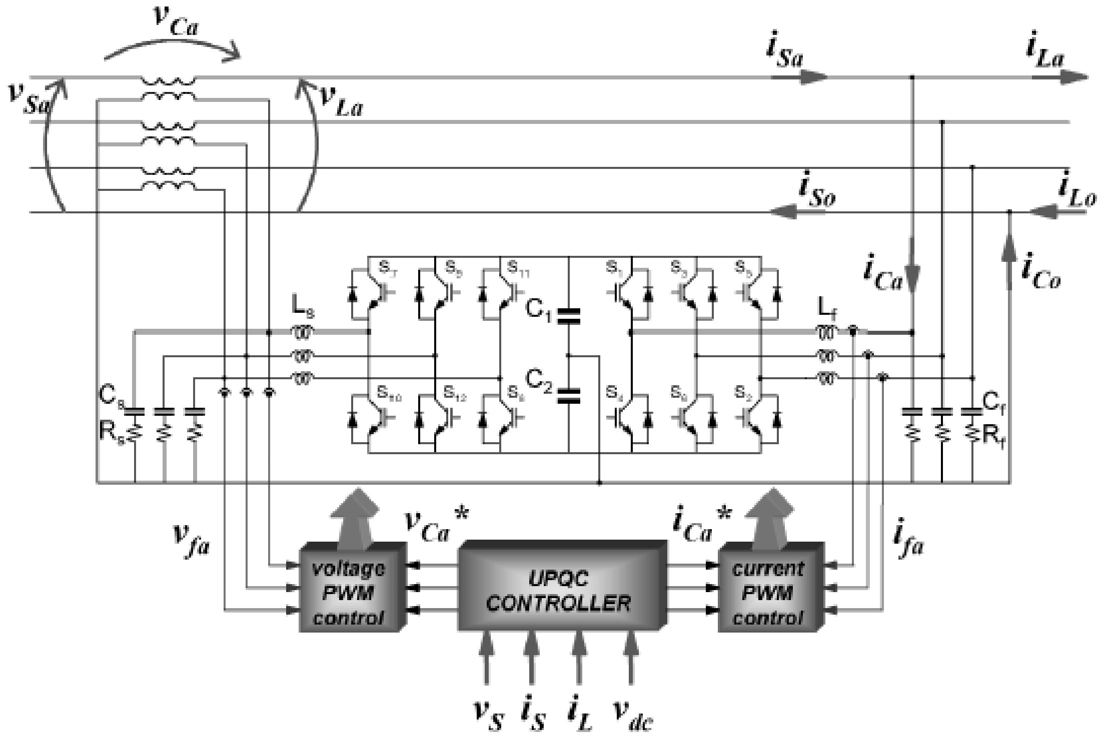
If no reactive power compensation is required the UPQC can be combined with shunt passive filters (LC filters) to reduce the total cost of the installation and to extend its use in very high power applications. This approach is called hybrid UPQC.

A Three – Phase, Four – Wire UPQC 1/

- The principal difference between a three – phase, four – wire and a three – phase, three – wire UPQC is that the first one is able to deal with zero – sequence components in phase voltage and line current

- This kind of imbalance and harmonic distortion is mostly caused by nonlinear loads in low – voltage distribution systems where the neutral conductor is provided

- In medium or high voltage systems, the absence of the neutral conductor naturally eliminates this problem, at least during normal operation



Combined series and shunt active filters (UPQC) to simultaneously compensate the voltages and currents in three – phase, four – wire systems

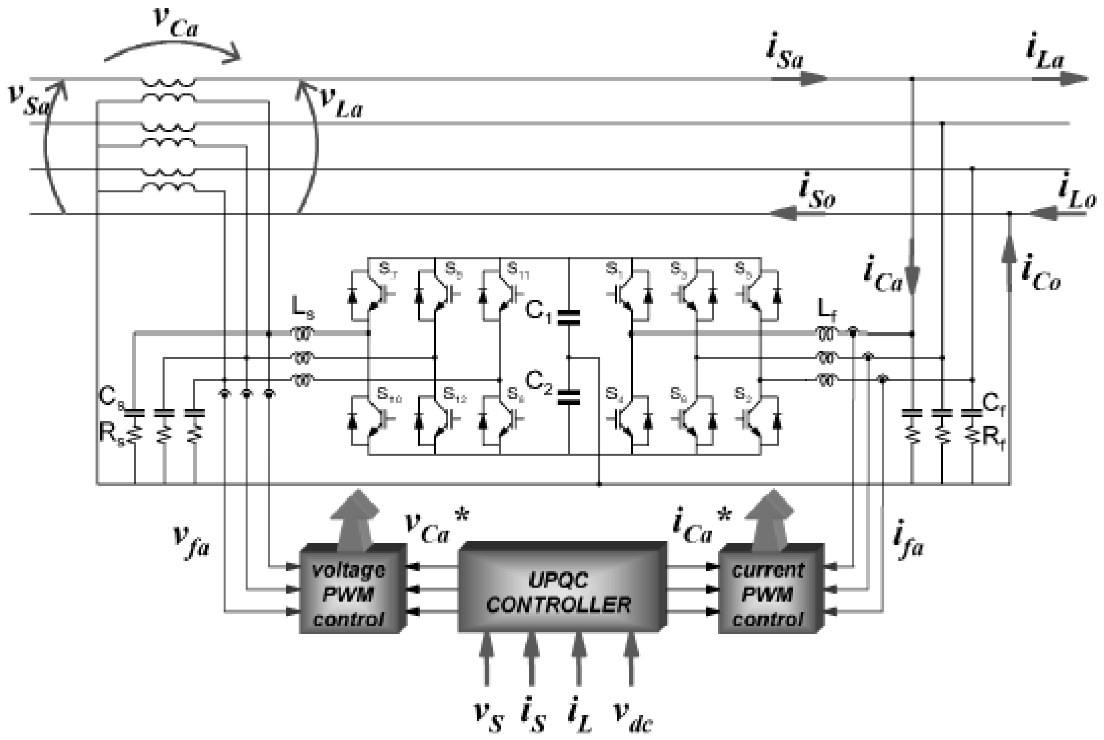
A Three – Phase, Four – Wire UPQC 2/

The main structural differences between the a three – phase, four – wire systems and a three – phase, three – wire system are:

- The elimination oh the neutral wires
- The elimination, in the UPQC controller, of all the variables related with zero – sequence components $(v_0 . i_0, p_0)$

A three – phase, four – wire UPQC consists of:

- Two conventional three – leg converters
    - the shunt active filter with PWM control (controlled current source)
    - the series active filter with PWM control (controlled voltage source)
- The ac neutral conductor
    - It is directly connected to the electrical midpoint of the common dc bus
- Two RC filters



A Three – Phase, Four – Wire UPQC 3/

Shunt Active Filter Assignments

- Compensates load current harmonics, including negative and zero sequence components at the fundamental frequency, that no current flows through the neutral wire
- Compensates reactive power of the load
- Regulates the capacitor voltage of the dc link

Series Active Filter Assignments

- Compensates source voltage harmonics, including negative and zero sequence components at the fundamental frequency
- Blocks harmonic currents flowing to the source (harmonic isolation)
- Improves the system stability (damping)

As a result:

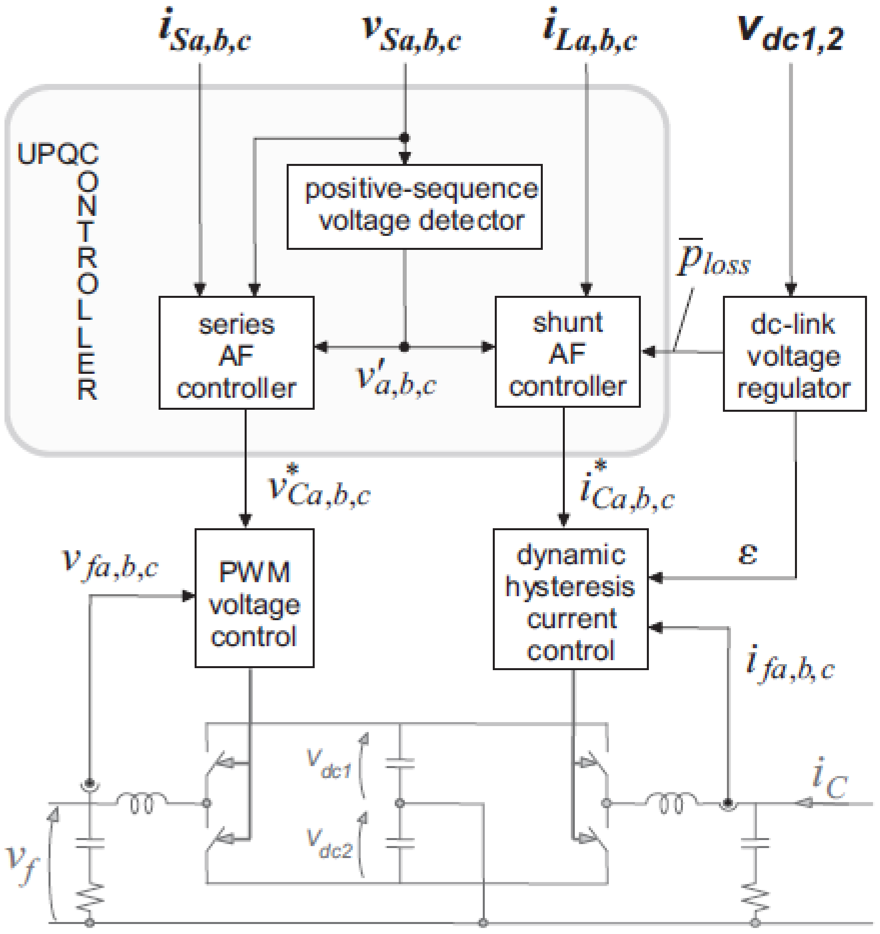
- The load voltages (V_{La}, V_{Lb}, V_{Lc}) become balanced and free of harmonics
- The combines action of the series and shunt active filters forces the compensated voltages (V_{La}, V_{Lb}, V_{Lc}) and currents (i_{Sa}, i_{Sb}, i_{Sc}) to become sinusoidal and balanced.
- Other loads could be connected close to the nonlinear load without being affected by harmonics, while they are supplied with higher power quality.

A Three – Phase, Four – Wire UPQC 4/

- The UPQC controller realizes almost instantaneous control algorithms to provide the current references $(i^*_{Ca}, i^*_{Cb}, i^*_{Cc})$ to the shunt filter and the voltage references $(v^*_{Ca}, v^*_{Cb}, v^*_{Cc})$ to the series active filter
- The high switching frequency of the PWM converters produces the currents (i_{fa}, i_{fb}, i_{fc}) and the voltages (v_{fa}, v_{fb}, v_{fc}) with some unwanted high order harmonics that can be easily filtered by using small passive filters represented by R_f, C_f, R_s and C_s
- If the filtering is ideal the compensating currents (i_{Ca}, i_{Cb}, i_{Cc}) and voltages (v_{Ca}, v_{Cb}, v_{Cc}) track strictly their references.

The UPQC Controller

- The UPQC controller is a merge of the control circuits of series and shunt active filters and has the advantage of saving computation efforts.



Functional block diagram of the UPQC controller

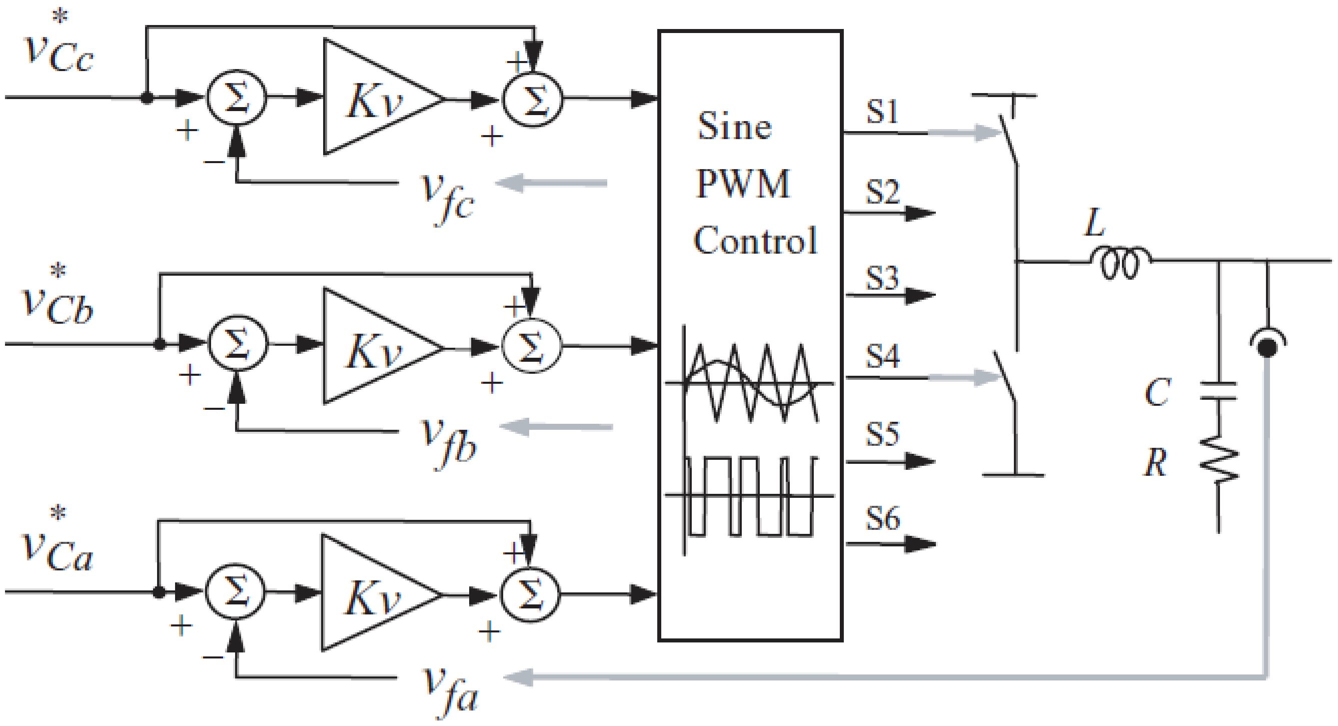
PWM Voltage Control with Minor Feedback Control Loop 1/

- The PWM voltage control must allow the series active filter to generate nonsinusoidal voltages $v_{Ca}^{*}, v_{Cb}^{*}, v_{Cc}^{*}$, which can vary widely in frequency and amplitude.
- Three minor feedback control loops use the values of v_{fa}, v_{fb}, v_{fc}, in order to minimize between the values $v_{Ca}^{*}, v_{Cb}^{*}, v_{Cc}^{*}$ and the compensating voltages v_{Ca}, v_{Cb}, v_{Cc}.

PWM Voltage Control with Minor Feedback Control Loop 2/

- K_V is a gain which multiplies the errors between the reference values and the values of compensating voltages.

- We can replace it with a PD or a PID controller in order to improve the system dynamics and eliminate steady-state errors.

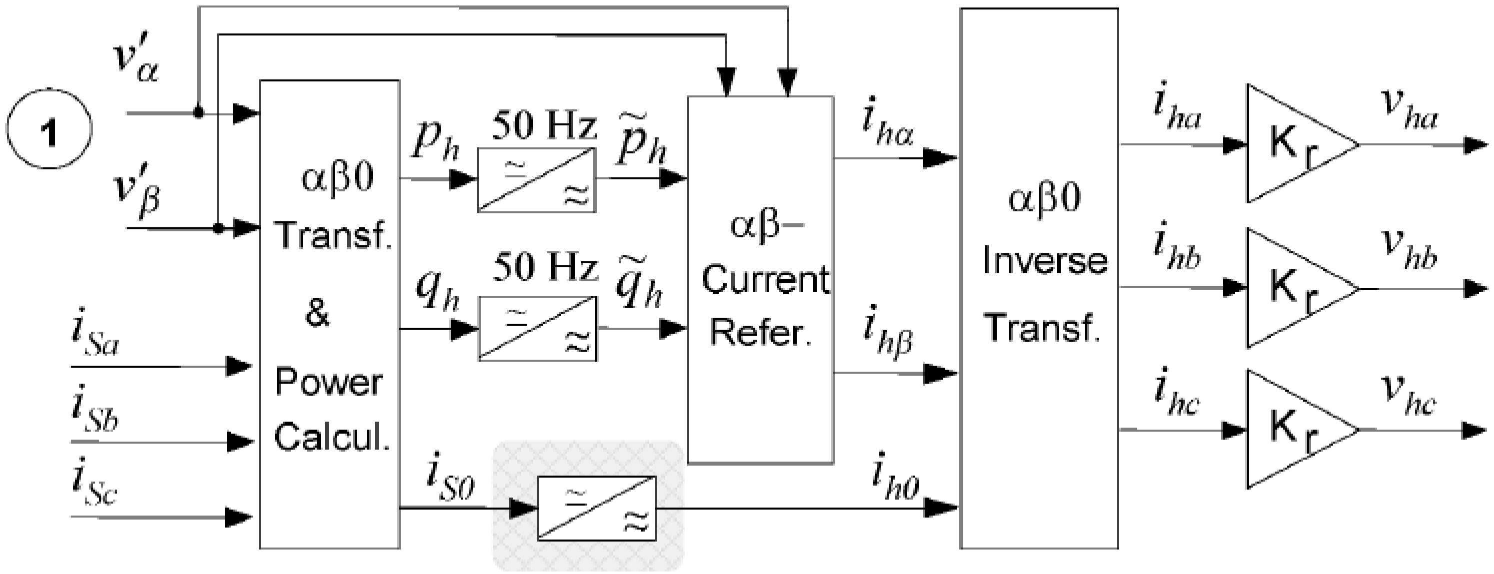


PWM voltage control with minor feedback control loops

Series Active Filter Controller

- The main use of the series active filter controller is to compensate all the harmonic voltage components in the supply voltage.
- A control algorithm will be used to generate an auxiliary control signal that enhances the overall system stability without degenerating the main compensation functions of the UPQC.

Block diagram of the control algorithm for damping of oscillations due to resonance phenomena 1/



Block diagram of the control algorithm for damping of oscillations due to resonance phenomena

This is an algorithm for the calculation of the currents i_{ha}, i_{hb}, i_{hc} using the instantaneous powers p_h, q_h.

Block diagram of the control algorithm for damping of oscillations due to resonance phenomena 2/

1) With Clarke transformation the currents i_{Sa}, i_{Sb}, i_{Sc} are transformed on the $\alpha\beta$ – reference frame:

$$\begin{bmatrix} i_{S0} \\ \hdashline i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \hdashline 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix}$$

2) The positive sequence voltages are represented by v_a', v_b', v_c' and are already transformed on the $\alpha\beta$ – reference frame. So we can calculate the instantaneous powers p_h, q_h:

$$\begin{bmatrix} p_h \\ q_h \end{bmatrix} = \begin{bmatrix} v_\alpha' & v_\beta' \\ -v_\beta' & v_\alpha' \end{bmatrix} \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix}$$

Block diagram of the control algorithm for damping of oscillations due to resonance phenomena 3/

3) High pass filters are used to separate the oscillating real and imaginary power $p_{\tilde{h}}, q_{\tilde{h}}$ from the calculated powers p_h, q_h.

4) From the oscillating real and imaginary power, the currents $i_{h\alpha}, i_{h\beta}$ can be calculated and with inverse Clarke transformation we can take the currents i_{ha}, i_{hb}, i_{hc}:

$$\begin{bmatrix} i_{h\alpha} \\ i_{h\beta} \end{bmatrix} = \frac{1}{v_{\alpha}'^2 + v_{\beta}'^2} \begin{bmatrix} v_{\alpha}' & -v_{\beta}' \\ v_{\beta}' & v_{\alpha}' \end{bmatrix} \begin{bmatrix} -\tilde{p}_h \\ -\tilde{q}_h \end{bmatrix}$$

$$\begin{bmatrix} i_{ha} \\ i_{hb} \\ i_{hc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} -i_{h0} \\ i_{h\alpha} \\ i_{h\beta} \end{bmatrix}$$

Block diagram of the control algorithm for damping of oscillations due to resonance phenomena 4/

5) The harmonic currents are multiplied by a control gain K_r to produce the voltage references v_{ha}, v_{hb}, v_{hc}.

$$\begin{bmatrix} v_{ha} \\ v_{hb} \\ v_{hc} \end{bmatrix} = K_r \begin{bmatrix} i_{ha} \\ i_{hb} \\ i_{hc} \end{bmatrix}$$

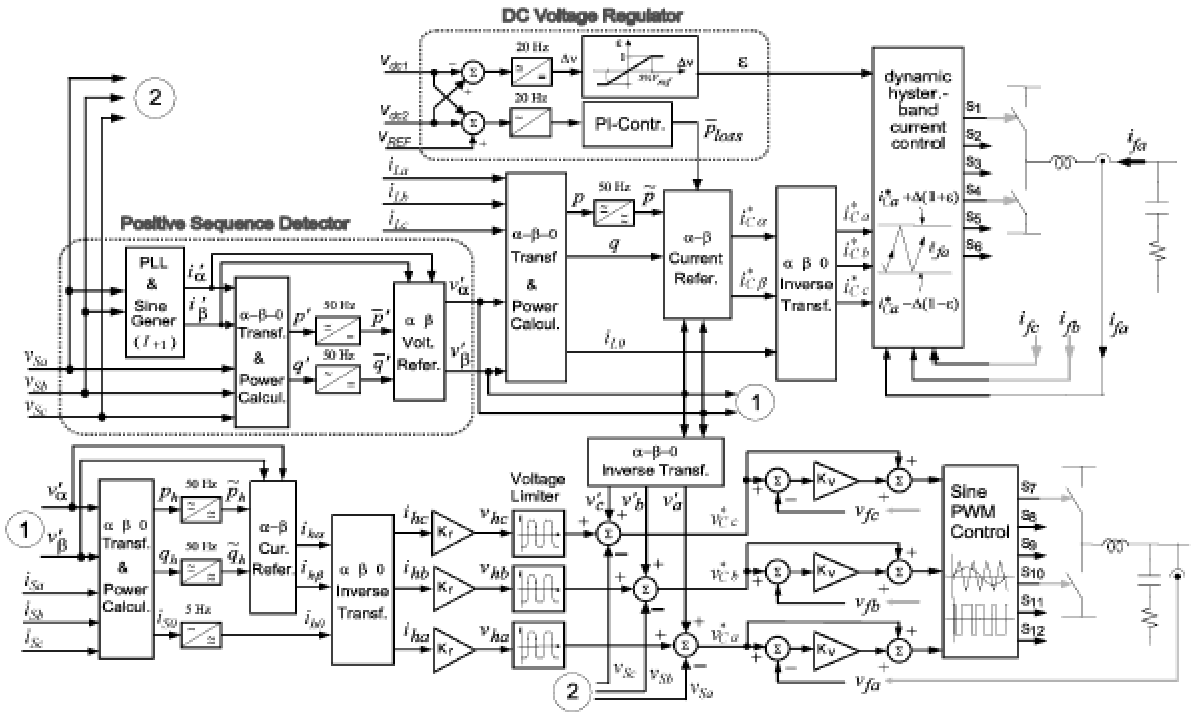
The control algorithm generates the voltage references v_{ha}, v_{hb}, v_{hc} that can be added to the compensating voltage signals $v'_{Ca}, v'_{Cb}, v'_{Cc}$ to compose the new compensating voltage references $v^*_{Ca}, v^*_{Cb}, v^*_{Cc}$, which force the series active filter to compensate all harmonics and voltage imbalance.

$$\begin{bmatrix} v^*_{Ca} \\ v^*_{Cb} \\ v^*_{Cc} \end{bmatrix} = \begin{bmatrix} v'_{Ca} \\ v'_{Cb} \\ v'_{Cc} \end{bmatrix} + \begin{bmatrix} v_{ha} \\ v_{hb} \\ v_{hc} \end{bmatrix}$$

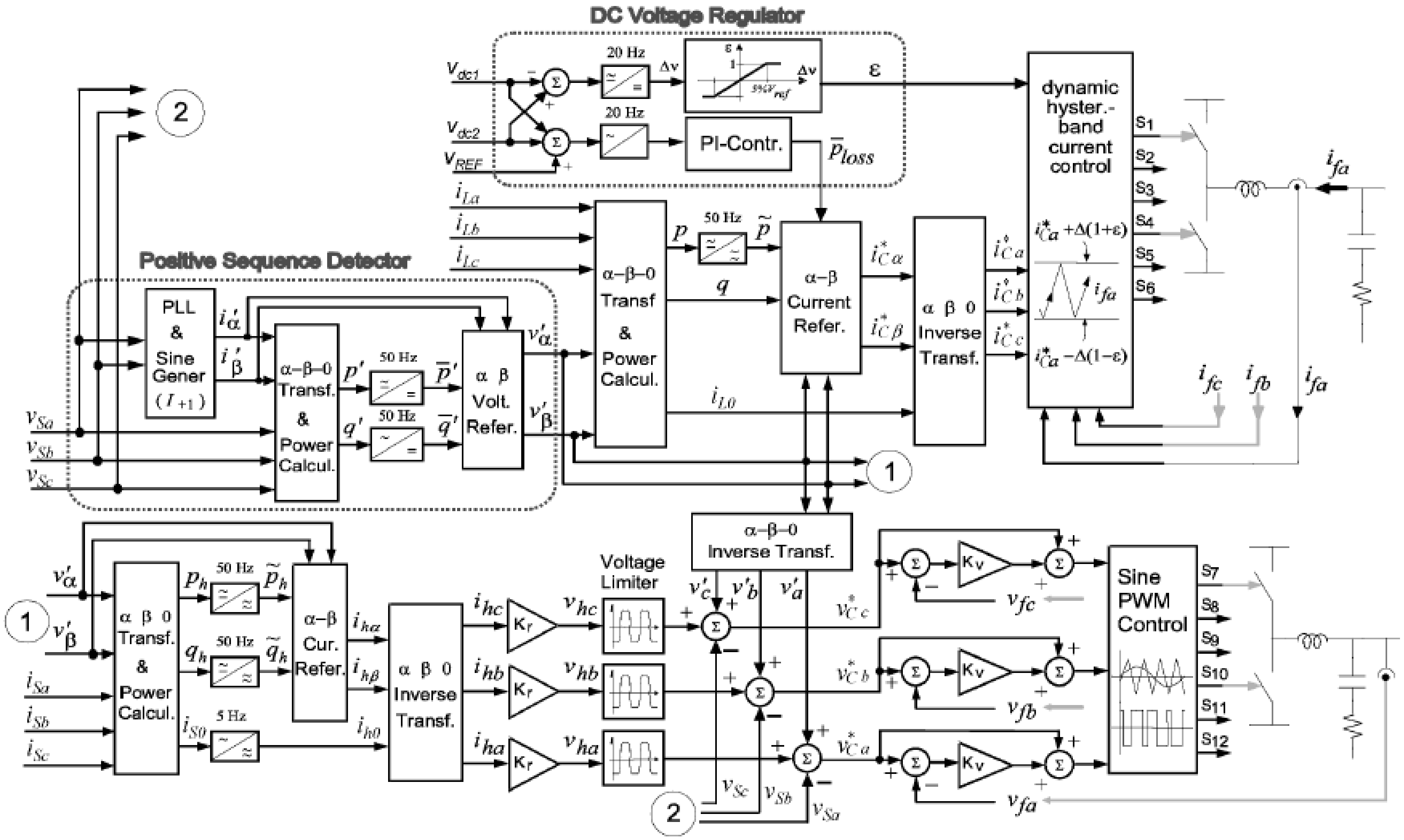
Integration of the Series and Shunt Active Filter Controllers 1/

The complete controller for the UPQC controller can be given with using all the series control parts for the series converter and the sinusoidal control strategy. All that have discussed.

The controller of the unified power quality conditioner:



The controller of a unified power quality conditioner

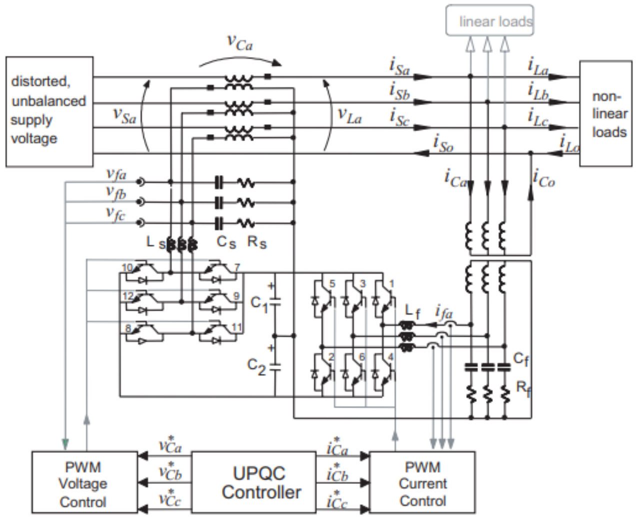


Integration of the Series and Shunt Active Filter Controllers 2/

1) The zero-sequence component of the source current i_{s0} should be zero, since the shunt active filter compensates the neutral current of the nonlinear load.
2) A dynamic hysteresis current control is used to control the dc voltage difference ($V_{dc2} - V_{dc1}$)
3) The voltage references v_{ha}, v_{hb}, v_{hc} would induce a very slow amplitude modulation on the phase voltages at the load side of the UPQC.
4) The values of i_{ha}, i_{hb}, i_{hc} are expected to be very small in the steady state.
5) The proportional gain K_r makes the series active filter behave as an additional series resistance of K_r Ω, connected between the source and the load, but effective only for harmonic currents.
6) The series active filter generates only negative and zero sequence components at the fundamental frequency with the aim of compensating unbalances in supply voltage. This compensation function is included in the control signals v'_{Ca}, v'_{Cb} and v'_{Cc}.

Analysis of the UPQC Dynamic

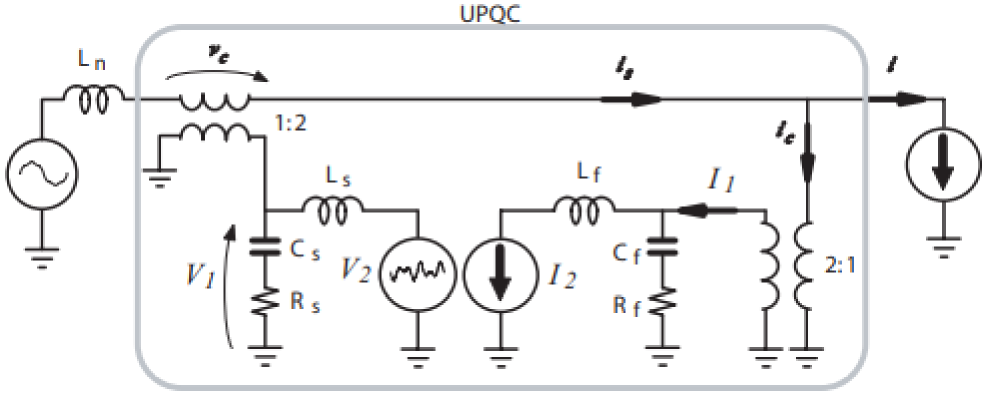
Combined series and shunt active filters (UPQC) to compensate voltages and currents in three-phase, four-wire systems:



1) The line to line voltage is 380 V.
2) The average switching frequency of the PWM converters should lie between 10 kHz and 15 kHz.
3) The UPQC can compensate harmonics up to 1 kHz.

Optimizing the Power System Parameters 1/

Equivalent circuit for optimizing main parameters of the UPQC:



1) High-pass filter of the shunt PWM converter reflected to the primary side:

$$Z_f' = \left(\frac{2}{1}\right)^2 \left(R_f + \frac{1}{j\omega C_f}\right)$$

Optimizing the Power System Parameters 2/

2) Z_f' and network impedance reflected to the secondary side of the series single-phase transformer:

$$Z'_{ns} = \left(\frac{2}{1}\right)^2 (Z'_f + j\omega L_n)$$

3) Z'_{ns} in parallel with the high-pass filter of the series PWM converter:

$$Z_{1s} = \frac{Z'_{ns}\left(R_s + \frac{1}{j\omega C_s}\right)}{Z'_{ns} + \left(R_s + \frac{1}{j\omega C_s}\right)}$$

4) The relation between V_1' and V_2' are:

$$\frac{\dot{V}_1}{\dot{V}_{+2}} = \frac{Z_{1s}}{Z_{1s} + j\omega L_s}$$

Optimizing the Power System Parameters 3/

Functions for describing the current of the shunt PWM converter:

1) Impedances of the series PWM converter reflected to the primary side:

$$Z'_s = \left(\frac{2}{1}\right)^2 \frac{j\omega L_s\left(R_s + \frac{1}{j\omega C_s}\right)}{j\omega L_s + \left(R_s + \frac{1}{j\omega C_s}\right)}$$

2) Z'_s and the network impedance reflected to the secondary side of the shunt three-phase transformer:

$$Z'_{nf} = \left(\frac{1}{2}\right)^2 (Z'_s + j\omega L_n)$$

3) The relation between I'_1 and I'_2:

$$\frac{\dot{I}_1}{\dot{I}_2} = \frac{\left(R_f + \frac{1}{j\omega C_f}\right)}{Z'_{nf} + \left(R_f + \frac{1}{j\omega C_f}\right)}$$

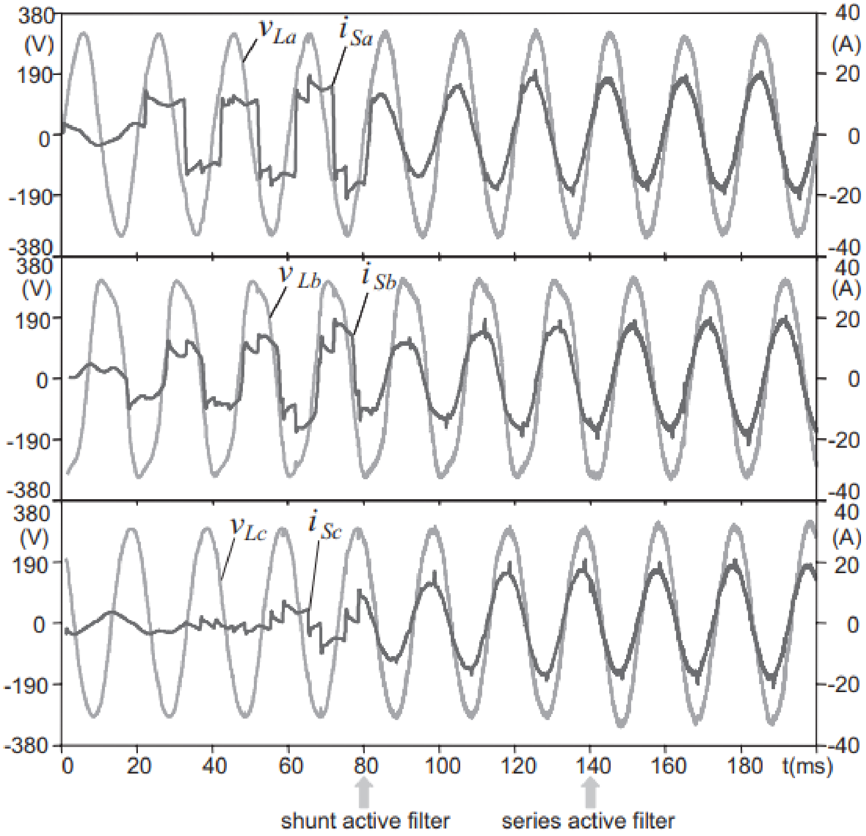
Simulation Results 1/

To composed an unbalanced, nonlinear load, the following power electronics devices are used:

1) One three phase thyristor converter with firing angle=30^o, $I_{dc} = 8\ A$, commutation inductance=3 mH
2) One single phase thyristor converter connected between the a phase and neutral wire with firing angle=15^o, $I_{dc} = 10\ A$, commutation inductance=3 mH
3) One single phase diode bridge connected between the b phase and neutral with $L_{dc} = 300\ mH$, $R_{dc} = 20\ \Omega$, commutation inductance=3 mH

Simulation Results 2/

The compensated voltages and currents with a successive connection of the shunt at t = 80 ms, and series active filter at t = 140 ms:



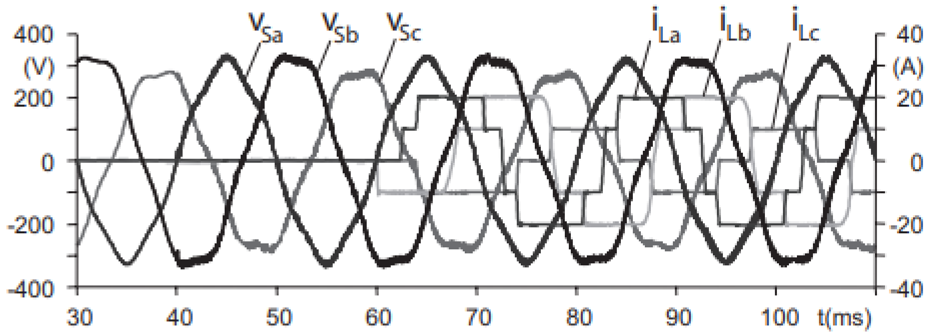
Simulation Results 4/

Another simulation case with the following events:

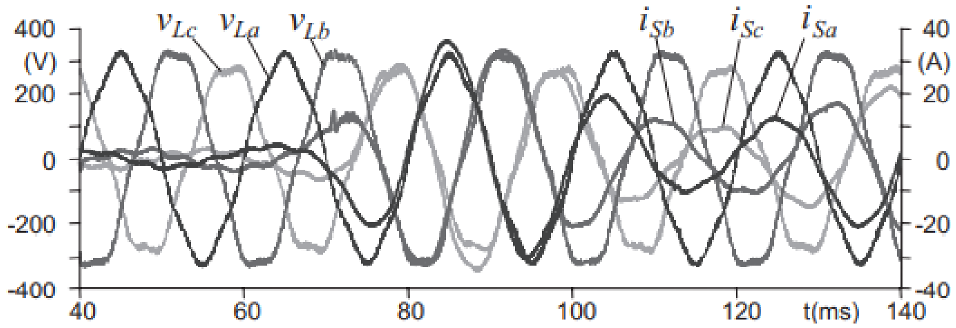
1) PWM converter starts at 40 ms.
2) A single phase diode bridge rectifier is connecting at 60 ms as a load between b phase and neutral conductor.
3) A single phase thyristor bridge rectifier with firing angle=30^o is connecting at 61.7 ms as a load between the a phase and the neutral conductor.
4) A six pulse thyristor bridge rectifier with firing angle=30^o is connecting at 63.3 ms as a three phase load.
5) The series active filter starts at 140 ms.
6) The six-pulse thyristor bridge rectifier is disconnecting at 140 ms.

Simulation Results 5/

The load currents and the supply voltages at the left side (source side) of the UPQC:

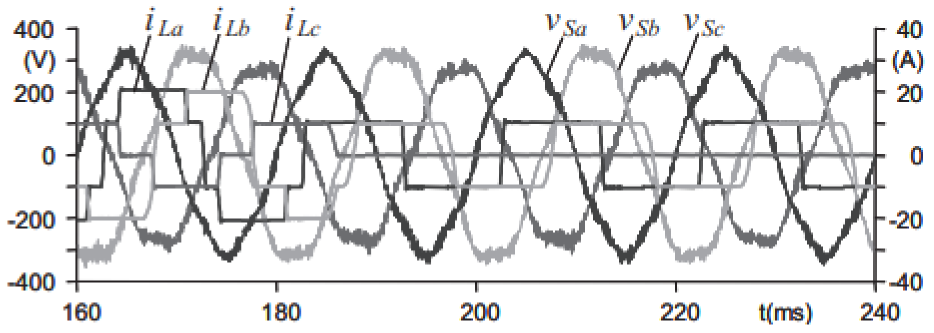


The compensated currents drawn from the network and the compensated voltages at the load terminal (right-hand side of the UPQC):

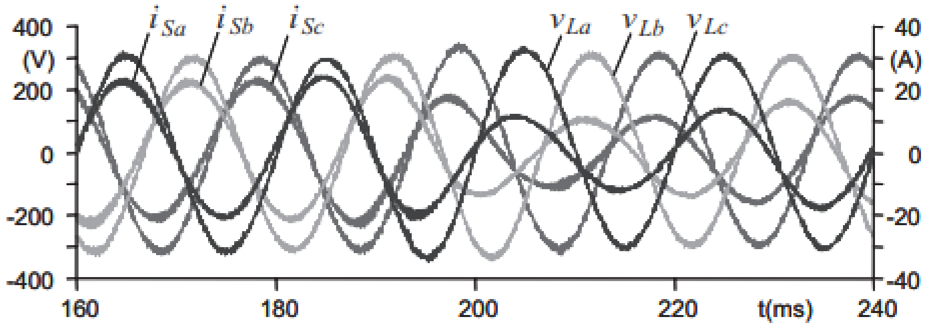


Simulation Results 6/

Supply voltages and load currents before and after the disconnection of the six-pulse thyristor bridge rectifier at 185 ms:

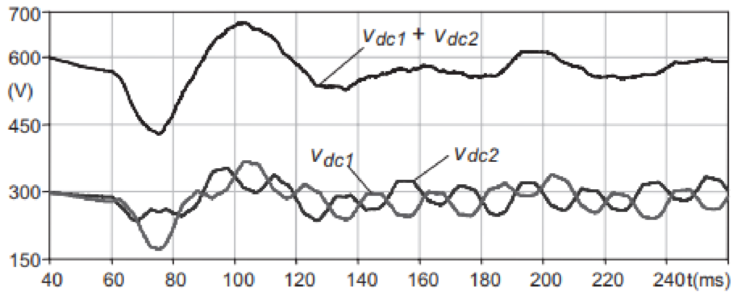


Compensated voltages and currents:

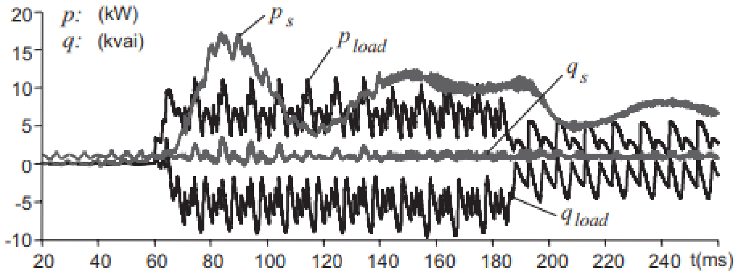


Simulation Results 7/

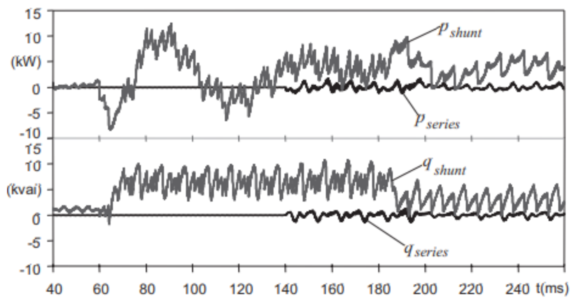
DC capacitor voltages:



Real and imaginary power of the load and the compensated voltage and current:



Real and imaginary powers of the series and shunt active filters:



Calculation of real powers and imaginary powers

After the transformation of voltages and currents on the αβ- reference frame with Clarke transformation we can find the following real and imaginary powers:

1) Load powers:

$$p_{load} = v_{L\alpha} i_{L\alpha} + v_{L\beta} i_{L\beta}$$

$$q_{load} = v_{L\alpha} i_{L\beta} - v_{L\beta} i_{L\alpha}$$

2) Shunt active filter powers:

$$p_{shunt} = v_{L\alpha} i_{C\alpha} + v_{L\beta} i_{C\beta}$$

$$q_{shunt} = v_{L\alpha} i_{C\beta} - v_{L\beta} i_{C\alpha}$$

3) Series active filter powers:

$$p_{series} = v_{C\alpha} i_{S\alpha} + v_{C\beta} i_{S\beta}$$

$$q_{series} = v_{C\alpha} i_{S\beta} - v_{C\beta} i_{S\alpha}$$

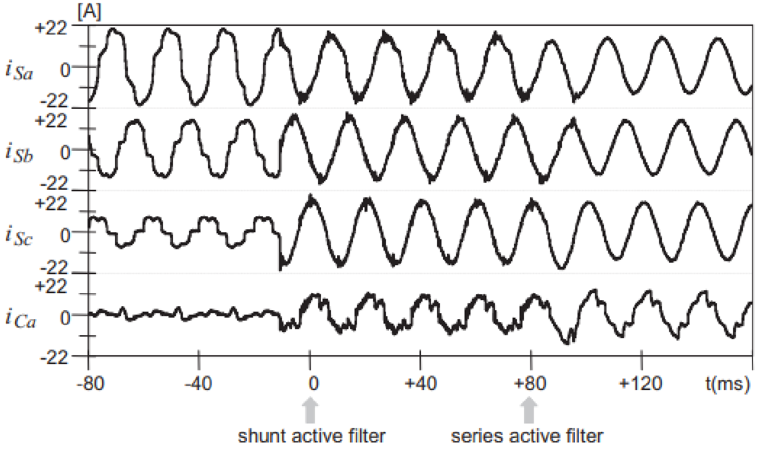
4) Compensated powers:

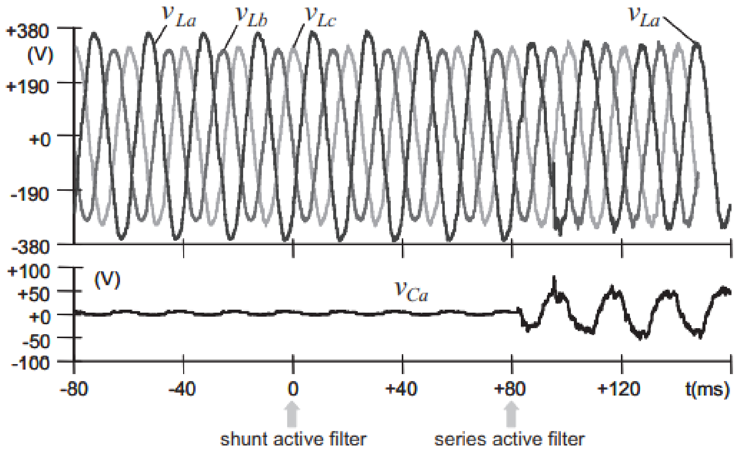
$$p_s = v_{L\alpha} i_{S\alpha} + v_{L\beta} i_{S\beta}$$

$$q_s = v_{L\alpha} i_{S\beta} - v_{L\beta} i_{S\alpha}$$

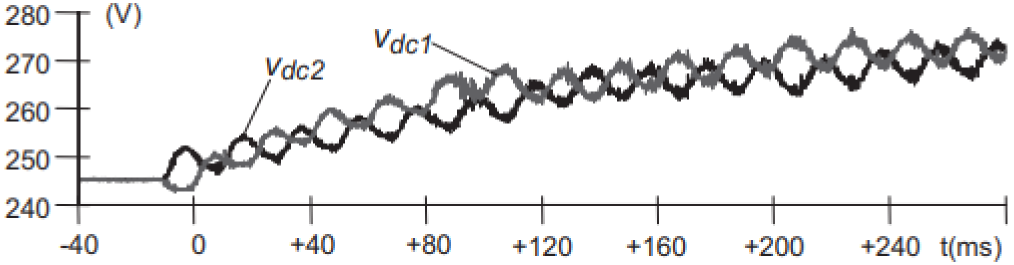
Experimental Results 1/

Currents and voltages from a successive connection of the shunt and series active filters:



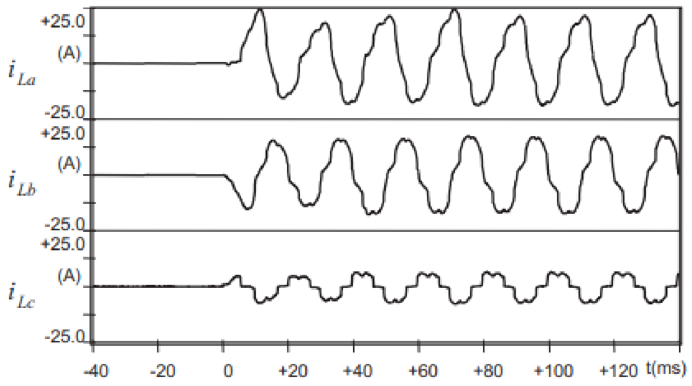


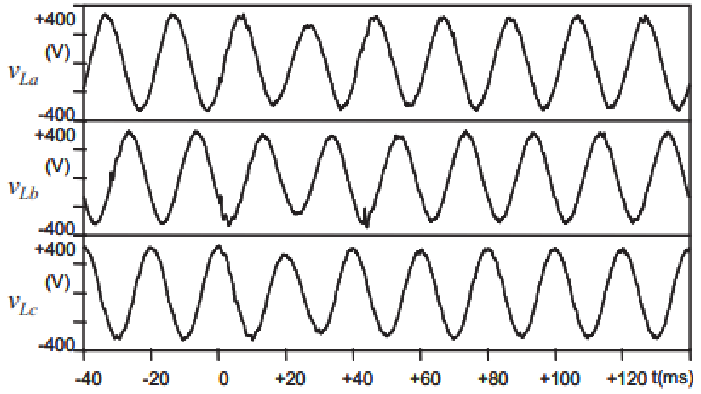
DC capacitor voltages:



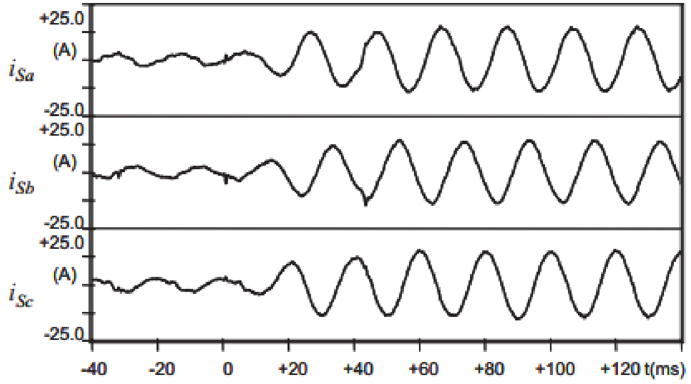
Experimental Results 2/

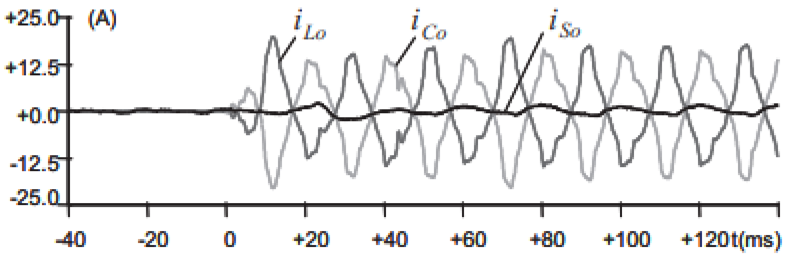
Experimental results during connection of the load (load voltages and load currents):





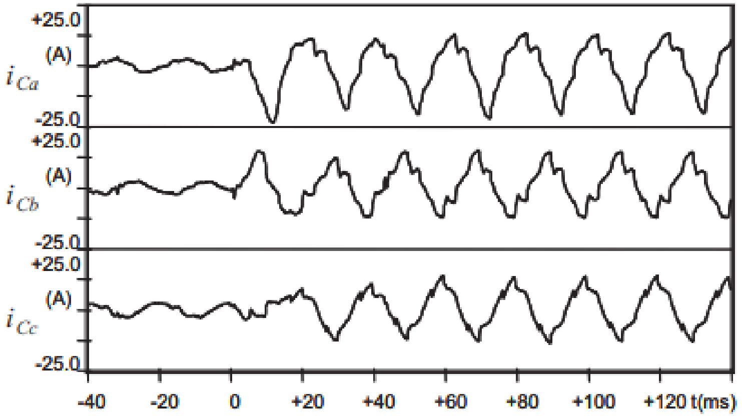
Experimental results during connection of the load (compensated currents drained from the network and neutral currents):

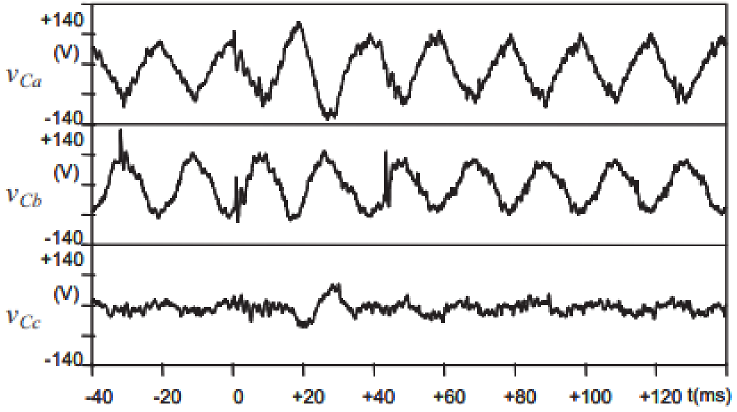




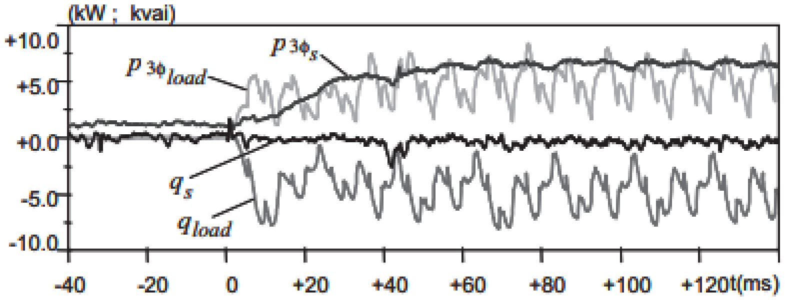
Experimental Results 3/

Experimental results during connection of the load(currents of the shunt active filter and voltages of the series active filter):



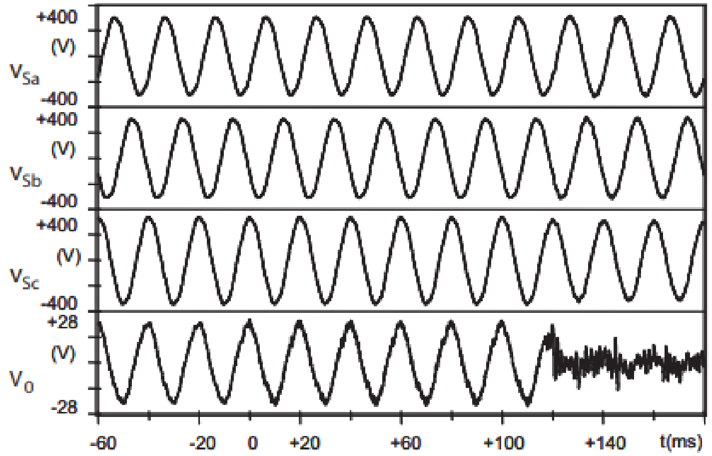


Instantaneous active three-phase power and imaginary power:

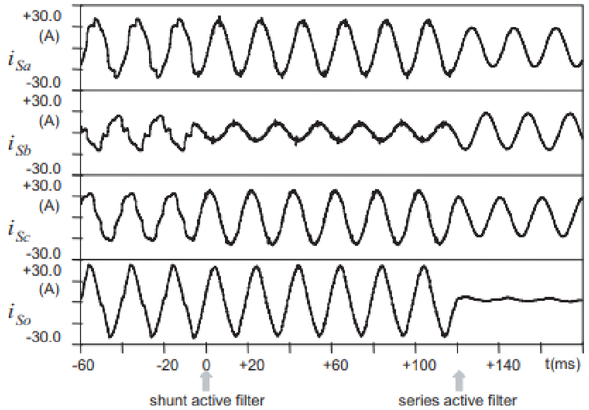


Experimental Results 4/

Voltages at load terminal for a compensation case involving zero-sequence components:

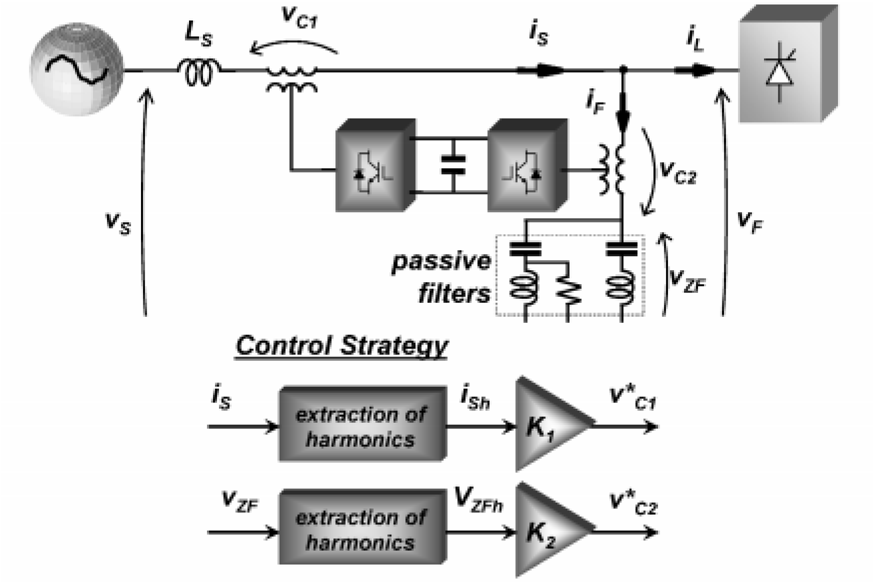


Currents of the source:



The UPQC Combined with Passive Filters (the Hybrid UPQC) 1/

If the shunt converter of the UPQC does not have to generate high reactive current at the fundamental frequency, a more cost-effective arrangement that combines active and passive filters may be considered.



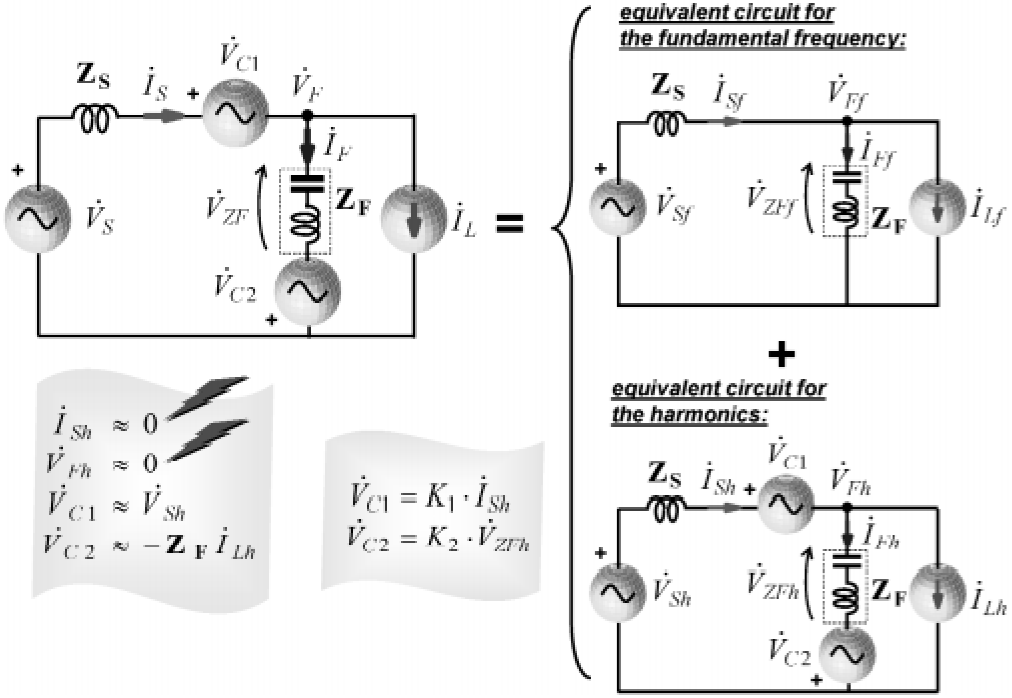
The hybrid UPQC approach

The UPQC Combined with Passive Filters (the Hybrid UPQC) 2/

- The current $i_{Sh} = i_S - \bar{i_S}$ represents all harmonics present in the network current. The component $\bar{i_S}$ of the current i_S is instantaneously calculated in the UPQC controller.
- If the current i_S is not purely sinusoidal, the series active filter inserts a compensating voltage calculated as: $v_{C1} = K_1 * i_{Sh}$.
- The voltage $v_{ZFh} = v_{ZF} - \bar{v_{ZF}}$, represents all harmonics in the voltage across the passive filter. The component v_{ZF} of the voltage v_{ZF}(appears across the passive filter) is instantaneously calculated from the measured voltage v_{ZF}.
- With the aim of reducing harmonic voltages at load terminal, the shunt active filter generates compensating voltage as: $v_{C2} = K_2 * v_{ZFh}$

The UPQC Combined with Passive Filters (the Hybrid UPQC) 3/

The hybrid UPQC approach can be divided as the sum oh two other circuits one for the fundamental frequency and other for the harmonics:



Single-phase equivalent circuits of the power system

The UPQC Combined with Passive Filters (the Hybrid UPQC) 4/

- The voltage at load terminal is: $\dot{V}_{Fh} = \dot{V}_{ZFh} - \dot{V}_{C2} = \mathbf{Z_F}\dot{I}_{Fh} - K_2\mathbf{Z_F}\dot{I}_{Fh} = (1 - K_2)\mathbf{Z_F}\dot{I}_{Fh}$

- The equivalent impedance for the shunt branch composed of the passive filter together with the active filter is:

$$\mathbf{Z} = \frac{\dot{V}_{Fh}}{\dot{I}_{Fh}} = (1 - K_2)\mathbf{Z_F}$$

- The best value we can have for the control gain K_2 is K_2=1, in order to obtain the ideally zero harmonic voltage ($v_{Fh} = 0$) at load terminal. This corresponds to one of the two principal objectives of a hybrid UPQC, that is, to provide high voltage quality to critical loads, attenuating-harmonic voltage propagations from the network to the load terminal.
- The second objective e is to prevent harmonic currents from flowing into the network. The shunt active filter of the hybrid UPQC imposes a “short circuit” for harmonic currents in the shunt branch if K_2, whereas the series active filter imposes an “open circuit” on the network path if $K_1 = \infty$.

The UPQC Combined with Passive Filters (the Hybrid UPQC) 5/

- The harmonic current flowing into the network I'_{Sh} is:

$$\dot{I}_{Sh} = \frac{1}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{V}_{Sh} + \frac{(1 - K_2)\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{I}_{Lh}$$

- The harmonic voltage that appears at load terminal is:

$$\dot{V}_{Fh} = \frac{(1 - K_2)\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{V}_{Sh} - \frac{(\mathbf{Z_S} + K_1)(1 - K_2)\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{I}_{Lh}$$

- With the optimal values at the control gains we have:

$$\lim_{K_1 \to \infty}\left[\lim_{K_2 \to 1} \dot{I}_{Sh}\right] = \lim_{K_1 \to \infty}\left[\lim_{K_2 \to 1}\left(\frac{1}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{V}_{Sh} + \frac{(1 - K_2)\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{I}_{Lh}\right)\right] \approx 0$$

$$\lim_{K_1 \to \infty}\left[\lim_{K_2 \to 1} \dot{V}_{Fh}\right] = \lim_{K_1 \to \infty}\left[\lim_{K_2 \to 1}\left(\frac{(1 - K_2)\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{V}_{Sh} - \frac{(\mathbf{Z_S} + K_1)(1 - K_2)\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{I}_{Lh}\right)\right] \approx 0$$

The UPQC Combined with Passive Filters (the Hybrid UPQC) 6/

- The compensating voltage of the series active filter is:

$$V_{C1} = \frac{K_1}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{V}_{Sh} + \frac{K_1(1 - K_2)\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{I}_{Lh}$$

- The compensating voltage of the shunt active filter is

$$\dot{V}_{C2} = \frac{K_2\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{V}_{Sh} + \frac{K_2(\mathbf{Z_S} + K_1)\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{I}_{Lh}$$

- With the optimal values $K_1 = \infty, K_2 = 1$:

$$\lim_{K_1\to\infty}\left[\lim_{K_2\to 1} \dot{V}_{C1}\right] =$$

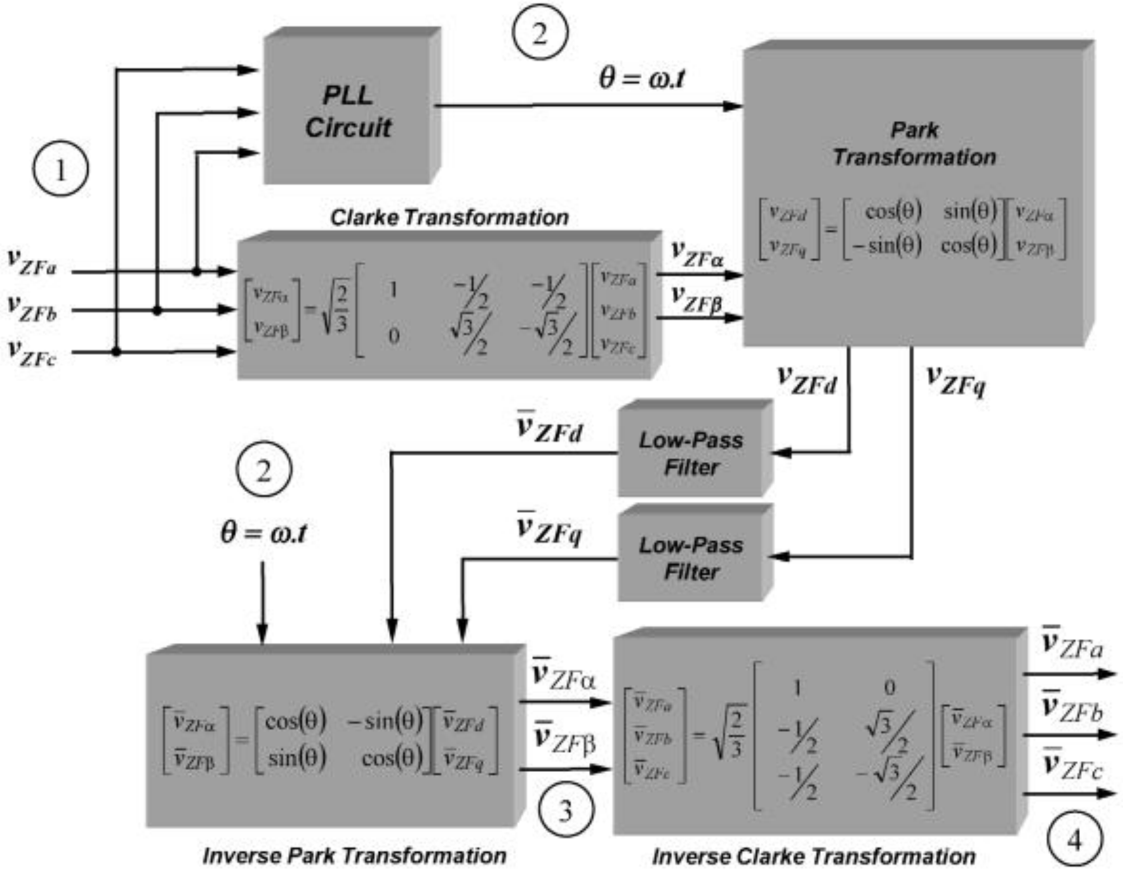
$$\lim_{K_1\to\infty}\left[\lim_{K_2\to 1}\left(\frac{K_1}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{V}_{Sh} + \frac{K_1(1 - K_2)\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{I}_{Lh}\right)\right] \approx \dot{V}_{Sh}$$

$$\lim_{K_1\to\infty}\left[\lim_{K_2\to 1} \dot{V}_{C2}\right] =$$

$$\lim_{K_1\to\infty}\left[\lim_{K_2\to 1}\left(\frac{K_2\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{V}_{Sh} - \frac{K_2(\mathbf{Z_S} + K_1)\mathbf{Z_F}}{\mathbf{Z_S} + K_1 + (1 - K_2)\mathbf{Z_F}} \dot{I}_{Lh}\right)\right] \approx -\mathbf{Z_F}\dot{I}_{Lh}$$

Controller of the Hybrid UPQC 1/

Circuit for extraction of the fundamental component $\bar{v}_{ZF}$ of the voltage v_{ZF} on the shunt passive filter:

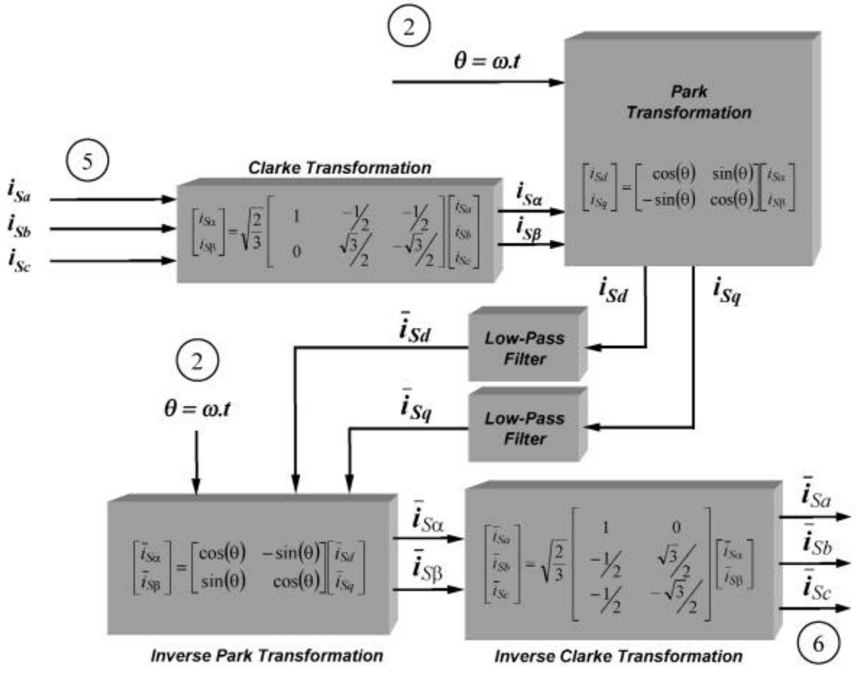


Controller of the Hybrid UPQC 2/

The voltages $v_{ZFa}, v_{ZFb}, v_{ZFc}$ are the inputs to the PLL circuit used to determine the angular frequency of the fundamental positive-sequence component contained in those voltages. The Clarke transformation is used to transform them into the αβ axes, the Park transformation is used for the calculation of the average values on the dq axes ($\bar{v}_{ZFd}$ and $\bar{v}_{ZFq}$) and the inverse Clarke and the inverse Park transformation give the fundamental components of the measured voltages on the shunt passive filter ($\bar{v}_{ZFa}, \bar{v}_{ZFb}, \bar{v}_{ZFc}$).

Controller of the Hybrid UPQC 3/

Circuit for extraction of the fundamental component $\bar{i_S}$ of the current i_S flowing through the series active filter:



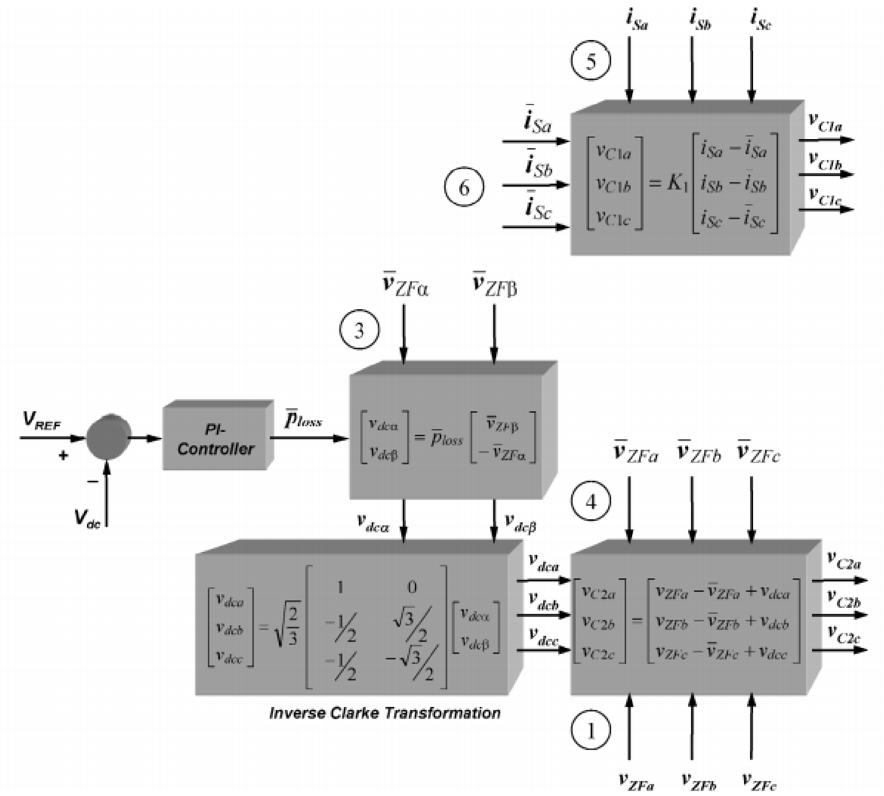
With a similar way we can find the fundamental components $\bar{i_{Sa}}, \bar{i_{Sb}}, \bar{i_{Sc}}$ of the measured line currents i_{Sa}, i_{Sb}, i_{Sc} flowing through the series active filter.

The compensating voltages of the series active filter:

$$\begin{bmatrix} v_{C1a} \\ v_{C1b} \\ v_{C1c} \end{bmatrix} = K_1 \begin{bmatrix} i_{Sa} - \bar{i}_{Sa} \\ i_{Sb} - \bar{i}_{Sb} \\ i_{Sc} - \bar{i}_{Sc} \end{bmatrix}$$

Controller of the Hybrid UPQC 4/

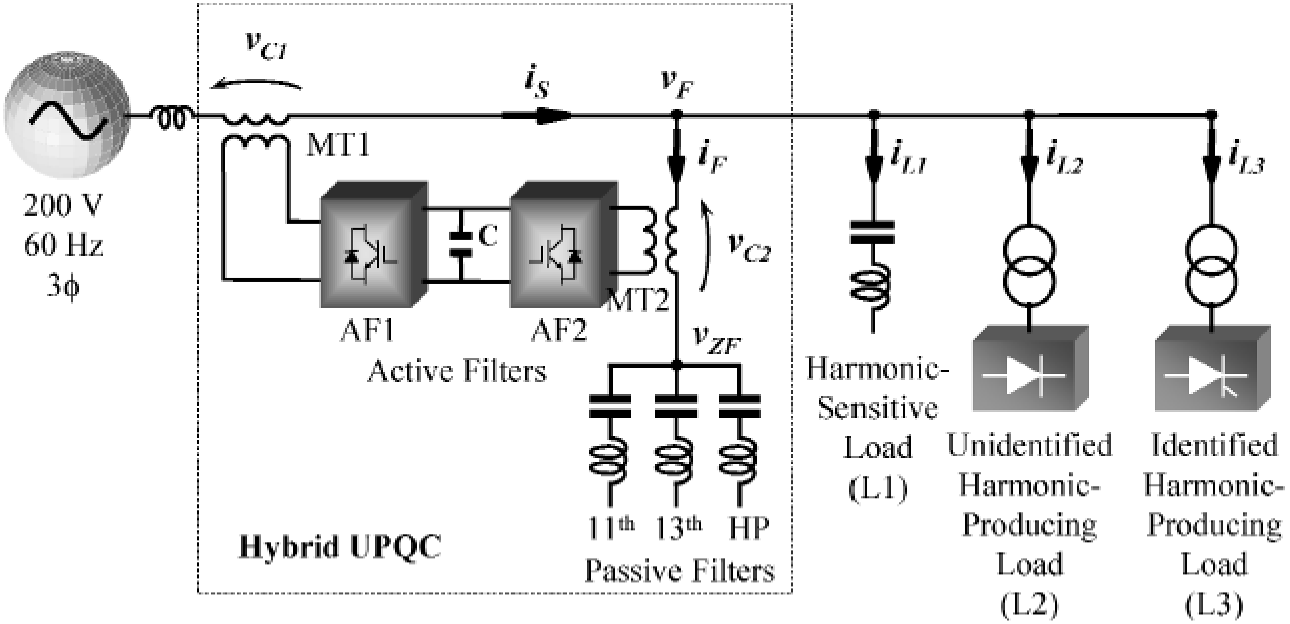
DC voltage regulator and composition of the compensating voltages references:



Experimental Results 1/

Here we will see some experimental results from a laboratory prototype of hybrid UPQC. The following picture shows the experimental power system for testing the hybrid UPQC.

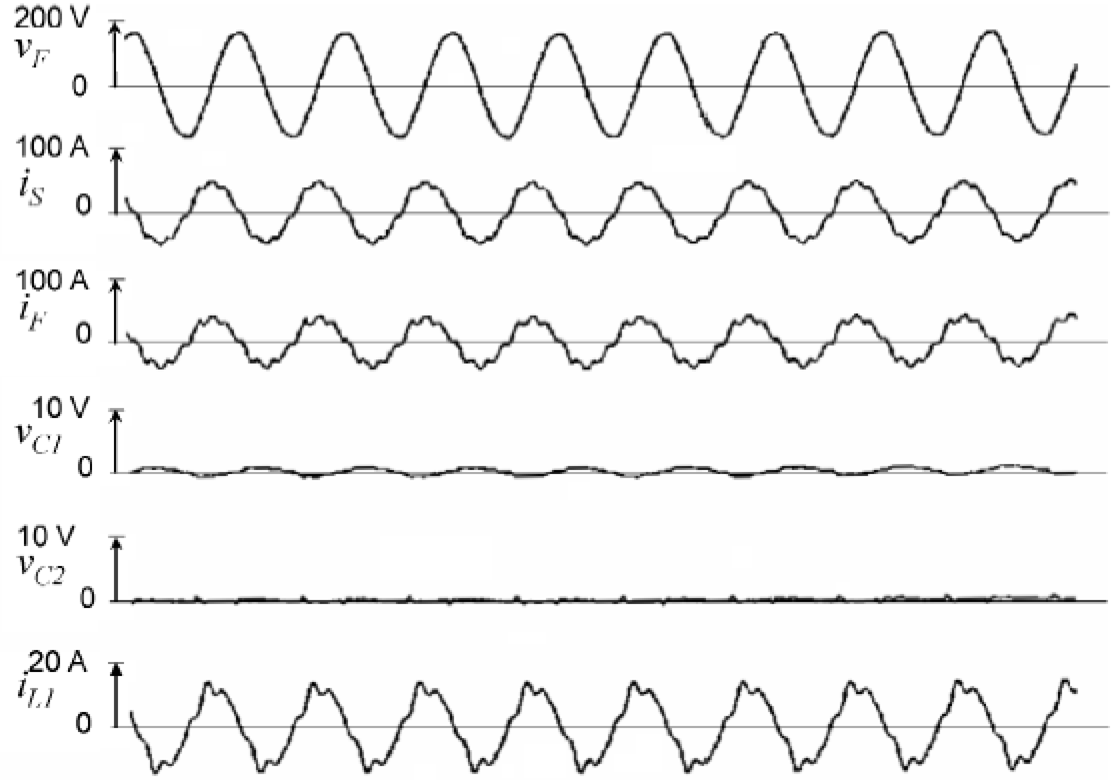
- Each active filter of 0.5 kVA consists of three single-phase voltage-source PWM converters using power MOSFETs.
- The dc terminals of the single-phase converters are connected in parallel to a dc capacitor of 2200 F. The matching transformers, MT1 and MT2, have a 1:20 turns ratio.
- The passive filter (PF) of 8 kVA consists of 11th and 13th tuned LC filters and a high-pass filter.



System configuration for testing the Hybrid UPQC

Experimental Results/2

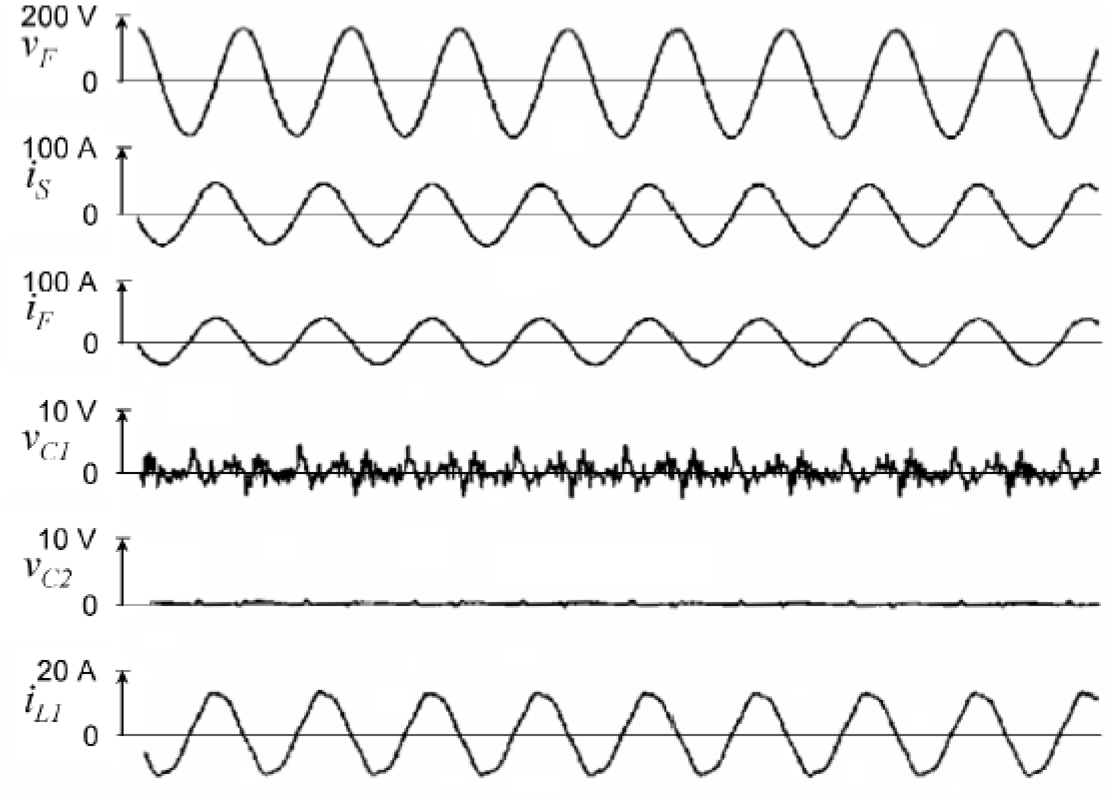
Because of the existence of fifth and seventh background harmonic voltages in the supply, fifth- and seventh-harmonic currents of 3.3% and 9.1% are present in the supply current. Also the active filters of the UPQC are out of operation, an amount of harmonic voltage appears on the common bus, so that a fifth-harmonic current of 12% is flowing into the harmonic-sensitive load L1. After the series active filter AF1 is switched on, the fifth-harmonic current is reduced to 0.7%.



Experimental Results/3

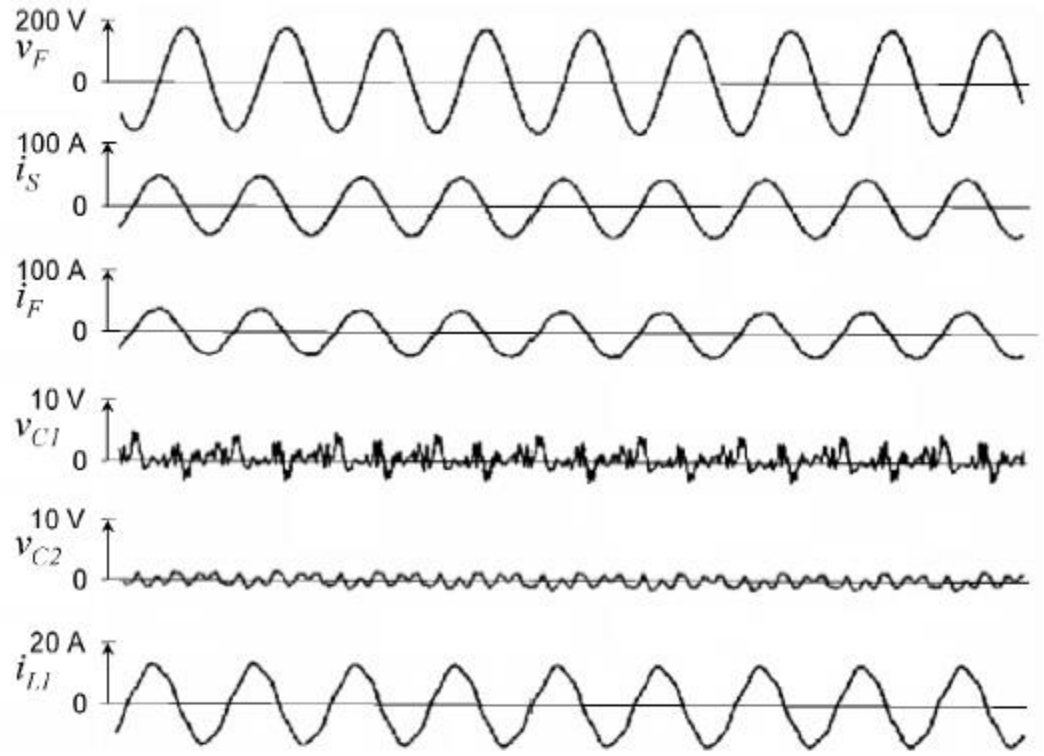
Then the series active filter AF1 is switched on, the fifth-harmonic current is reduced to 0.7%, because this active filter acts as a blocking high resistor at the fifth-harmonic frequency.

As a result, the harmonics in VF and IL1 are reduced by two-thirds as we can see below.



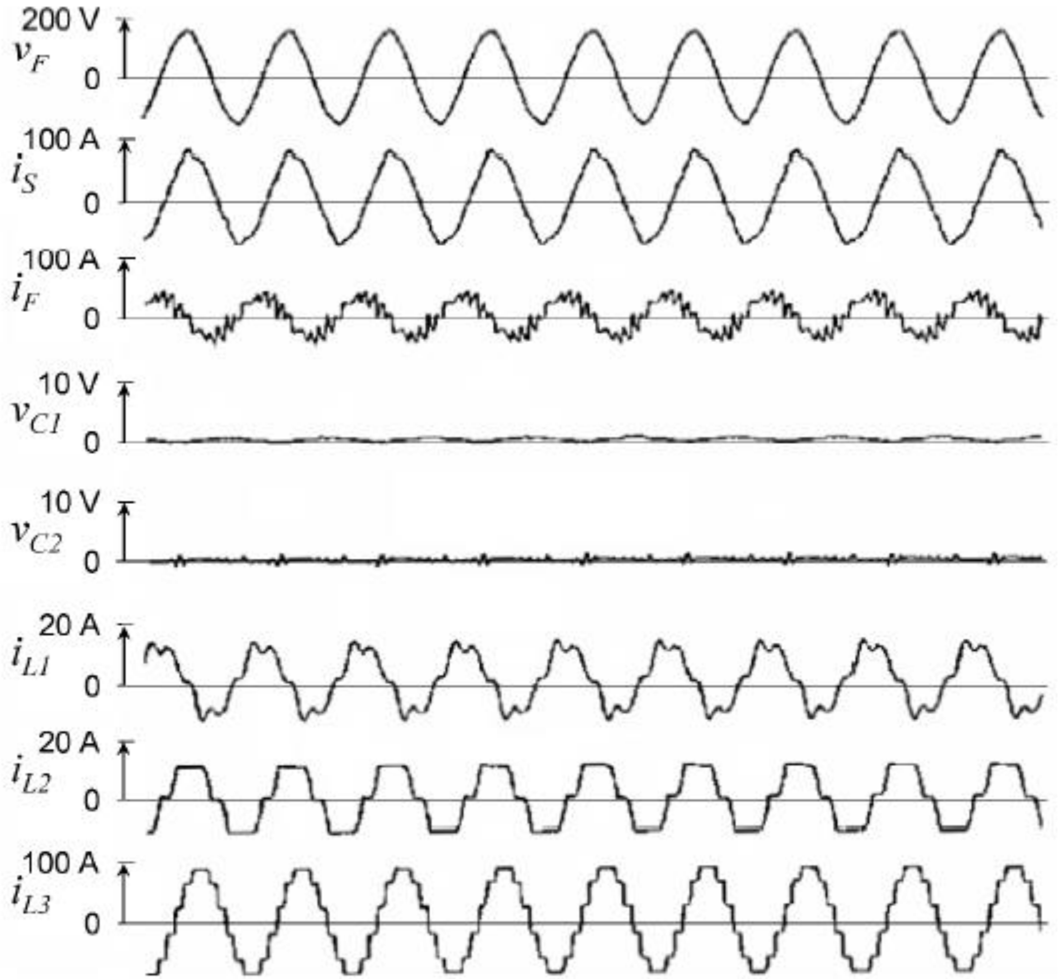
Experimental Results/4

Now the second active filter is also operating but there is no further improvement.



Experimental Results/5

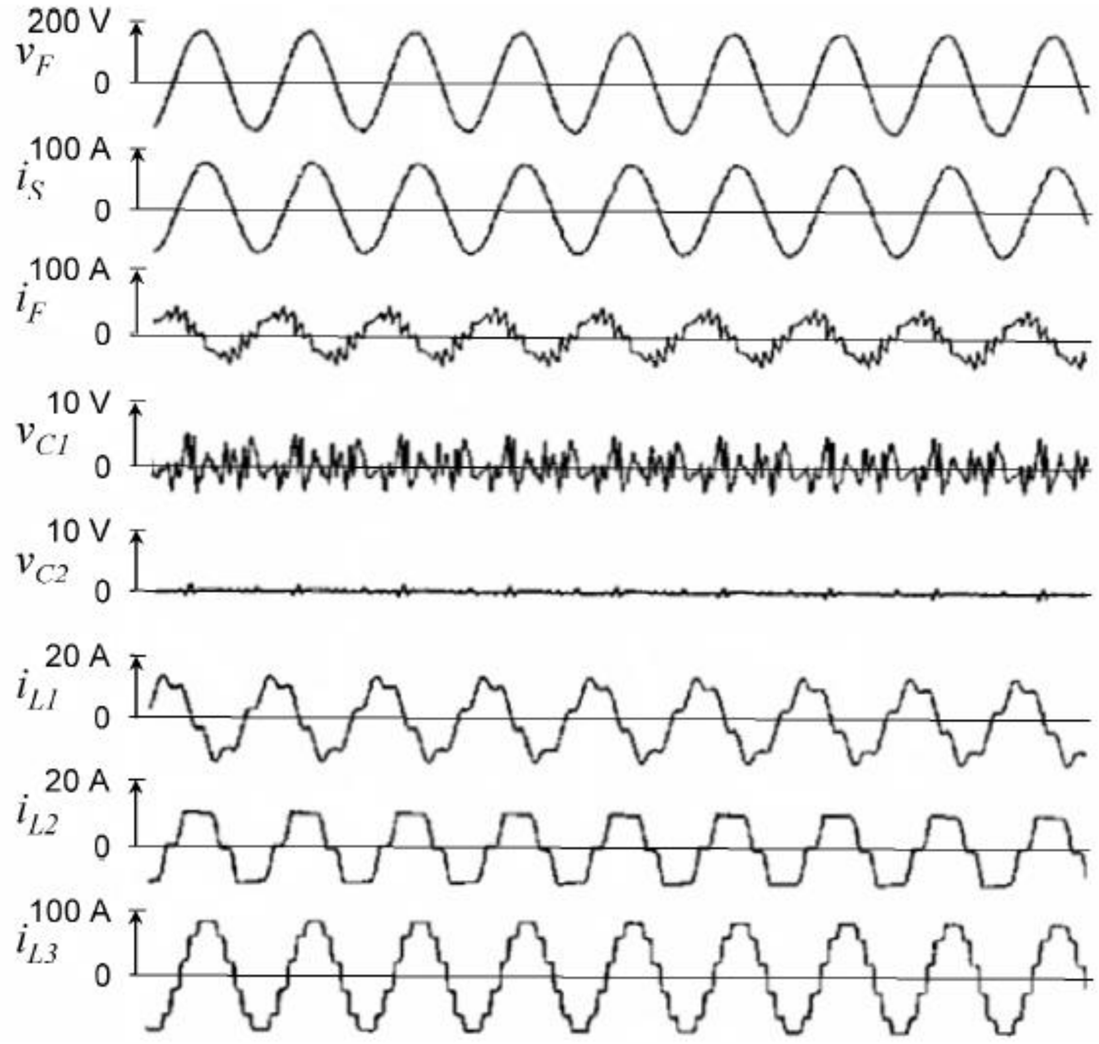
All loads are connected in this case but filters are out. The amount of these harmonic currents flowing into the network are very large in both situations. In both cases, this hardly distorts the voltage on the common bus that, in turn, affects the current IL1 flowing into the harmonic-sensitive load.



Experimental Results/6

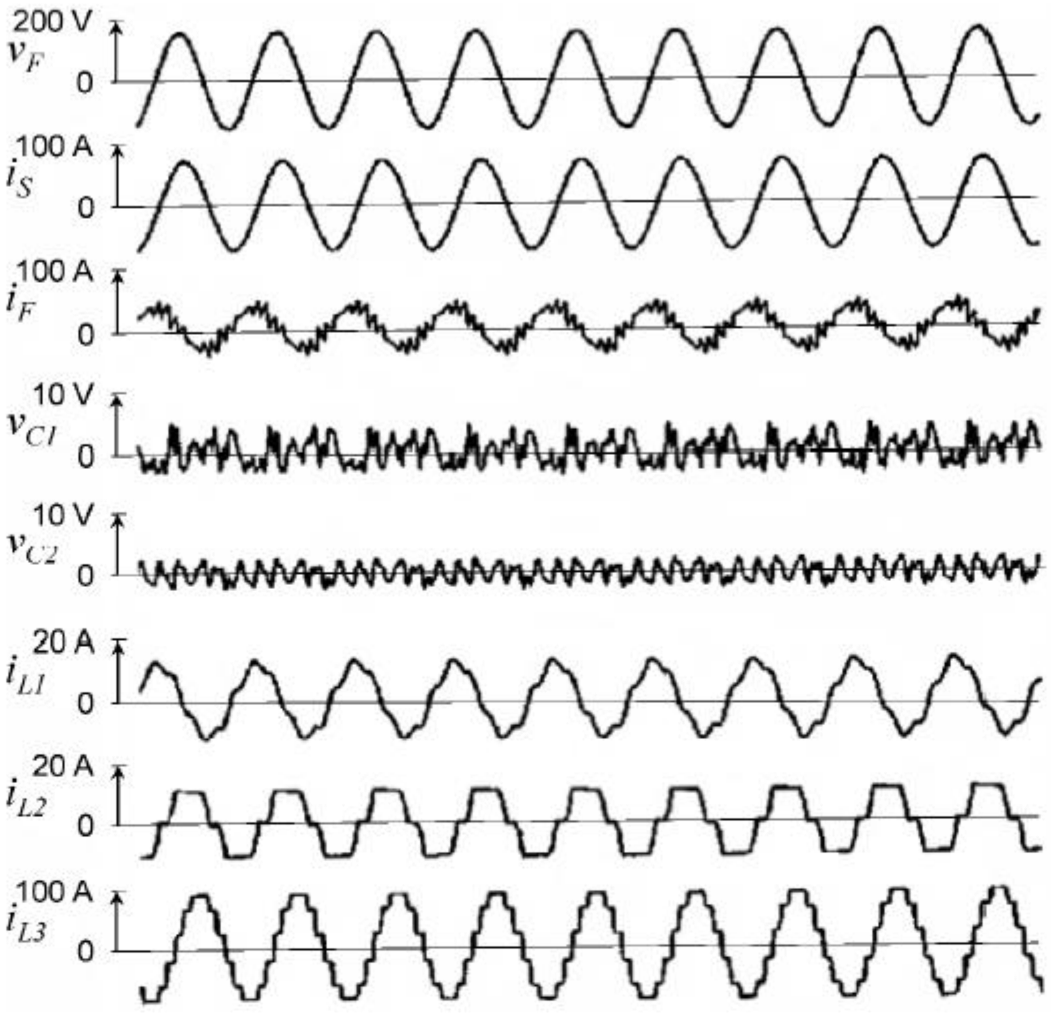
Here the AF1 filter is connected :

- The fifth-order harmonic flowing to the network is reduced from 3.8% to 1.1%, and the seventh from 1.8% to 0.2%, so that the current i_s becomes almost sinusoidal. But the fifth- and seventh-order harmonics produced by the unidentified load L2 flow through the passive filter of the hybrid UPQC causing high voltage distortions on the voltage at the common bus.
- Also, harmonic current is still flowing into the harmonic-sensitive load L1.



Experimental Results/7

We connect the UPQC hybrid and we see that the shunt active filter of the hybrid UPQC can improve the performance of the whole system by reducing further the voltage distortion on the common bus while it also reduces a bit more the fifth-harmonic flowing into the harmonic-sensitive load L1.



The Universal Active Power Line Conditioner (UPLC)

An appealing approach to FACTS devices is the unified power flow controller (UPFC).

- It allows the possibility of controlling together all three principal parameters that determine the power flow through a transmission line.
- It joins into a single compensator all those compensation functions of the UPFC , which involves compensating voltages and currents at the fundamental frequency, with those active filtering capabilities of the unified power quality conditioner (UPQC). That’s why the device is called Universal Active Power Line Conditioner (UPLC).

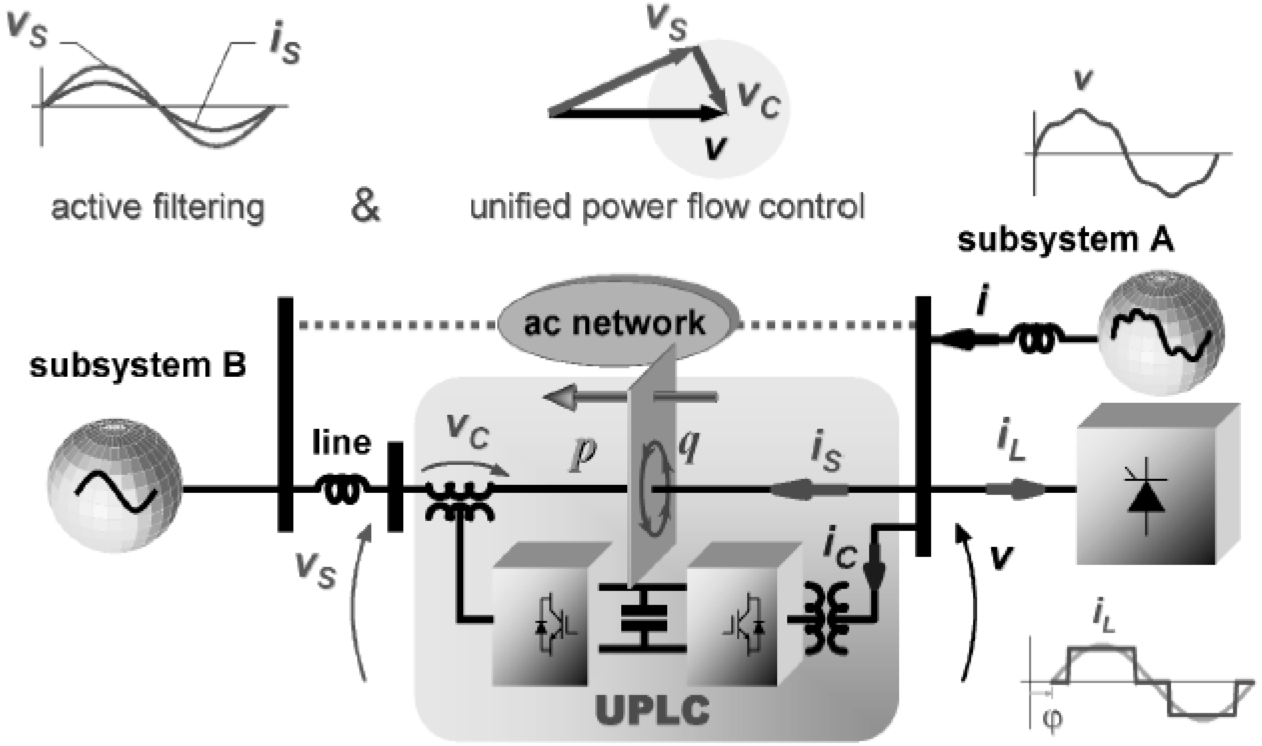
General Description of the UPLC/1

An appealing approach to FACTS devices is the unified power flow controller (UPFC).

- Scenario #1 as will be shown in the next slide, distorted supply voltage and the nonlinear load are on the same side and they create subsystem A which is connected to subsystem B through a transmission line, in which a UPLC is installed and in this way it can control the voltage on the line end terminal and the active and reactive power flow.

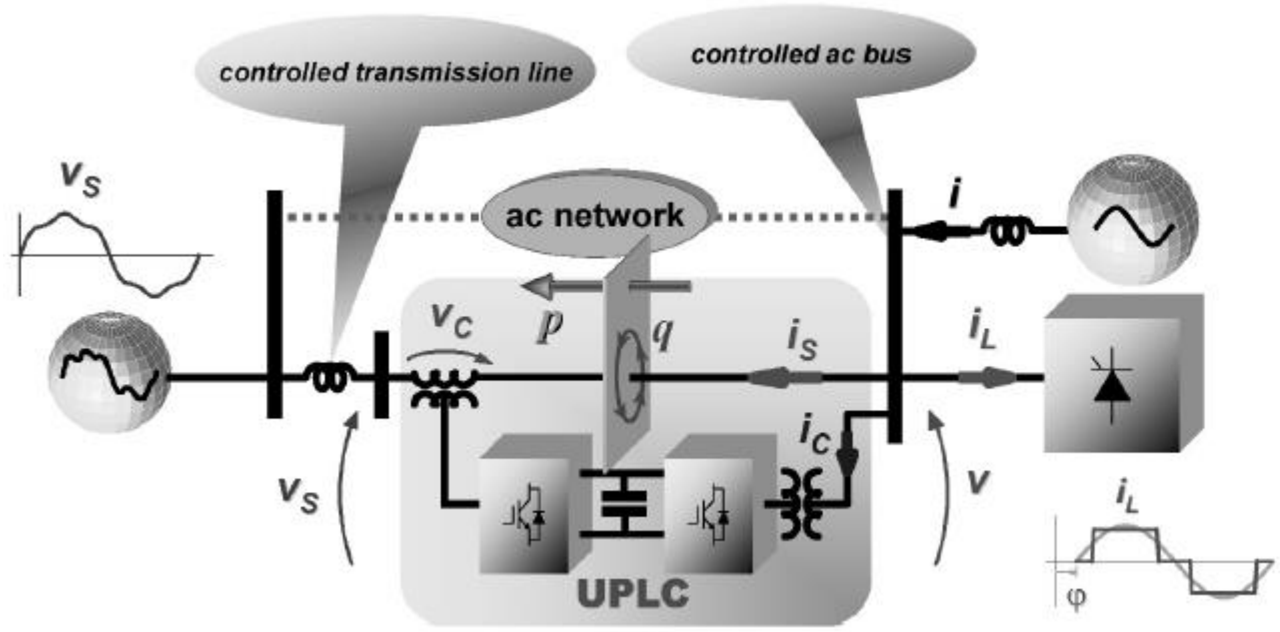
General Description of the UPLC/2

As is shown below configuration #1 is best when the active filtering of both voltage and current are needed on the same side (right side of the UPLC). In this case, the voltage v of the controlled bus is already distorted by power subsystem A and the nonlinear load (IL) is also connected at the same side. Furthermore, the harmonic voltages and eventual imbalances from negative-sequence and as zero-sequence components at the fundamental frequency, which can be found in voltage v, will be compensated by the active filtering that the series converter of the UPLC are capable of. In this way they are prohibited of going towards the left side.



General Description of the UPLC/3

The following figure shows scenario #2 , for which the configuration #2 of UPLC was developed. The difference with configuration #1 is that the series active filtering of voltage Vs is on the left side of the UPLC, whereas the shunt active filtering of current stays on the right side. This configuration gives also an extra measurement of voltage and it includes a positive sequence detector for this voltage.



Configuration #2 of the universal active power line conditioner (UPLC)

General Description of the UPLC/4

The UPLC combines all active filtering capabilities of the UPQC and voltage regulation, as well as power flow control capabilities of the UPFC, as it was mentioned before, into a single device. The following table shows that the UPLC is able to solve almost all problems related to power quality. Only the functionality for compensating voltage sags and swells are omitted which is left for future improvements. As it is shown in the next slide.

General Description of the UPLC/5

UPLC Series Converter

- Compensation of voltage harmonics, including negative- and zero-sequence components at the fundamental frequency.(UPQC)
- Suppression of harmonic currents through the power line (harmonic isolation)(UPQC)
- Improvement of the system stability (damping)(UPQC)
- Control of the active and reactive power of the flow through the line(UPFC)

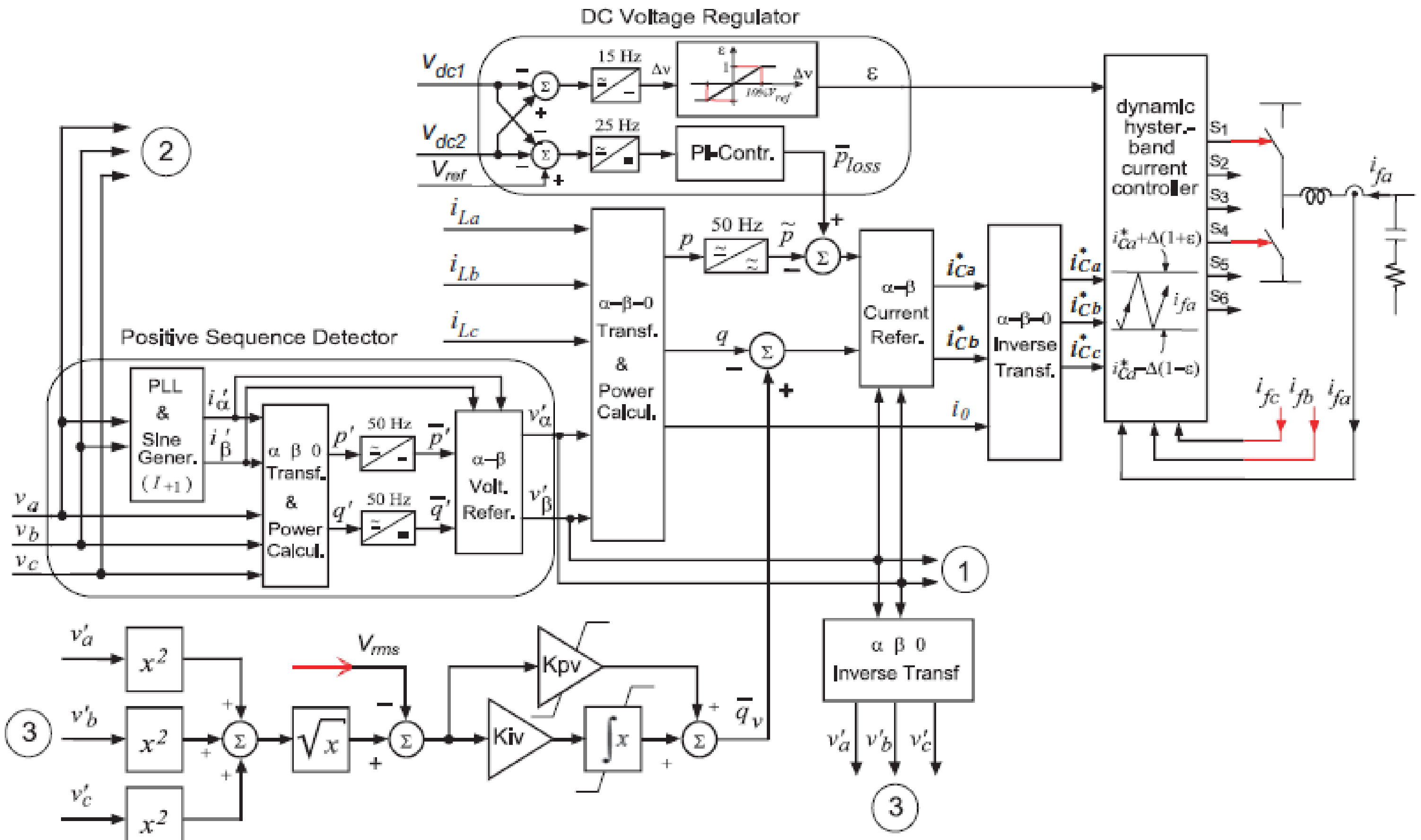
UPLC Shunt converter

- Compensation of voltage harmonics, including negative- and zero-sequence components at the fundamental frequency.(UPQC)
- Compensation of the reactive power of the load.(UPQC)
- Regulation of the capacitor voltage of the common dc link(UPQC)
- Regulation of the terminal voltage of the line (controlled bus)(UPFC)

The Controller of the UPLC /1

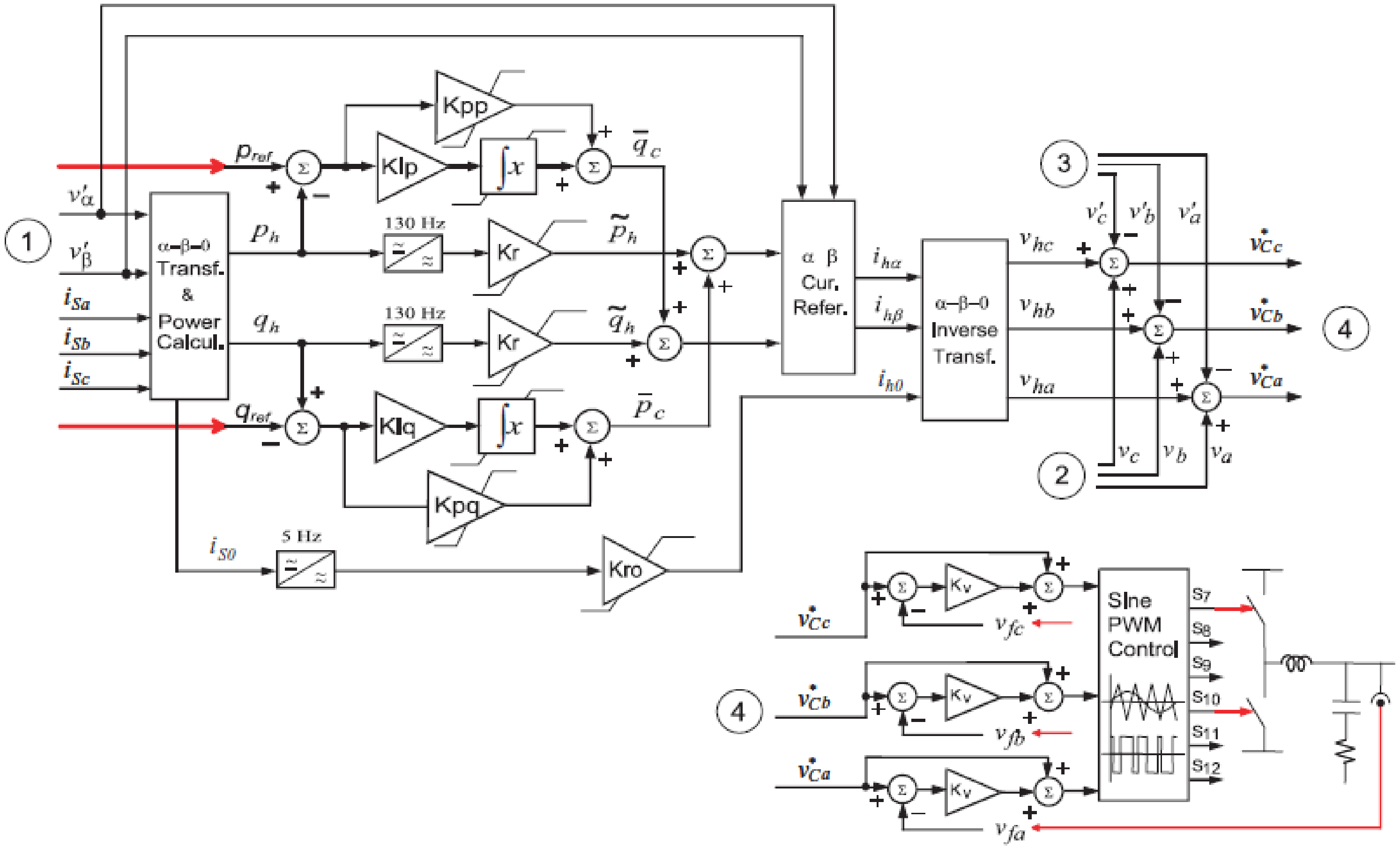
- Active filtering, power factor compensation, voltage regulation, as well as power flow control included in the UPLC controller have been analyzed before.
- All active filtering functions of the shunt converter of the UPLC correspond to a control strategy for three-phase, four-wire, shunt active filter, called the sinusoidal current control strategy.
- Consequently , the UPLC controller for the shunt converter in the figure of the next slide contains the whole control circuit shown in that figure without changes as will be shown next.

The Controller of the UPLC /2



Controller of the shunt converter of the UPLC for configuration #1

The Controller of the UPLC /3



Controller of the series converter of the UPLC for configuration #1

The Controller of the UPLC /4

The difference between the measured voltage on the right side of the UPLC and its fundamental positive-sequence component comprises all harmonics and imbalances from negative- and zero-sequence components at the fundamental frequency.

This constitutes the principle of series voltage compensation (active filtering) of the series PWM converter. It is determined as:

$$\begin{bmatrix} v'_{Ca} \\ v'_{Cb} \\ v'_{Cc} \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v'_a \\ v'_b \\ v'_c \end{bmatrix}$$

The Controller of the UPLC /5

The currents i_{Sa}, i_{Sb}, and i_{Sc} are transformed into the $\alpha\beta 0$-reference frame as:

$$\begin{bmatrix} i_{S0} \\ \hline i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \hline 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix}$$

Then, the control signals $v_a{}'$, and $v_\beta{}'$, marked by ① that come from the positive-sequence voltage detector of "Controller of the shunt converter of the UPLC for configuration #1" are used together with these currents to calculate instantaneous real and imaginary powers as:

$$\begin{bmatrix} p_h \\ q_h \end{bmatrix} = \begin{bmatrix} v'_\alpha & v'_\beta \\ v'_\beta & -v'_\alpha \end{bmatrix} \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix}$$

The Controller of the UPLC/6

The “$\alpha\beta$-current references” in "Controller of the series converter of the UPLC for configuration #1", which in fact are used as voltage references, are calculated as:

$$\begin{bmatrix} i_{h\alpha} \\ i_{h\beta} \end{bmatrix} = \frac{1}{v_\alpha'^2 + v_\beta'^2} \begin{bmatrix} v_\alpha' & v_\beta' \\ v_\beta' & -v_\alpha' \end{bmatrix} \begin{bmatrix} \tilde{p}_h + \bar{p}_c \\ \tilde{q}_h + \bar{q}_c \end{bmatrix}$$

The Controller of the UPLC /7

Finally, the compensating voltage components that provide harmonic isolation, damping of oscillations, and also active and reactive power flow control in the controlled transmission line, are determined as:

$$\begin{bmatrix} v_{ha} \\ v_{hb} \\ v_{hc} \end{bmatrix} = \sqrt{\frac{2}{3}} \left[\begin{array}{c:cc} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{array} \right] \left[\begin{array}{c} i_{h0} \\ \hdashline i_{h\alpha} \\ i_{h\beta} \end{array} \right]$$

Performance of the UPLC

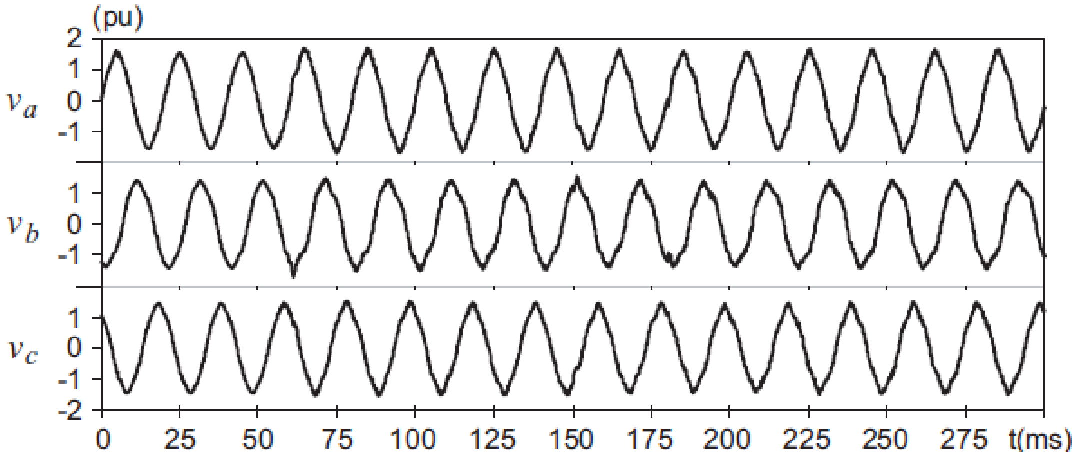
The response of the UPLC can be described as dynamic because it has been very fast, which would might not be achieved if traditional power theories described in Chapter 2 were used in the controller.

Simulation Results of Configuration #1 of the UPLC/1

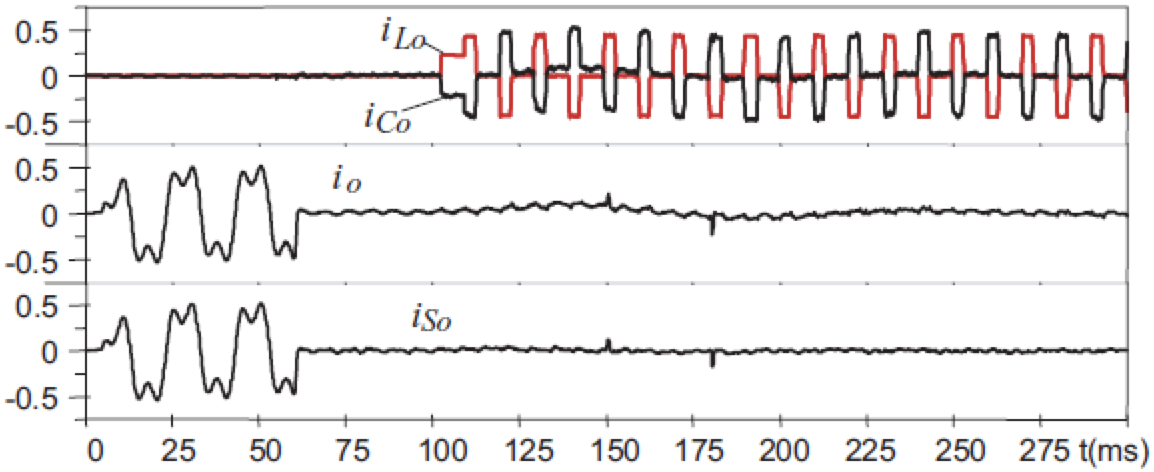
The total simulation time interval is $300\ ms$, and involves the following events:

- starting of the shunt converter of the UPLC at $55\ ms$
- starting of the series converter of the UPLC at $60\ ms$
- connecting of a single-phase thyristor bridge rectifier as a load between a phase and neutral wire, and another between b phase and neutral wire, at $101.7\ ms$ ($30°$ firing angle)
- connecting of a six – pulse thyristor bridge rectifier, as a three-phase load, at $103.3\ ms$
- change in the imaginary power order q_{ref} from $-0.33\ pu$ to $+0.33\ pu$, at $150\ ms$
- change in the real power order p_{ref} from $-1\ pu$ to $+1\ pu$, at $180\ ms$
- disconnecting of the six – pulse thyristor bridge rectifier at $245\ ms$

Simulation Results of Configuration #1 of the UPLC/2

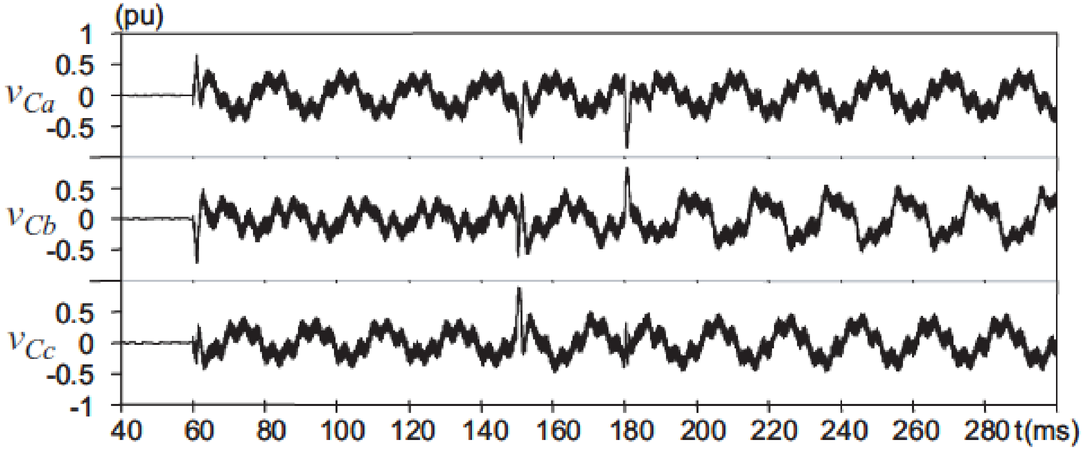


Phase voltages on the right side of the UPLC

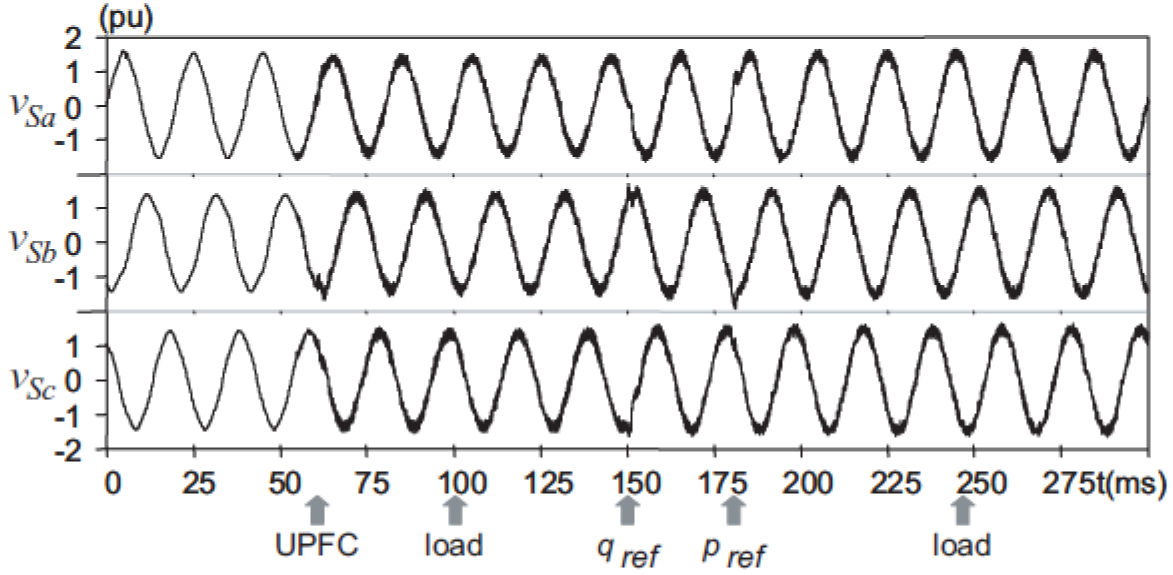


Neutral currents

Simulation Results of Configuration #1 of the UPLC /3

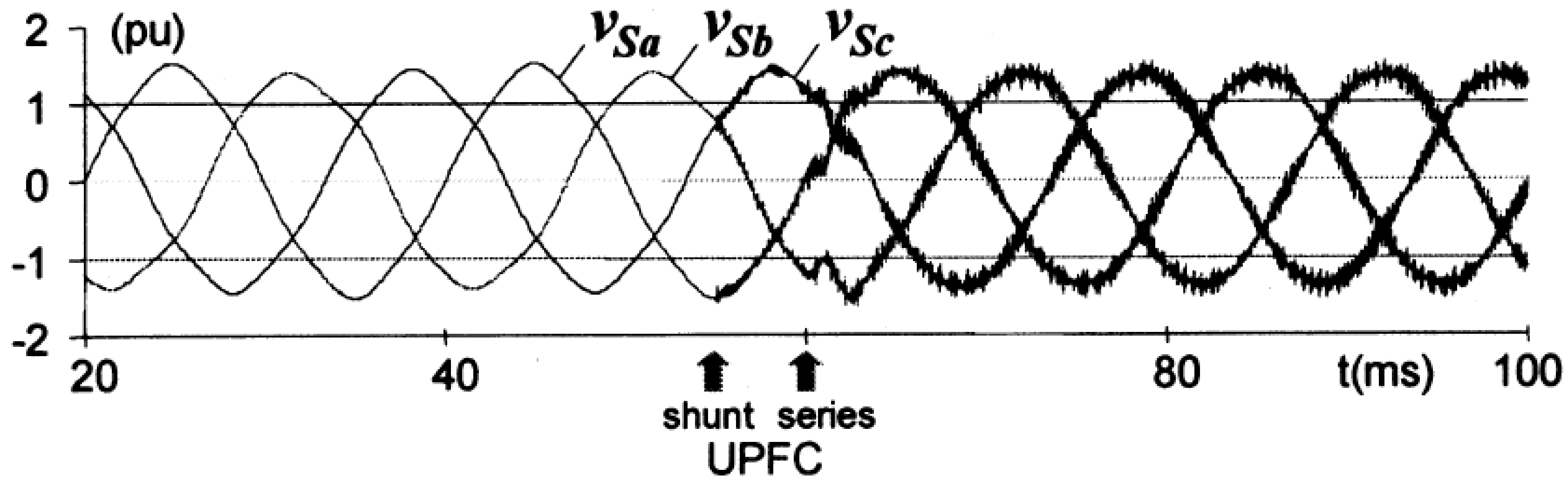


Compensating voltages of the series converter of the UPLC



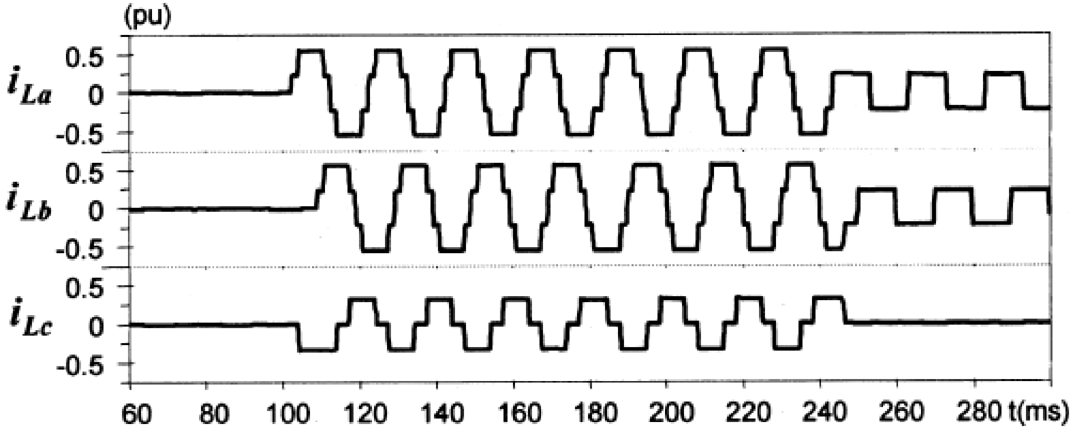
Compensated voltages on the left side of the UPLC

Simulation Results of Configuration #1 of the UPLC /4

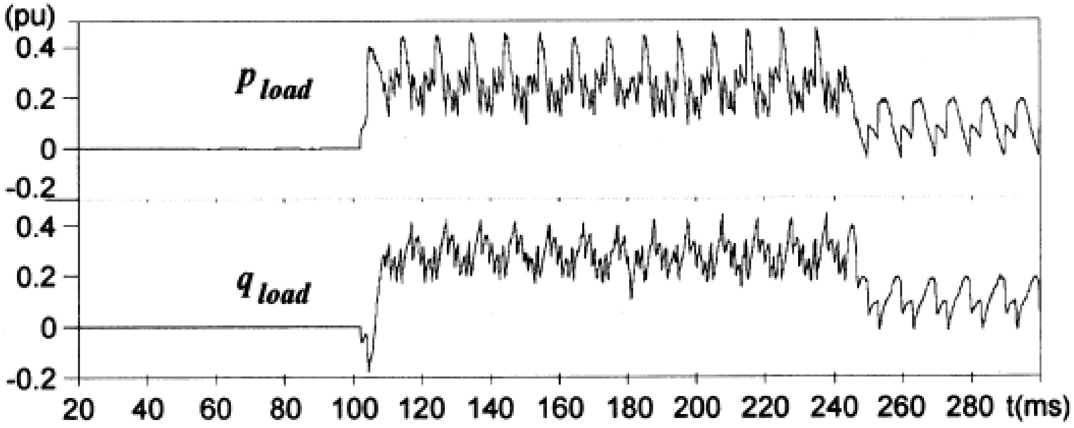


Compensated voltages at the left side of the UPLC

Simulation Results of Configuration #1 of the UPLC /5

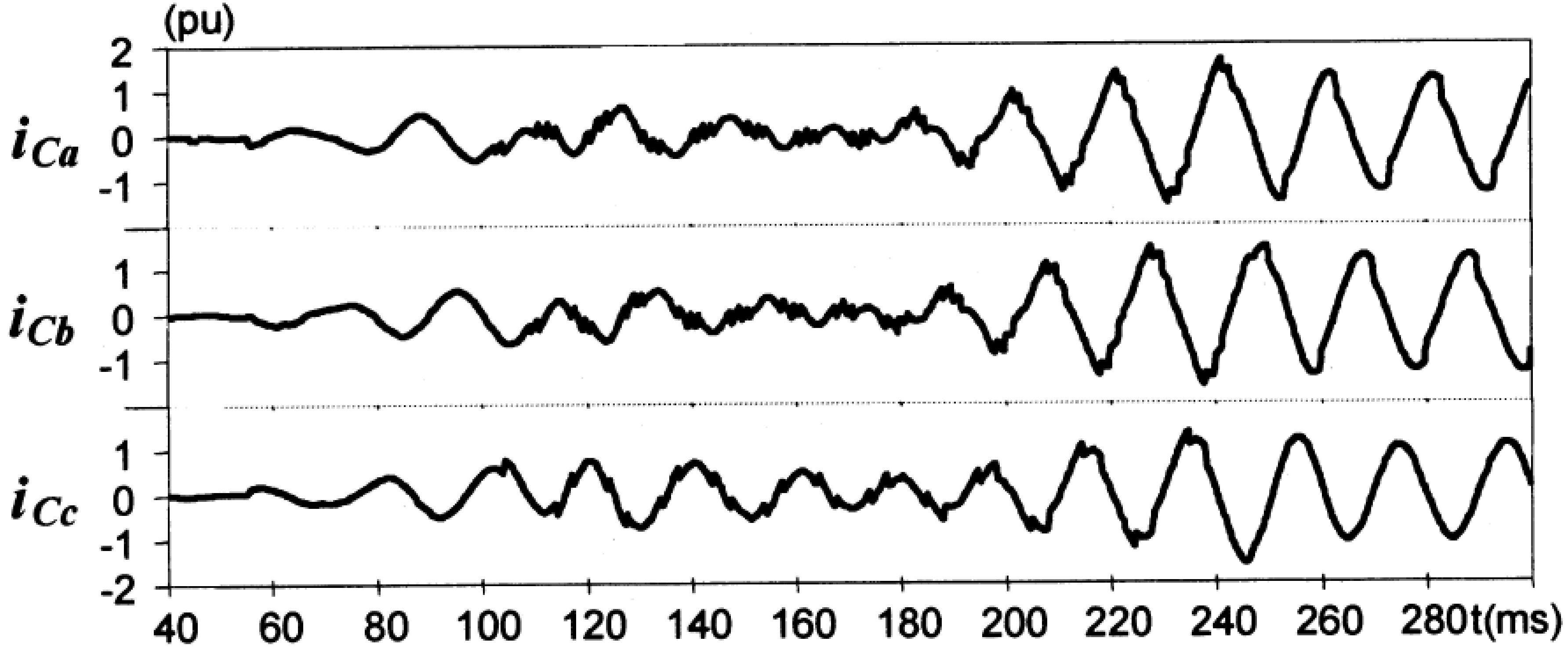


Totalized currents of the nonlinear loads



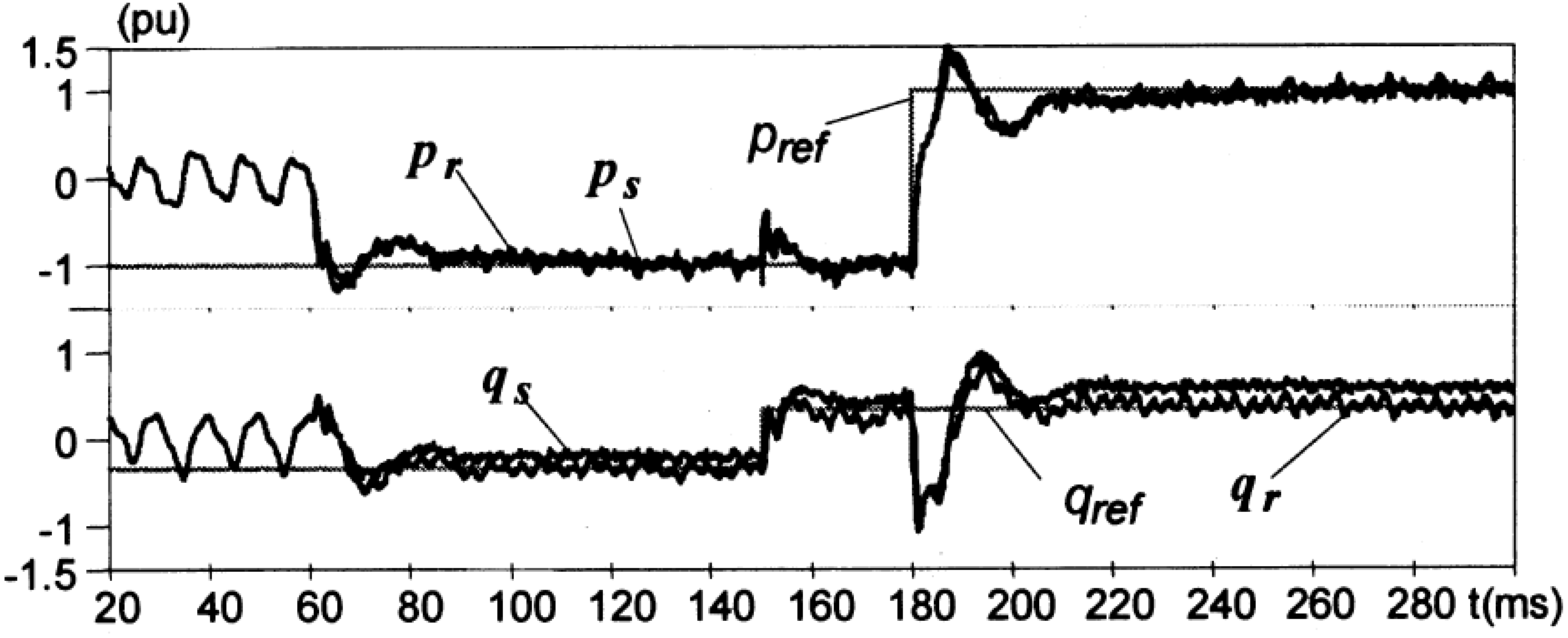
Instantaneous real and imaginary powers of the nonlinear loads

Simulation Results of Configuration #1 of the UPLC /6



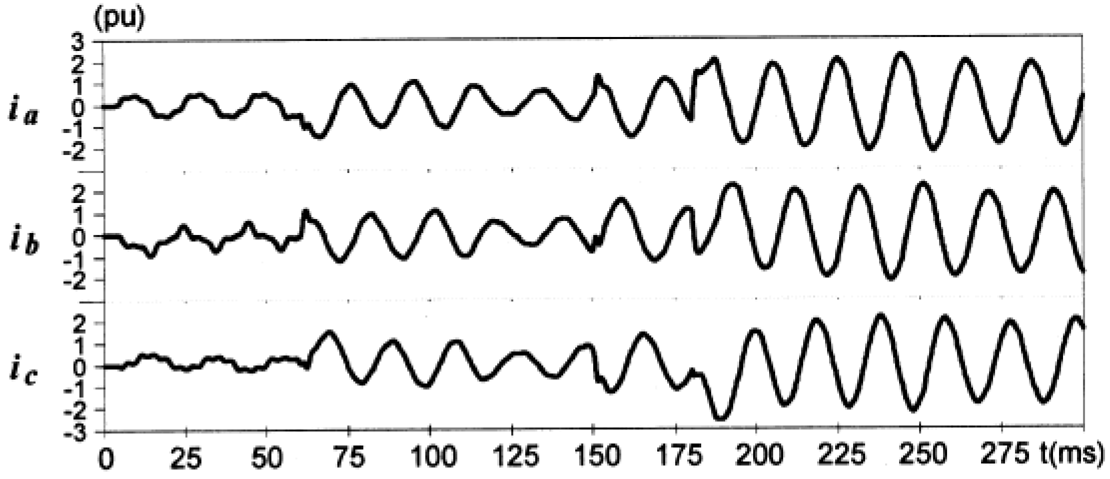
Compensating currents of the shunt converter of the UPLC

Simulation Results of Configuration #1 of the UPLC /7

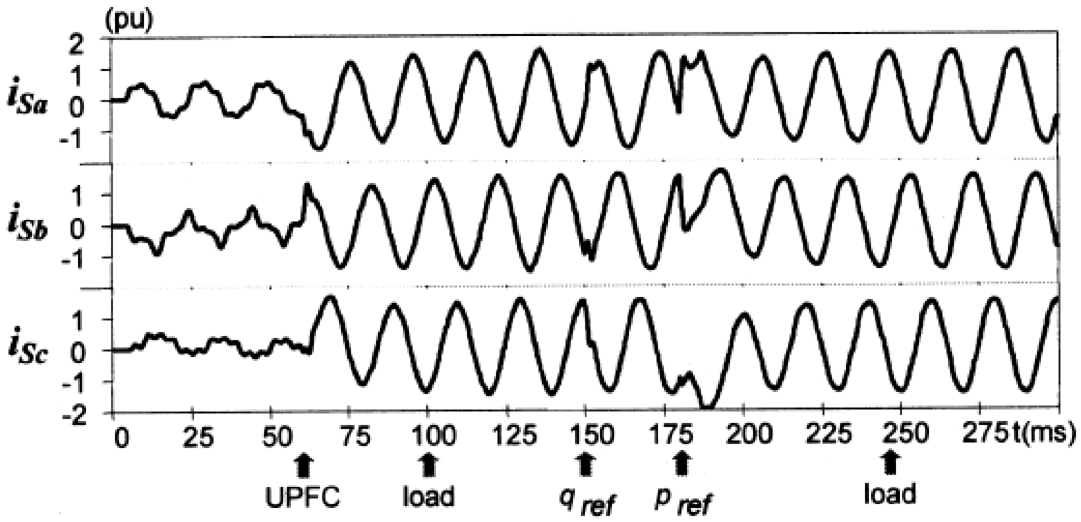


Instantaneous powers of the controlled transmission line.

Simulation Results of Configuration #1 of the UPLC /8

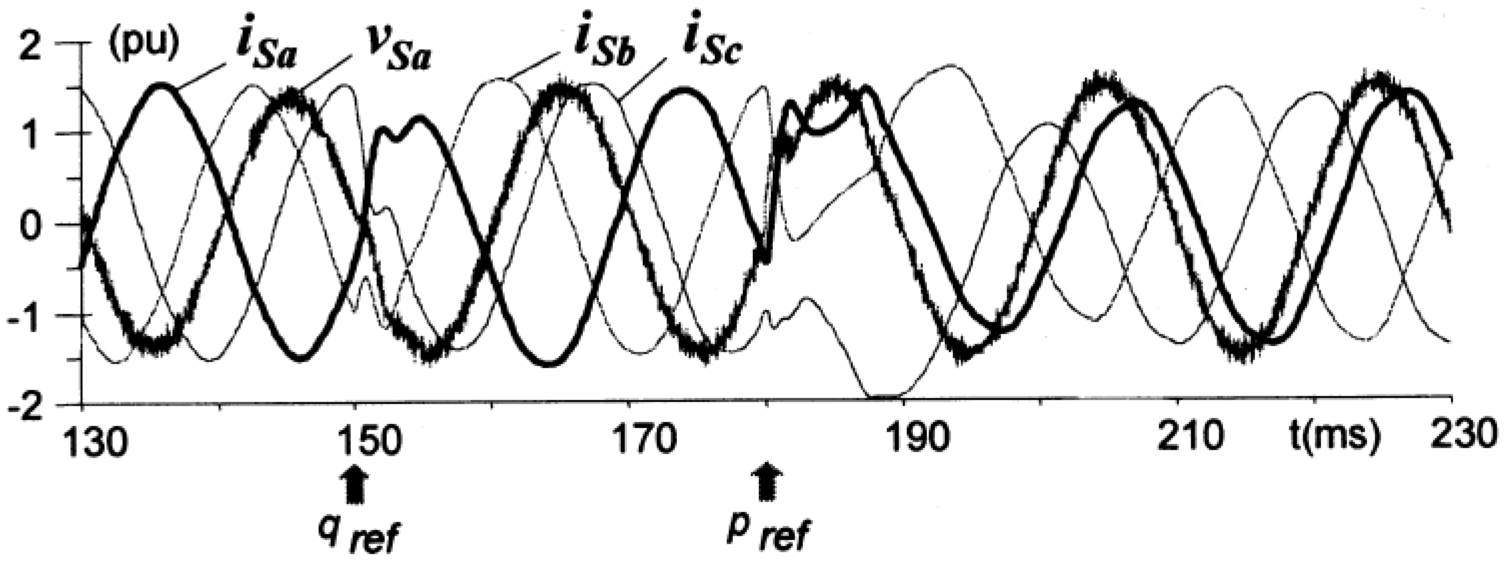


Currents of the power subsystem G1



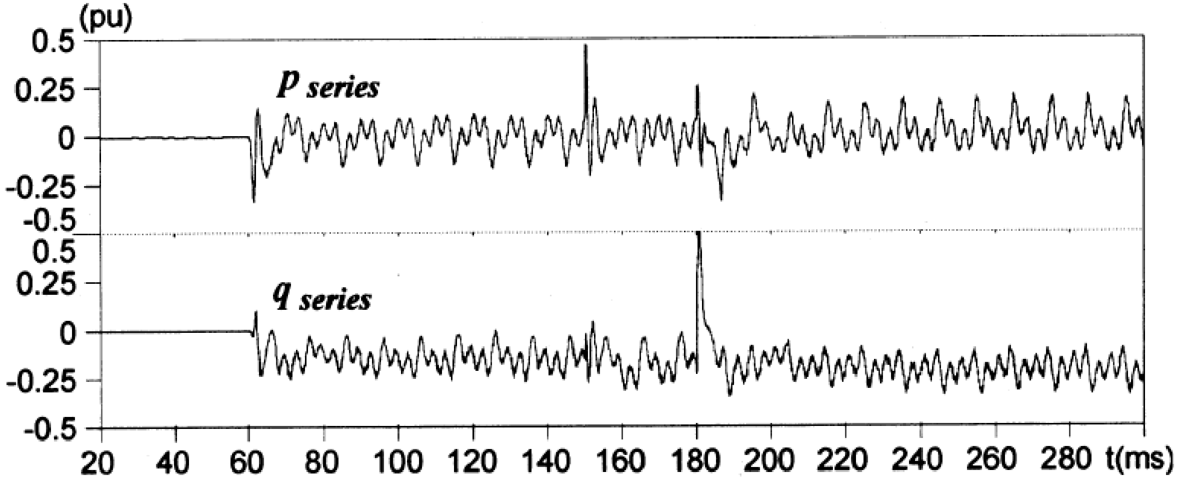
Currents of the controlled transmission line

Simulation Results of Configuration #1 of the UPLC /9

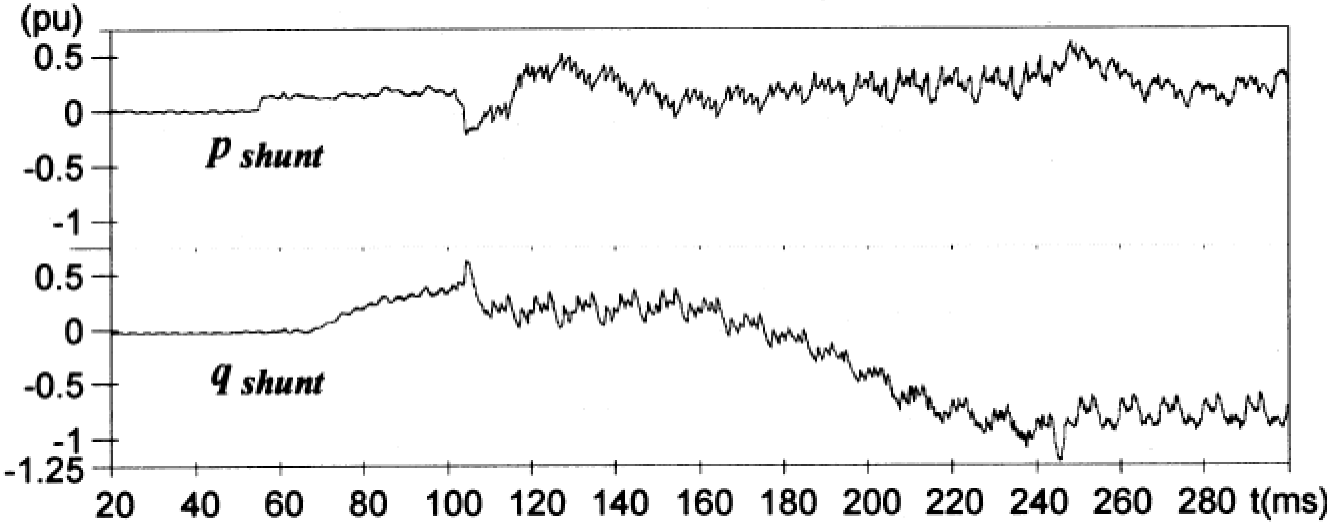


Currents of the controlled transmission line

Simulation Results of Configuration #1 of the UPLC /10

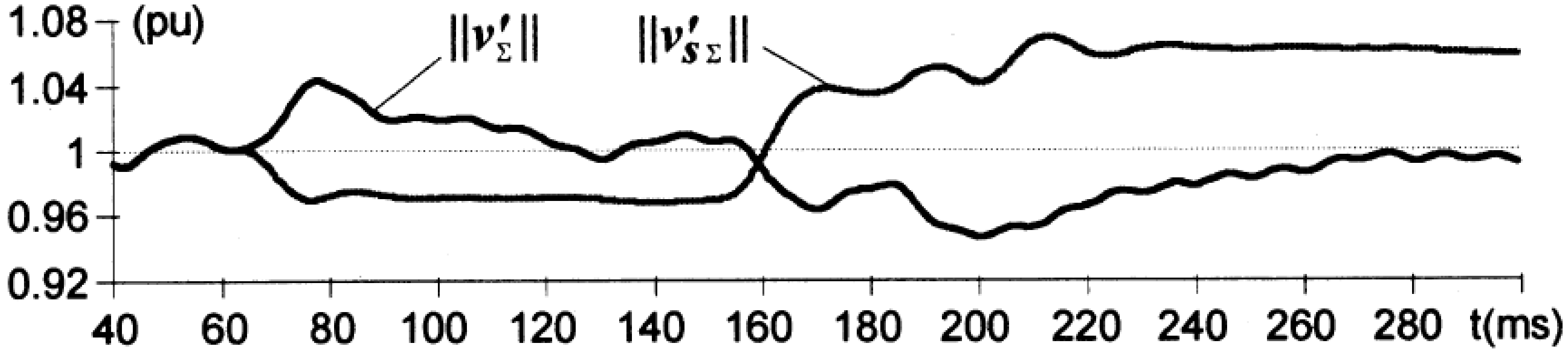


Instantaneous powers of the series converter of the UPLC



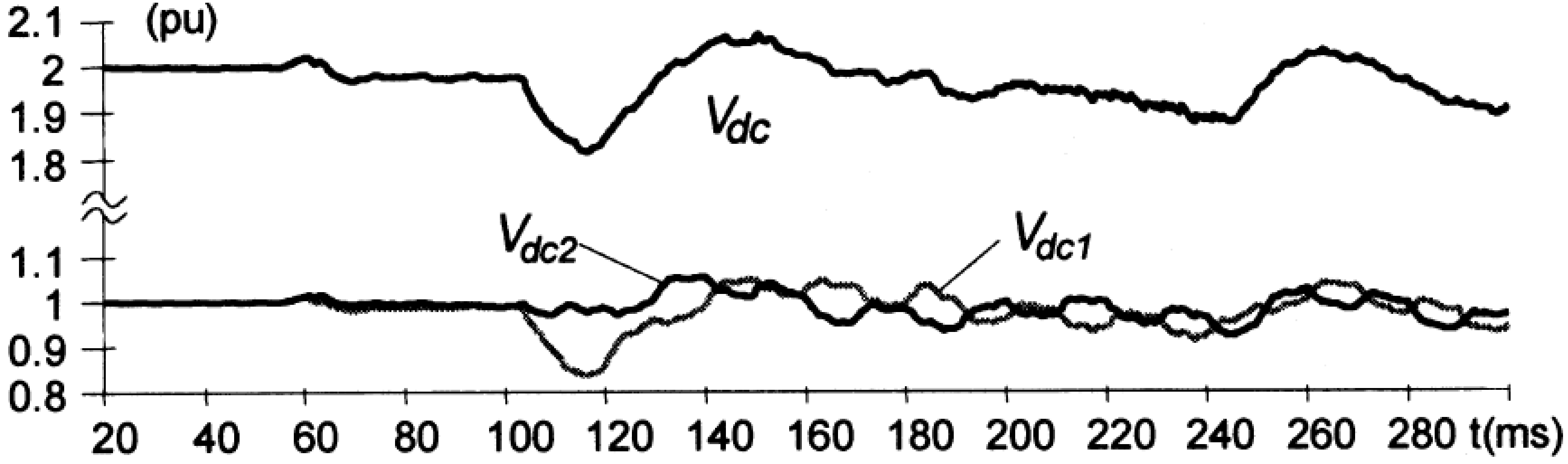
Instantaneous powers of the shunt converter of the UPLC

Simulation Results of Configuration #1 of the UPLC /11



Instantaneous aggregate values of the fundamental positive-sequence voltages v and v_s

Simulation Results of Configuration #1 of the UPLC /12

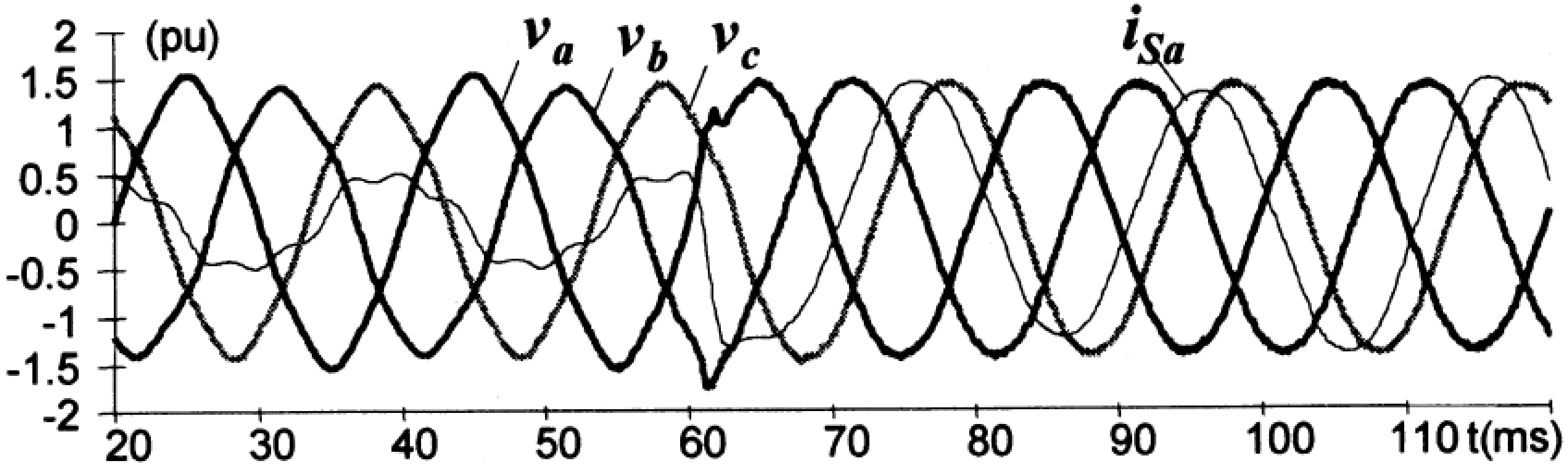


Voltages at the common dc link of the UPLC

Simulation Results of Configuration #2 of the UPLC /1

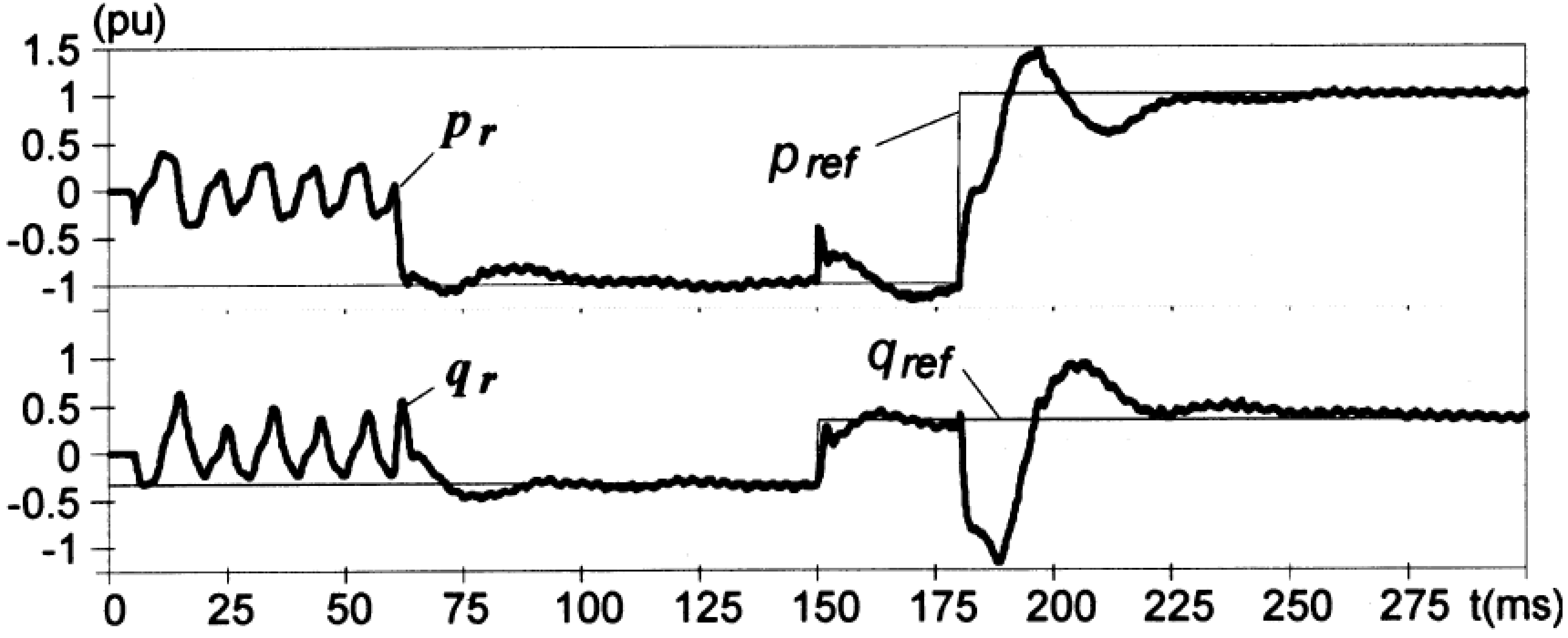
- Here the power subsystem G1 is moved to the left side of the UPLC and another subsystem G2 takes the place of G1.
- The voltage Vs now is the one to be compensated in order to keep the voltage V balanced and sinusoidal.
- The nonlinear loads were the same as those in Fig. "Totalized currents of the nonlinear loads." and the sequence of events is equal to that given on " Simulation Results of Configuration #1 of the UPLC/1"

Simulation Results of Configuration #2 of the UPLC /2



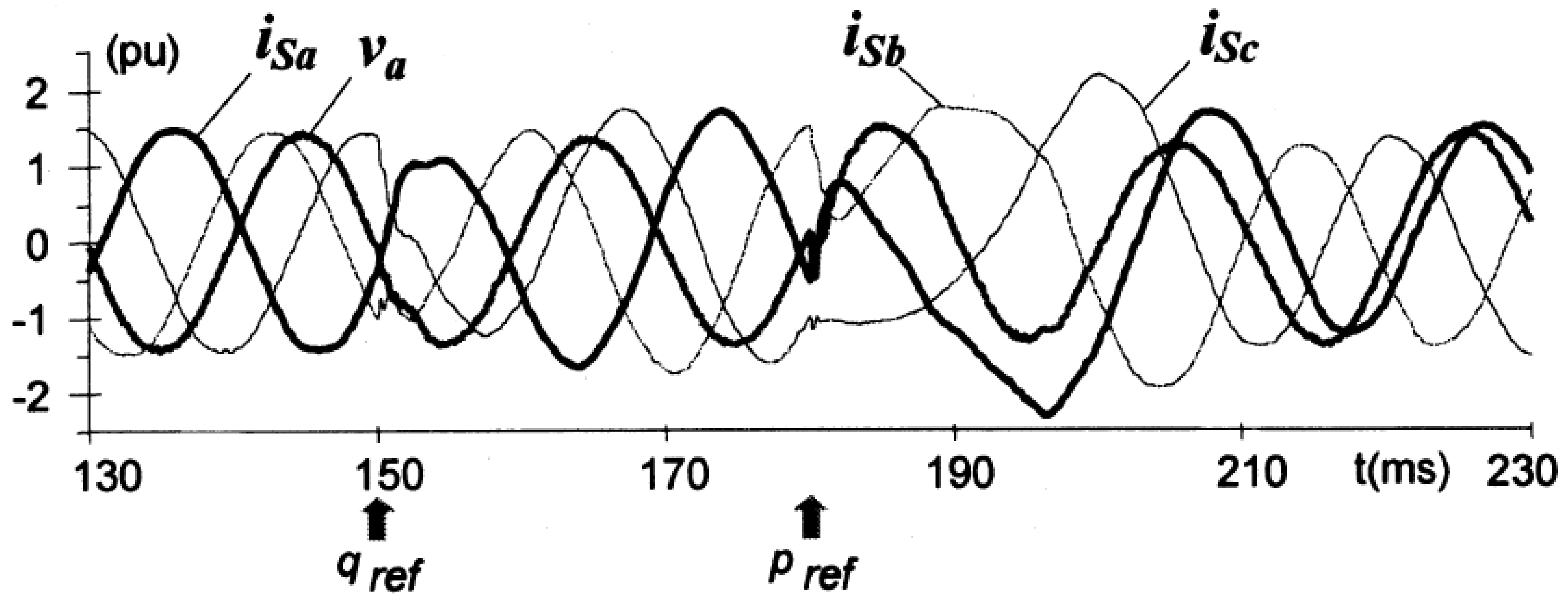
Compensated voltages at the right side of the UPLC

Simulation Results of Configuration #2 of the UPLC /3



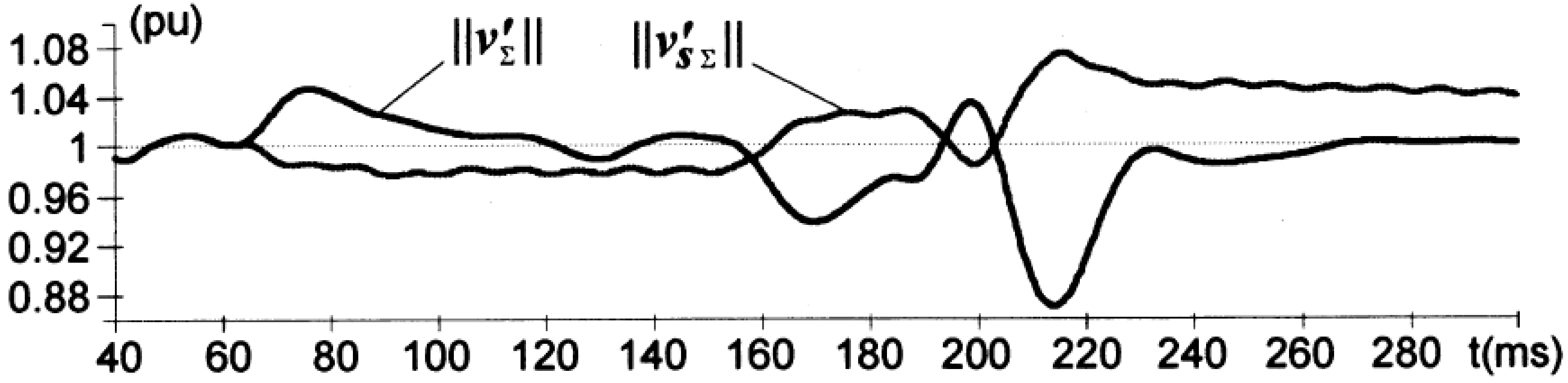
Instantaneous powers of the controlled transmission line (right side of the UPLC)

Simulation Results of Configuration #2 of the UPLC /4



Currents of the controlled transmission line

Simulation Results of Configuration #2 of the UPLC /5



Aggregate values of the fundamental positive-sequence voltage v and v_s

Summary

- The control techniques for active filters have been successfully merged with a FACTS device, the unified power flow controller (UPFC)
- A three-phase, four-wire power system has been considered in the analysis, which allowed the evaluation of the performance of the UPLC
- The UPLC incorporates almost all compensation characteristics of active power line conditioners that can be implemented with PWM converters into a single device
- Two major issues have been left for future work: the dimensioning of the dc capacitors of the UPLC, and the analysis of stability under subsynchronous resonances

Thank you for your time!

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Sidiropoulos Andreas (andrsidi@ee.duth.gr)