SYSTEC Summer School, Sept, 2021

Electric Power Quality

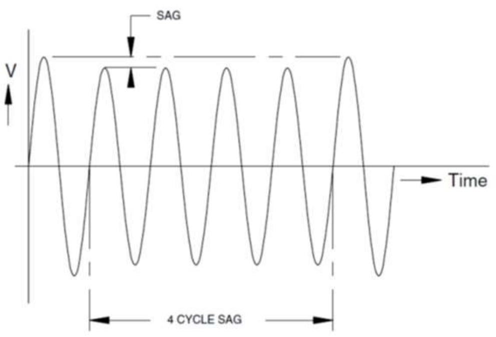
Issues and Solutions

Contents

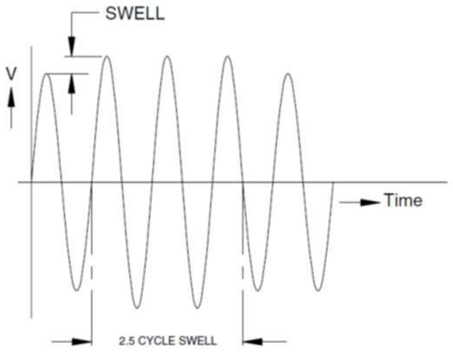
- Voltage quality phenomena definitions
- Low voltage supply characteristics (EN50160)
- Interface with the electrical network
- Passive solutions
- Grid interface optimization of AC/DC converters
  - Current control methods
- Introduction to PWM-controlled rectifiers

I. Overview of Voltage Quality Phenomena

- Voltage variation: voltage sags and overvoltages (voltage swells)
  - An increase or decrease of voltage normally due to variation of the total load of a distribution system or a part of it



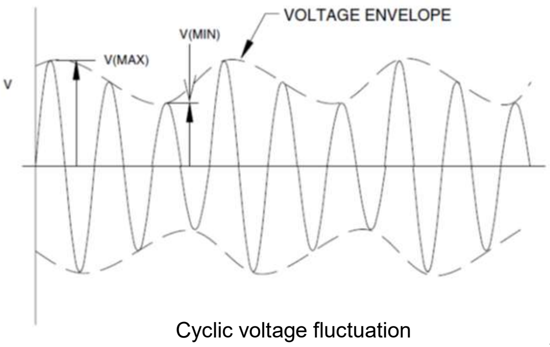
Voltage sag/drop with a duration of 4 cycles



Voltage swell with a duration of 2,5 cycles

Overview of Voltage Quality Phenomena

- Rapid voltage change
  - A single rapid variation of the root mean square (rms) value of a voltage between two consecutive levels which are sustained for definite but unspecified durations
- Voltage fluctuation
  - A series of voltage changes or a cyclic variation of the voltage envelope
- Flicker
  - Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time



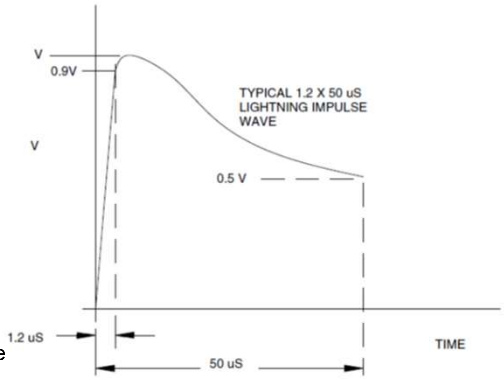
Cyclic voltage fluctuation

Overview of Voltage Quality Phenomena

- Supply voltage dip
  - A sudden reduction of the supply voltage to a value between 90% and 1% of the declared voltage U_c followed by a voltage recovery after a short period of time
    - Conventionally the duration of a voltage dip is between 10 ms and 1 minute
    - The depth of a voltage dip is defined as the difference between the minimum rms voltage during the voltage dip and the declared voltage
    - Voltage changes which do not reduce the supply voltage to less than 90% of the declared voltage U_c are not considered to be dips
- Supply interruption
  - A condition in which the voltage at the supply terminals is lower than 1% of the declared voltage, U_c. A supply interruption can be classified as:
    - Prearranged, when network users are informed in advance, to allow the execution of scheduled works on the distribution system, or
    - Accidental, caused by permanent or transient faults, mostly related to external events, equipment failures or interference

Overview of Voltage Quality Phenomena

- An accidental interruption is classified as:
  - A long interruption (longer than three minutes) caused by a permanent fault,
  - A short interruption (up to three minutes) caused by a transient fault
- Transient overvoltage
  - A short duration oscillatory or non-oscillatory overvoltage usually highly damped and with a duration of a few milliseconds or less
    - NOTE: Transient overvoltages are usually caused by lightning, switching or operation of fuses. The rise time of a transient overvoltage can vary from less than one microsecond up to a few milliseconds



Transient overvoltage

Overview of Voltage Quality Phenomena

- Harmonic voltage
  - A sinusoidal voltage with a frequency equal to an integer multiple of the fundamental frequency of the supply voltage
  - Harmonic voltages can be evaluated:
    - Individually by their relative amplitude (U_h) related to the fundamental voltage U_1, where h is the order of the harmonic;
    - Globally, for example by the total harmonic distortion factor THD, calculated using the following expression:

$$THD_v = \frac{1}{V_1}\sqrt{\sum_{h=2}^{40} V_h^2}$$

- Inter-harmonic voltage
  - A sinusoidal voltage with a frequency between the harmonics, i.e. the frequency is not an integer multiple of the fundamental
    - NOTE: Inter-harmonic voltages at closely adjacent frequencies can appear at the same time forming a wide band spectrum

Overview of Voltage Quality Phenomena

- Voltage unbalance
  - In a three-phase system, a condition in which the rms values of the phase voltages or the phase angles between consecutive phases are not equal
- Resonances
- Mains signalling voltage
  - A signal superimposed on the supply voltage for the purpose of transmission of information in the public distribution system and to network users' premises
  - Three types of signals in the public distribution system can be classified:
    - Ripple control signals: superimposed sinusoidal voltage signals in the range of 110 Hz to 3000 Hz;
    - Power-line-carrier signals: superimposed sinusoidal voltage signals in the range between 3 kHz to 148,5 kHz;
    - Mains marking signals: superimposed short time alterations (transients) at selected points of the voltage waveform

II. Low Voltage Supply Characteristics (EN 50160)

- Power frequency
- The nominal frequency of the supply voltage shall be 50 Hz
- Under normal operating conditions the mean value of the fundamental frequency measured over 10 s shall be within a range of:
  - For systems with synchronous connection to an interconnected system
    - 50 Hz ± 1% (i.e. 49,5 ... 50,5 Hz) during 99,5% of a year,
    - 50 Hz + 4% / -6 % (i.e. 47 ... 52 Hz) during 100% of the time
  - For systems with no synchronous connection to an interconnected system (e.g. supply systems on certain islands)
    - 50 Hz ± 2% (i.e. 49 ... 51 Hz) during 95% of a week,
    - 50 Hz ± 15% (i.e. 42,5 ... 57,5 Hz) during 100% of the time

Low Voltage Supply Characteristics

- Magnitude of the supply voltage
- The standard nominal voltage U_n for public low voltage is:
  - For four-wire three phase systems:
    - U_n = 230 V between phase and neutral
  - For three-wire three phase systems:
    - U_n = 400 V between phases
- NOTE: In low voltage systems declared and nominal voltage are equal

Low Voltage Supply Characteristics

- Under normal operating conditions:
  - During each period of one week 95% of the 10 min mean rms values of the supply voltage shall be within the range of U_n ± 10%, and
  - All 10 minutes mean rms values of the supply voltage shall be within the range of U_n +10%/-15%
- Rapid voltage changes
  - Rapid voltage changes of the supply voltage are mainly caused either by load changes in network users' installations or by switching in the system
  - Under normal operating conditions a rapid voltage change generally does not exceed 5% U_n but a change of up to 10% U_n with a short duration might occur some times per day in some circumstances
    - NOTE: A voltage change resulting in a voltage less than 90% U_n is considered a supply voltage sag

Low Voltage Supply Characteristics

- Supply voltage unbalance
- Under normal operating conditions, during each period of one week, 95% of the 10 minute mean rms values of the negative phase sequence component of the supply voltage shall be within the range 0 to 2 % of the positive phase sequence component*
- In some areas with partly single phase or two phase connected network users' installations, unbalances up to about 3% at three-phase supply terminals occur

- Harmonic voltage
- Under normal operating conditions, during each period of one week, 95% of the 10 minute mean rms values of each individual harmonic voltage shall be less than or equal to the value given in Table

Low Voltage Supply Characteristics

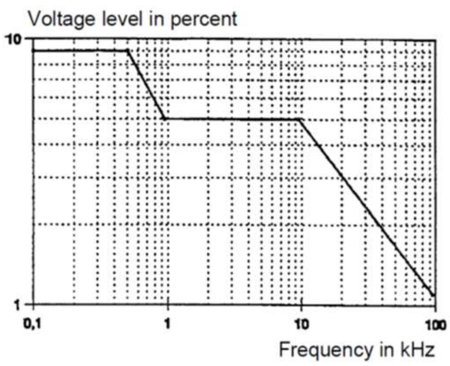
- Harmonic voltage
  - Resonances may cause higher voltages for an individual harmonic
- Moreover, the THD of the supply voltage (including all harmonics up to the order 40*) shall be less than or equal to 8%

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative voltage	Order h	Relative voltage	Order h	Relative voltage
5	6 %	3	5 %	2	2 %
7	5 %	9	1,5 %	4	1 %
11	3,5 %	15	0,5 %	6...24	0,5 %
13	3 %	21	0,5 %		
17	2 %				
19	1,5 %				
23	1,5 %				
25					

NOTE: No values are given for harmonics of order higher than 25, as they are usually small, but largely unpredictable due to resonance effects.

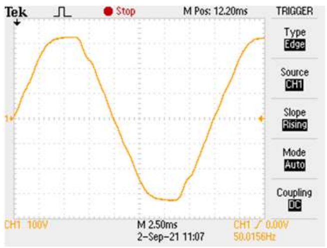
Low Voltage Supply Characteristics

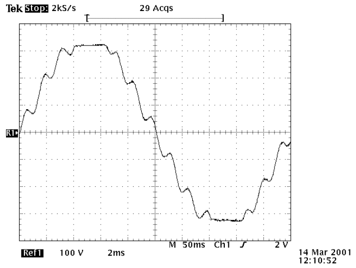
- Mains signalling voltage on the supply voltage
- The public distribution systems may be used by the public supplier for the transmission of signals
  - Over 99 % of a day the three second mean of signal voltages shall be less or equal to the values given below



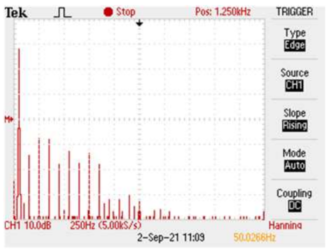
Voltage levels of signal frequencies in percent of U_n used in public LV distribution systems

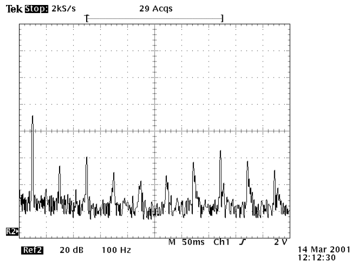
Practical Examples: Distortion and Resonance





THD=2.9 %





Voltage waveform (due to the presence of nonlinear loads) and its spectrum

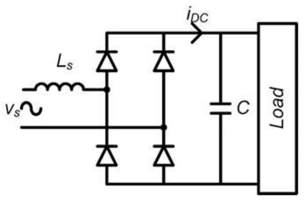
Voltage waveform (with a 740 Hz harmonic present) and its spectrum

III. Interface with the Electrical Network

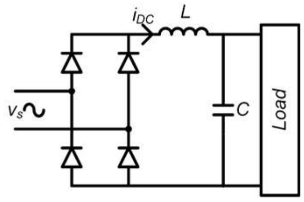
- How do customers connect to the electrical network?
  - Passive linear loads (resistive, inductive, …)
  - Passive non-linear loads (diode bridges, lamp dimmers, …)
  - Active linear loads/generators (motors, ...)
  - Active non-linear loads/generators (thyristor bridges, …)
- What are the problems in terms of Power Quality?
  - Being supplied by a voltage source with possible power quality issues
  - Consuming current with possible power quality issues

Electronic Interface with the Electrical Network

- Single-phase rectifiers, diode- or thyristor-based
  - In general, the single-phase converter is used in linear or switching power supplies (low-power, diode-based) or in industrial applications (with medium/high-power, diode- or thyristor-based)
- Two main topologies: low- and medium/high-power



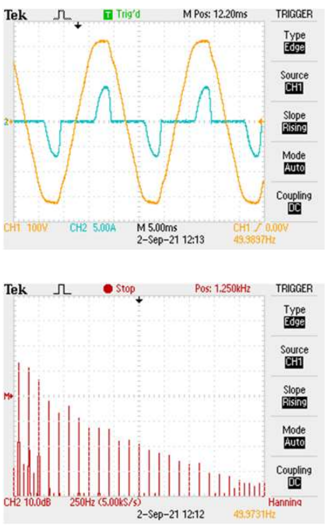
Low-power rectifier. [L_s is an equivalent inductance]



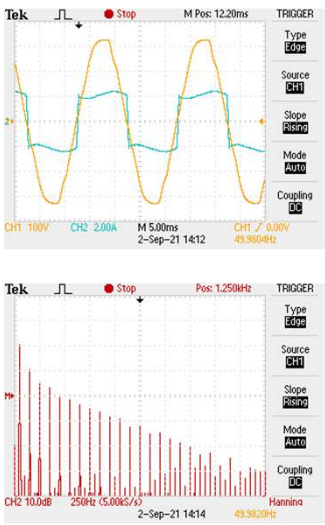
Medium/high-power rectifier with an *LC* output filter

- In the left, the bridge output current is discontinuous; in the right the current is continuous and can be considered almost constant

Practical Examples (single-phase)



AC voltage and current (with discontinuous DC current) and its LF spectrum



AC voltage and current (with continuous DC output current) and LF spectrum

Input Current of Single-phase Rectifiers

- Assuming a constant output current (simplification), the AC input current is a square wave, being the respective harmonics given by:

$$\frac{I_h}{I_1} = \frac{1}{h}, \quad \text{for } h \text{ odd}$$

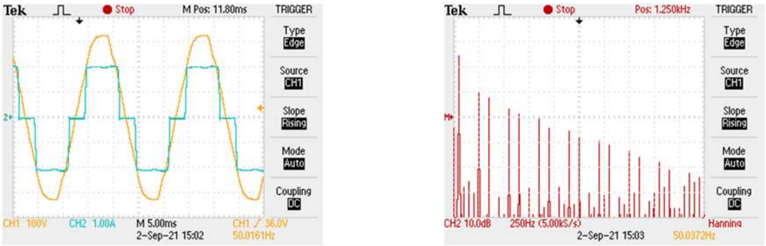
- The current Total Harmonic Distortion (*THD*) is given by:

$$THD_i = \frac{1}{I_1}\sqrt{\sum_{h=2}^{\infty} I_h^2} = \frac{1}{I_1}\sqrt{I_{rms}^2 - I_1^2}$$

- For the single-phase bridge it is verified that *THD*=48.3%
  - For discontinuous currents, the distortion is higher
  - For a half-controlled converter, with constant current, there are different relations…

Practical Examples (three-phase)

- Assuming a symmetric and balanced system, with sinusoidal voltages, the active power is only related with the line current fundamental component
  - Use Fourier analysis to verify



AC voltage and input current (continuous DC current) of a three-phase rectifier and low-frequency spectrum

Input Current of Three-phase Rectifiers

- Besides the current fundamental component, there are only harmonics of order *h*, with *p* dependent on the converter topology:

$$h = kp \pm 1, \quad \text{with } p \text{ multiple of } 3$$

$$\begin{cases} p=3: & h=2, 4, 5, 7, 8, 10, \ldots \\ p=6: & h=5, 7, 11, 13, 17, 19, \ldots \\ p=9: & h=8, 10, 17, 19, \ldots \end{cases}$$

  – More relevant is the characterization of the primary current of the input transformer …

- Again, it is verified:

$$I_h = \frac{I_1}{h} = \frac{I_1}{kp \pm 1}$$

Disturbances Introduced in the Electrical Network

- Seen from the electric grid, the rectifier is a nonlinear load
  – It is supplied by a sinusoidal voltage and absorbs a nonlinear current
  – It can be considered a harmonic current generator
- The analyses show that the more far a point is from the harmonics source generator more the harmonics voltages are reduced, since:
  – Harmonic currents reduce because of the parallel branches
  – With the increased short-circuit power, the impedances are smaller
- In general, the highest disturbances occur near the disturbing circuit and the neighbor circuits

Disturbances Introduced in the Electrical Network

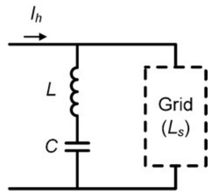
- The disturbances introduced in the electrical network by the harmonics generated by the rectifier give origin to
  - Additional losses in rotating electric machines, torque reduction and increased noise level
  - Higher losses in capacitors and increased operating temperature
  - Interference in telecommunication circuits
  - Erroneous zero-crossing detection
  - Measuring and counting errors
  - Possibility of occurrence of parallel resonance in grids with parallel connected capacitors

IV. Solutions: Harmonics Passive Filtering

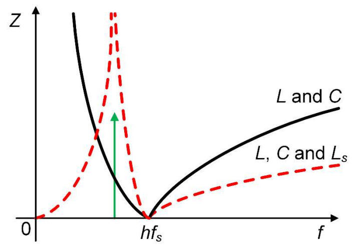
- The connection of tuned filters at the input of nonlinear circuits (AC/DC converters) can help, or not, to the filtering of the current consumed by the converter (or any other nonlinear load)
- In general, three filters are used:
  - Tuned filters, for the two first harmonics (5^{th} and 7^{th}, for p=6; 11^{th} and 13^{th}, for p=12, …)
  - A damped series resonant circuit, with a low impedance in a large frequency range (h=12, for p=6, …)

- It is necessary to know the filter influence in all the frequency range
  - Namely for all the spectrum created by the disturbing circuit and for selected frequency ranges (tele-command circuits, …)

Harmonics Passive Filtering



Parallel tuned filter



Equivalent impedance

- The equivalent impedance at the connecting node:

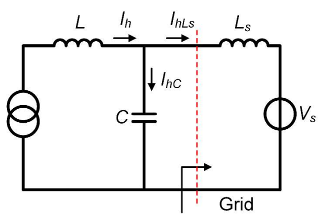
$$Z(jh\omega) = \frac{jh\omega L_s (h\omega L - \frac{1}{h\omega C})}{h\omega(L_s + L) - \frac{1}{h\omega C}} = \frac{jh\omega L_s (h^2\omega^2 LC - 1)}{h^2\omega^2 (L_s + L)C - 1}$$

- The grid impedance, L_s, can originate the occurrence of resonances ($Z(h\omega) = \infty$) at undesirable frequencies

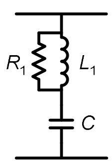
Harmonics Passive Filtering

- The existence of capacitor banks can give origin to parallel resonances
  - Extremely high impedance
  - Very high harmonic voltage

$$Z(jh\omega) = \frac{jh\omega L_s C}{1 - h^2\omega^2 L_s C}$$



Parallel resonance effect with basic compensation [$V_s(h\omega)$=0]



Additional elements in the capacitive circuit

- The correct design of the additional elements in the capacitive circuit minimizes the parallel resonance occurrence

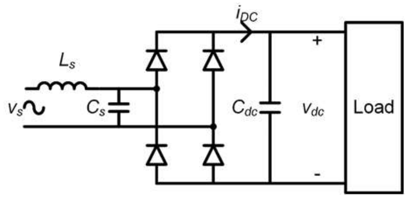
Comments

- The currents supplied by the grid to conventional rectifiers (diode- or thyristor-based) have a high THD, and contain low-frequency harmonics
- The circulation of harmonic currents in the electric grid give origin to different disturbances in the operation of electric and electronic circuits
- The use of tuned filters in the rectifiers' input can help, or not, to the filtering of the distorted current supplied by the electric grid
- Other power conversion topologies and control methods are the best solution to optimize the AC/DC conversion

V. Grid Interface Optimization of AC/DC Converters

- The input current of conventional DC power supplies (linear or SMPS) or generic AC/DC converters is not sinusoidal
  - Harmonic currents cause distortion in the input voltage and other disturbances
- Under a sinusoidal voltage, only the fundamental component of the current is associated with active power flow
- The increasingly used nonlinear loads has increased this type of problems (distortion, resonance, noise, losses, …)
- Standards EN 61000-3-2 and 3-12, and IEEE 519, establish limits to the harmonic currents at the input of certain electric/electronic equipment
  - It is necessary to introduce additional or different elements or circuits to limit the harmonics penetrating the input supply lines

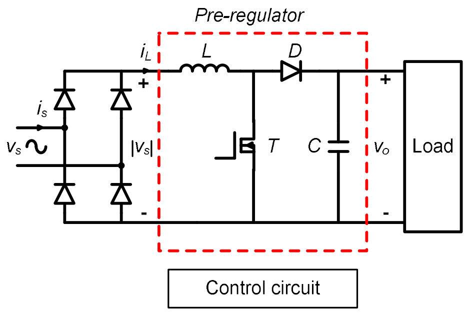
Passive Filtering



Single-phase rectifier with a LC input filter

- The filter offers a low impedance path to the circulation of harmonic currents
  - The power factor increases, but
  - It has the disadvantage of needing high *L* and *C* values, due to the low frequency of the harmonics to be filtered
  - The filter causes attenuation of the fundamental component, lowering V_{dc}
- The equipment becomes more bulky and heavy

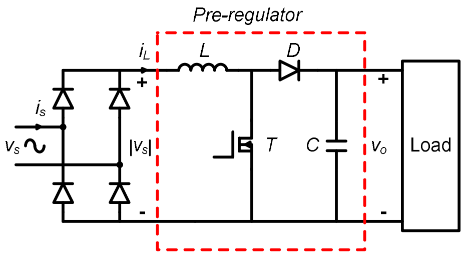
Pre-regulation Circuit



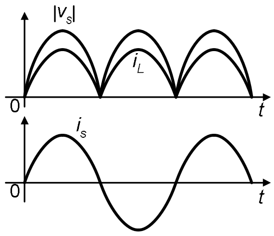
Use of a pre-regulator circuit in the electrical grid interface

- It is a step-up DC/DC converter with time varying input voltage
  - It can be controlled in order to obtain in the input inductor a quasi-sinusoidal current or a high frequency pulsed current (depending on the control method)
  - The grid current, i_s, is almost sinusoidal

Operation with Continuous Current



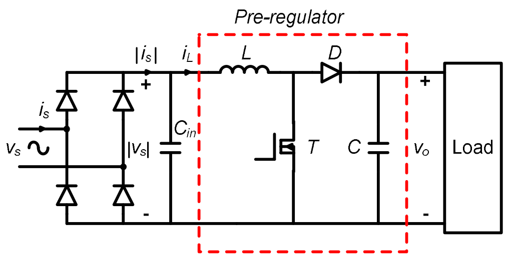
Pre-regulation circuit for a DC power supply



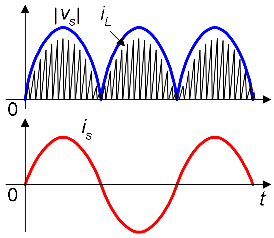
Diode bridge output voltage and current and input line current

- In <u>continuous conduction</u>, the inductance current, i_L, does not come to zero
  - It facilitates the input filtering; but the transistor and the diode commutate with high losses
  - It generates high electromagnetic noise

Operation in Critical Conduction Mode (CCM)



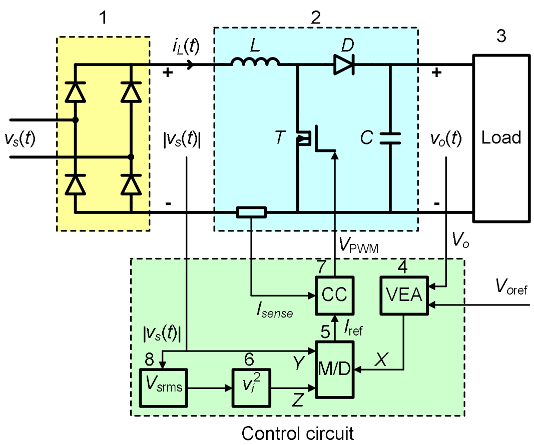
Pre-regulation circuit for CCM and discontinuous current operation



Diode bridge output voltage and current and input current in CCM

- In <u>Critical Conduction Mode (CCM)</u> and <u>discontinuous conduction</u>, the inductance current is pulsed
  - It is needed to filter the pre-regulator input current; the transistor and the diode operate with lower switching losses
  - It generates lower electromagnetic noise
  - The peak current is higher

Control Circuit for Continuous Conduction



Control diagram of a pre-regulating circuit for continuous conduction

1- Input diode bridge
2- Step-up DC/DC converter
3- Load (e.g. SMPS)
4- Error amplifier (P, PI)
5- Multiplier/Divider
6- Nonlinear circuit ($v_o = v_i^2$)
7- Current controller
8- Nonlinear circuit ($v_o = v_{iRMS}$)

X- Proportional to the current peak value
Y- Proportional to $\sin\theta$
Z- Proportional to V_{srms}^2
$I_{ref} = XY/Z$

Analysis in Continuous Conduction

- The instantaneous power at the input of the diode bridge:

$$p_{in}(t) = \underbrace{\sqrt{2}V_s\left|\sin\omega t\right|}\cdot\underbrace{\sqrt{2}I_s\left|\sin\omega t\right|} = V_s I_s - V_s I_s \cos 2\omega t$$

- The instantaneous power at the DC output, assuming a ripple free voltage:

$$p_{dc}(t) = V_o i_D(t)$$

- The diode current is:

$$i_D(t) = I_o + i_C(t)$$

- Considering an extremely low inductance it can be assumed that the instantaneous output power is the same of the input:

$$i_D(t) = I_o + i_C(t) = \frac{p_{dc}}{V_o} \cong \frac{V_s I_s}{V_o} - \frac{V_s I_s}{V_o}\cos 2\omega t + \text{HF terms}$$

Analysis in Continuous Conduction

- The average value of $i_D(t)$:

$$I_D = I_o = \frac{V_s I_s}{V_o}$$

- The capacitor current:

$$i_C(t) \approx -\frac{V_s I_s}{V_o}\cos 2\omega t = -I_D \cos 2\omega t$$

- The output voltage ripple:

$$\Delta V_o(t) \cong \frac{1}{C}\int i_C dt = -\frac{I_D}{2\omega C}\sin 2\omega t$$

  - Useful expression for designing the output capacitor

Analysis in Continuous Conduction

- Imposing a constant ripple current during t_{on} and t_{off} it results in:

$$t_{on} = \frac{L\Delta I}{|v_s|}; \qquad t_{off} = \frac{L\Delta I}{V_o - |v_s|}$$

- The (variable) switching frequency is obtained as:

$$f_s(t) = \frac{1}{t_{on}(t) + t_{off}(t)} = \frac{\left(V_o - |v_s(t)|\right)\cdot |v_s(t)|}{L\Delta I V_o}$$

- Imposing a constant switching frequency it results for the (variable) ripple current:

$$\Delta I(t) = \frac{\left(V_o - |v_s(t)|\right)\cdot |v_s(t)|}{f_s L V_o}$$

$$\Delta I_{\max} = \frac{V_o}{4 f_s L}\,, \quad \text{for } |v_s| = \frac{1}{2}V_o$$

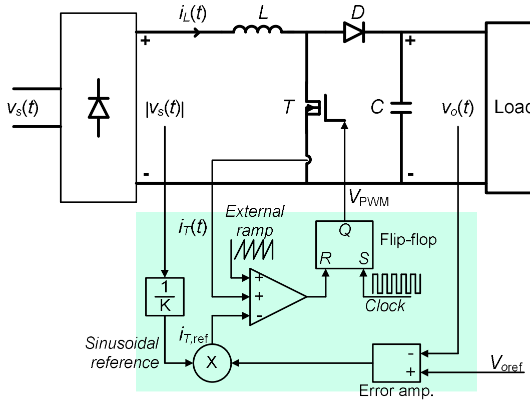
Analysis in Continuous Conduction

- The precedent analysis allows the following conclusions:
  - The output voltage contains a 100 Hz ripple component (for a 50 Hz input)
  - Increasing f_s allows a lower L, but increases the losses (inductance, transistor, diode, capacitor)
- It should be noted that:
  - The initial peak current, when the capacitor is discharged can be limited with a series resistance and/or a by-pass diode
  - An output voltage much higher (i.e. >20%) then the v_s peak value causes an efficiency deterioration
  - In a constant switching frequency mode, the (variable) duty-cycle value along a period is given by:

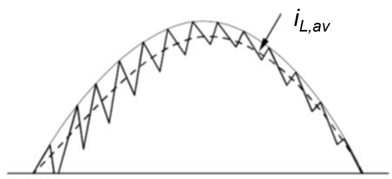
$$\delta(t) = 1 - \frac{|v_S(t)|}{V_O}$$

    - High currents (near the peak voltage) flow during a short time interval in the transistor

Current Control Methods: Peak Current



Peak current control: main diagram

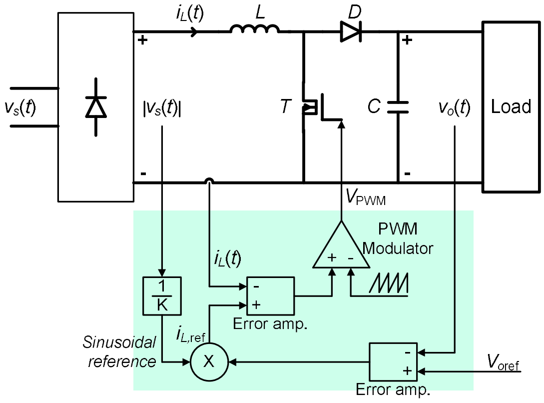


Peak current control: inductor current

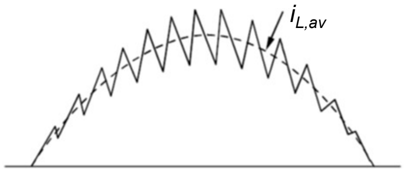
Advantages:
- Constant switching frequency
- Only the switch current must be sensed
- No need of current error amplifier
- Possibility of a true switch current limiting

Disadvantages:
- Presence of subharmonic oscillations at duty-cycles greater than 50%, so a compensation ramp is needed
- Input current distortion which increases at high line voltages and light load and is worsened by the presence of the compensation ramp
- Control more sensitive to commutation noises

Current Control Methods: Average Current



Average current control method: main diagram



Average current control method: inductor current

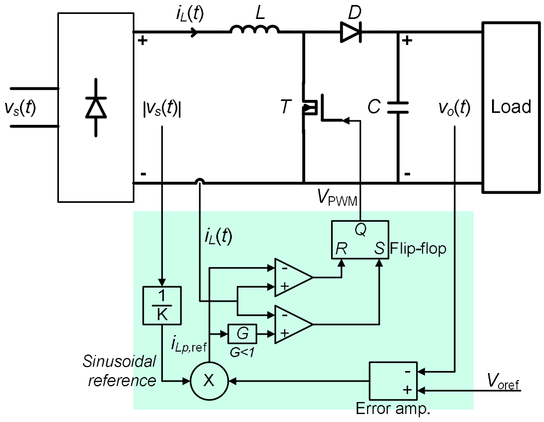
Advantages:

- Constant switching frequency
- No need of compensation ramp
- Control is less sensitive to commutation noises, due to current filtering
- Better input current waveforms than for the peak current control

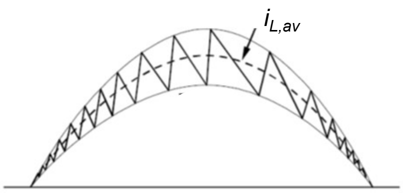
Disadvantages:

- Inductor current must be sensed
- A current error amplifier is needed and its design must take into account the different converter operating points during the line cycle

Current Control Methods: Hysteresis



Hysteresis: main control diagram



Hysteresis: inductor current waveform

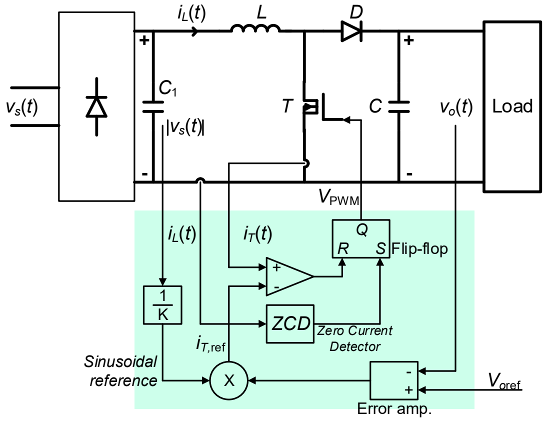
Advantages:

- No need of compensation ramp
- Low distorted input current waveforms

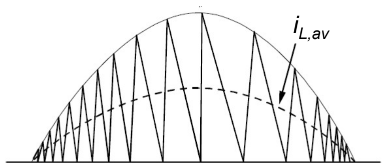
Disadvantages:

- Variable switching frequency
- Inductor current must be sensed
- Control sensitive to commutation noises

Current Control Methods: CCM (or borderline)



CCM current control method: main diagram

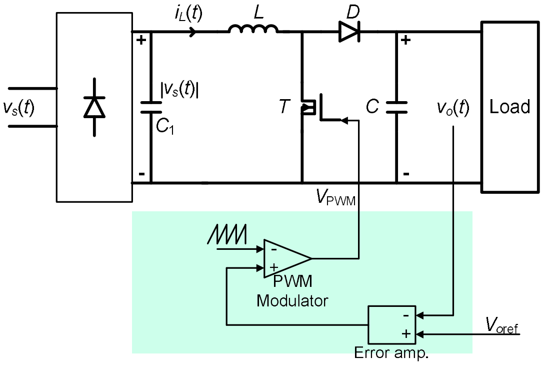


CCM current control method: inductor current waveform

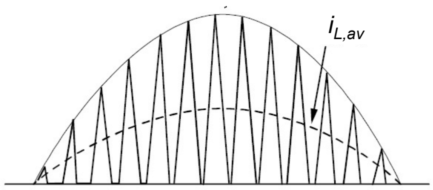
Advantages:
- No need of a compensation ramp
- No need of a current error amplifier
- For controllers using switch current sensing, switch current limitation can be introduced

Disadvantages:
- Variable switching frequency
- Inductor voltage/current must be sensed (to detect the zeroing of the inductor current)
- For controllers in which the switch current is sensed, control is sensitive to commutation noises

Current Control Methods: Discontinuous Conduction



Discontinuous current control: main diagram



Discontinuous current control method: inductor current waveform

Advantages:
- Constant switching frequency
- No need of current sensing
- Simple PWM control (DC-type)

Disadvantages:
- Higher device's current stress than for borderline control
- Input current distortion with boost topology

Comments

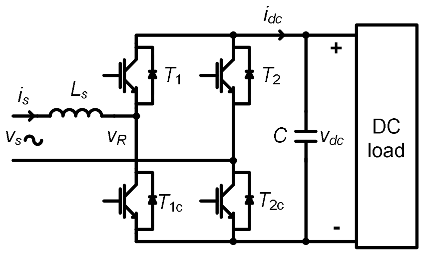
- The output voltage V_o can be stabilized for large variations in the input voltage
- Without high input current peaks the EMI filters can be smaller
- For an equal DC voltage ripple, it is necessary a small capacitor faced to a conventional circuit
- The efficiency is typically around 96% compared to 99% of a conventional power supply
- Different current control methods can be applied to control de PFC converter

VI. Introduction to PWM-controlled Rectifiers

- In drive systems with regenerative capability, the braking energy is transferred to the grid through a thyristor-based controlled rectifier in anti-parallel with the main one
  - The system has some drawbacks:
    - Distorted current waveform with low power factor
    - Limited DC voltage due to rectifier operation with a safety margin from 180º
    - Possibility of commutation failure due to disturbances in the grid
- In renewable energy sources connected to the grid it is mandatory a high quality current
- The use of a forced commutated converter, e.g. a voltage source inverter, can surpass the limitations and meet the requirements
  - Single- and three-phase converters
  - Medium/high-power

Single-phase PWM-controlled Rectifier

- The DC current is bidirectional



Voltage-source single-phase rectifier/inverter, PWM-controlled, with bidirectional power flow

- In the input loop:

$$v_s(t) = v_R(t) + v_L(t)$$

- In the connecting inductance:

$$v_L(t) = L_s \frac{di_s}{dt}$$

Operating Analysis

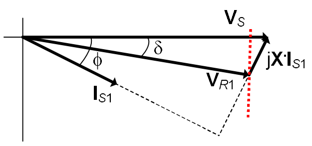
- Considering fundamental components and phasor representation:

$$\mathbf{V}_s = \mathbf{V}_{R1} + j\omega L_s \mathbf{I}_{s1}$$

- The active power, *P*, *supplied* by the AC source is (with rms values):

$$P = \mathrm{Re}\left\{\mathbf{V}_s \mathbf{I}_{s1}^*\right\} = V_s I_{s1} \cos\varphi = \frac{V_s^2}{\omega L_s}\left(\frac{V_{R1}}{V_s}\sin\delta\right) = \frac{V_s}{\omega L_s} V_{R1} \sin\delta$$

since $V_{L1}\cos\phi = \omega L_s I_{s1} \cos\phi = V_{R1}\sin\delta$



Generic single-phase diagram of the PWM-controlled rectifier
(φ and δ are lagging angles)

Operating Analysis

- The reactive power, Q, *supplied* by the AC source is positive and is given by:

$$Q = V_s I_{s1} \sin\phi = \frac{V_s^2}{\omega L_s}\left(1 - \frac{V_{R1}}{V_s}\cos\delta\right)$$

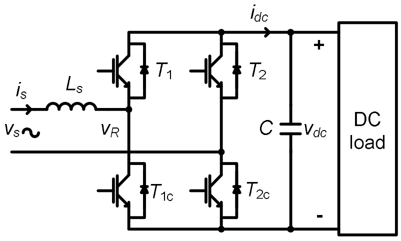
since $V_s - \omega L_s I_{s1} \sin\phi = V_{R1}\cos\delta$

- The phasor $\mathbf{I}_{s1}$ can be expressed by:

$$\mathbf{I}_{s1} = \frac{\mathbf{V}_s - \mathbf{V}_{R1}}{j\omega L_s}$$

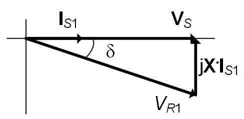
- For constant V_s, ω and L_s, the P and Q values can be imposed controlling the magnitude and phase of $\mathbf{V}_{R1}$

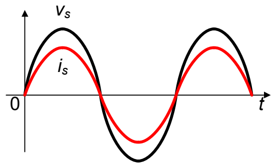
Unity Power Factor as Rectifier



Single-phase PWM-controlled rectifier

$$\mathbf{V}_s = \mathbf{V}_{R1} + j\omega L_s \mathbf{I}_{s1}$$

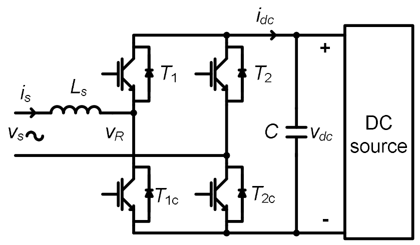




Phasor diagram and waveforms for unity power factor in rectifier mode

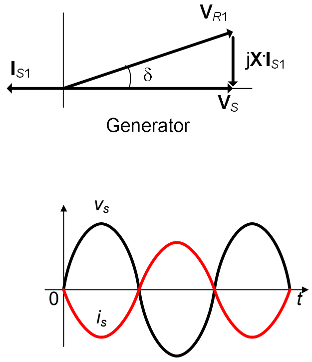
- In rectifier mode, the average value of i_{dc} is positive
- The current i_s is in phase with v_s

Unity Power Factor as Generator



Single-phase PWM-controlled rectifier

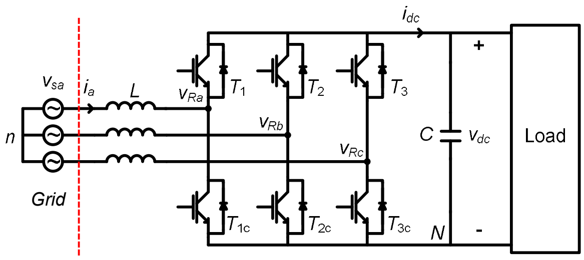
$$\mathbf{V}_s = \mathbf{V}_{R1} + j\omega L_s \mathbf{I}_{s1}$$



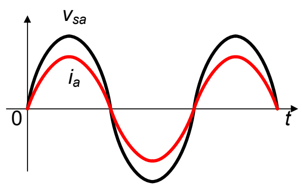
Phasor diagram and waveforms for unity power factor in generator mode

- In generator mode, the average value of i_{dc} is negative
- The current i_s is in phase opposition with v_s

Three-phase PWM-controlled Rectifier



Three-phase PWM-controlled rectifier/inverter

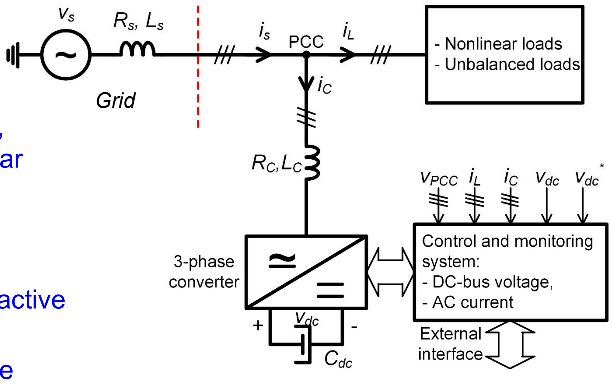


Waveforms in phase *a*, as a front-end rectifier

- The three-phase converter presents the same operating modes as the single-phase one and can use the same controller types
  - Scalar control methods (similar to the single-phase) or
  - Vector control methods, with better dynamic characteristics (also possible in single-phase converters)

Active Power Filtering

- The PWM converter can control the AC current with fast dynamics
  – Almost arbitrary currents can be generated
  – Without DC active power capability the converter operates as an active power filter
- The active power filter (APF)*
  – Injects nonlinear currents, i_C, to compensate nonlinear currents, i_L
  – Balances unbalanced 3-phase loads
  – Compensates the load reactive power
  – Stabilizes the PCC voltage



Three-phase active power filter

Conclusion

- Electronic equipment generates a significant harmonic content in the grid current; its filtering is a necessity and an obligation
  – The circulation of harmonic currents in the electric grid give origin to different disturbances in the operation of electrical and electronic circuits
  – Standards establish limits to the harmonic content injected into the grid, namely low-frequency harmonics
  – In diode rectifiers, inductance L_s reduces the harmonic content
  – The use of tuned filters in the rectifiers input can help, or not, to the filtering of the grid supplied current
- In single- and three-phase circuits, with uni- or bidirectional power flow, PWM rectifiers generate a sinusoidal input current
- The bidirectional DC current allows
  – Regenerative braking in voltage source inverters
  – Grid connection of renewable energy sources or energy storage devices

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- EN 61000: Electromagnetic Compatibility (several parts)