Input Harmonics with AC inverters.

Martien Heesterbeek/ August, 2020

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- *What is Harmonic Distortion*
- *Effects of Harmonic Distortion*
- *Solutions to reduce harmonics in Drives*
- *Delta Power Quality Solutions*

THD, Harmonics

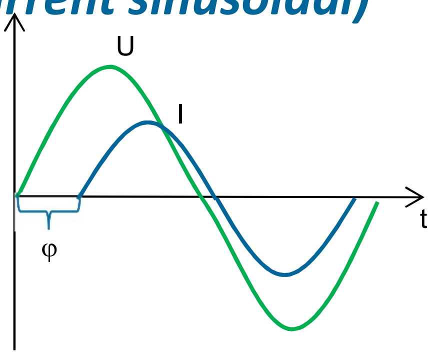
What is THD (Total Harmonic Distortion)?

- *In an electric power system, a harmonic is a voltage or current with a multiple of the fundamental frequency of the system.*

- *Harmonic currents are caused by non-linear loads.*
    - *When a linear load is excited by a sinusoidal voltage, the current is also sinusoidal.*
    - *When a non-linear load is excited by a sinusoidal voltage, the current is not sinusoidal and contains harmonics.*

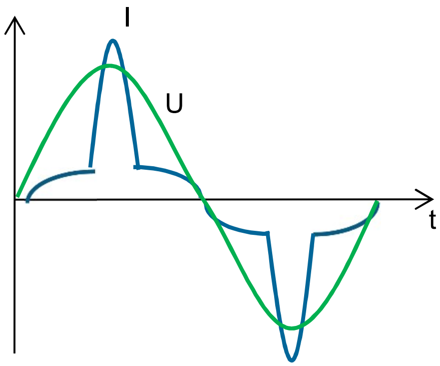
THD, Harmonics

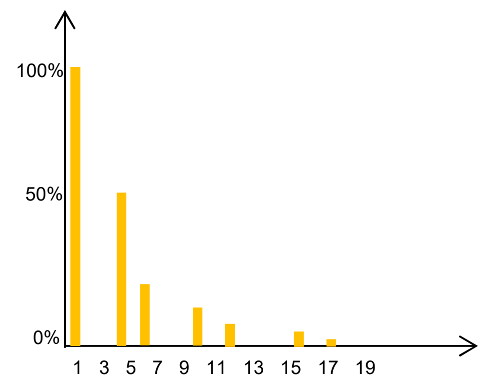
- *Linear loads (voltage and current sinusoidal)*
  - ***- Resistors***
  - ***- Capacitors***
  - ***- Inductors***
  - ***- Motors***
  - ***- Transformers***



- *Non linear loads (sinusoidal voltage gives non-sinusoidal current)*
  - ***- Semiconductors & tubes***
  - ***- PTC, NTC***

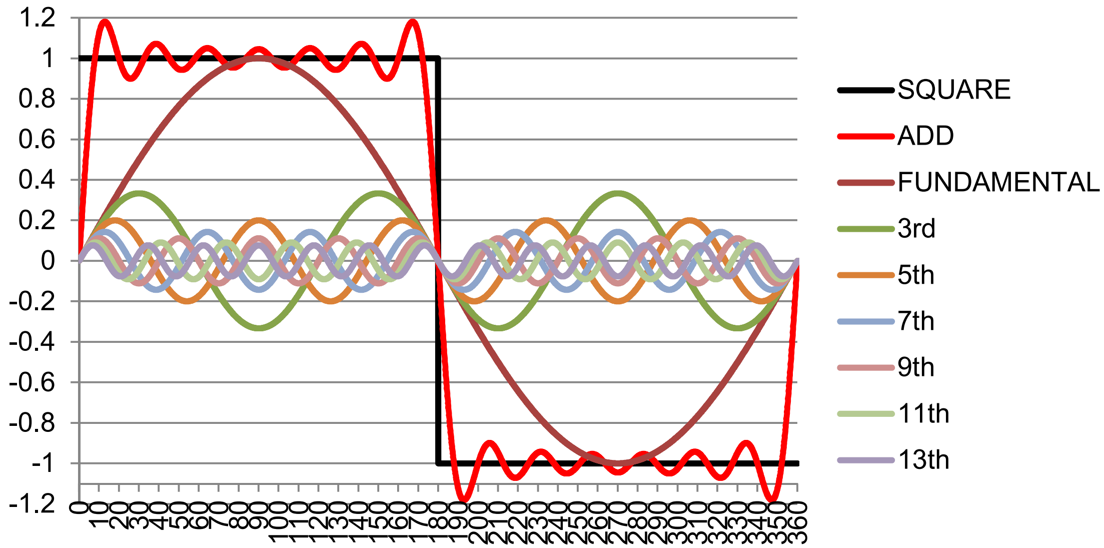
(as used in e.g.
power electronics like
AC motor drives,
soft starters,
servo drives, etc)

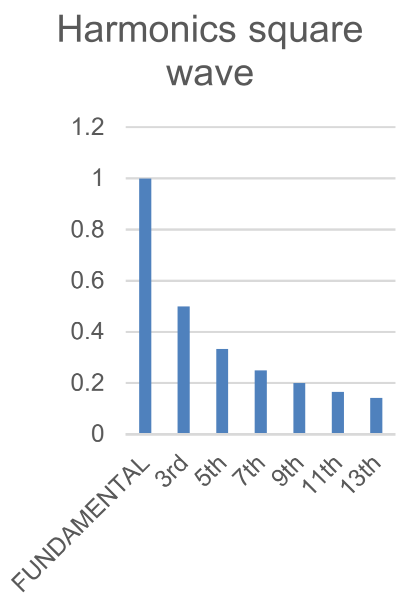




THD, Harmonics

- *Acc. to theory (Fourier analysis) a non-sinusoidal signal can be built from sine waves:*

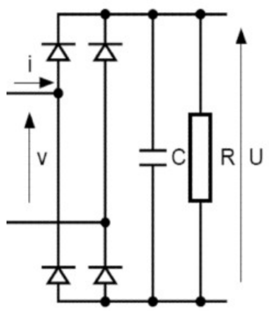


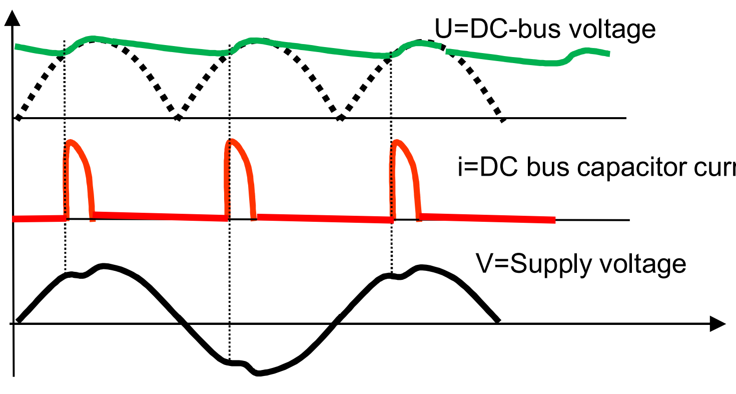


- *The **black** square wave can be "deconstructed" into sine waves (fundamental and harmonics).*
- *Similarly any non-sinusoidal signal can be " constructed" by adding sine waves (fundamental and harmonics). The more harmonics are taken into account, the better the non-linear signal is approximated (red vs **black**).*
- *The more the signal deviates from a sine wave, the more harmonics it will contain.*

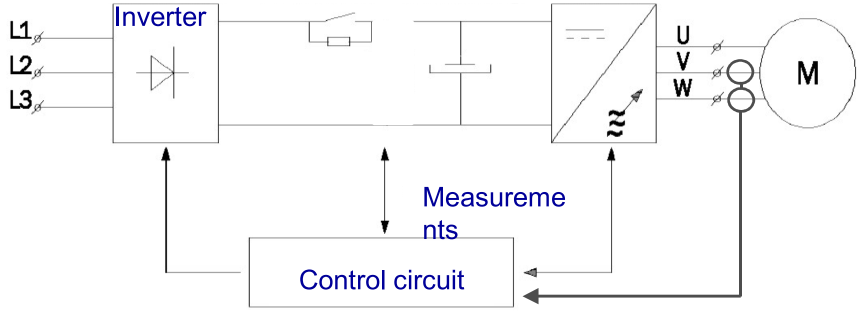
THD, Harmonics

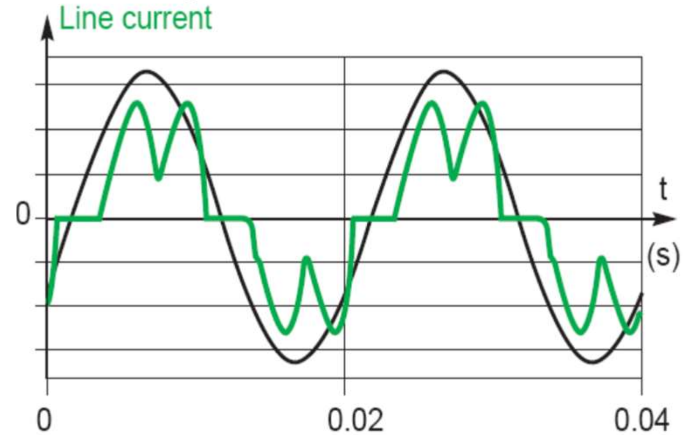
Example for input of a single phase AC drive





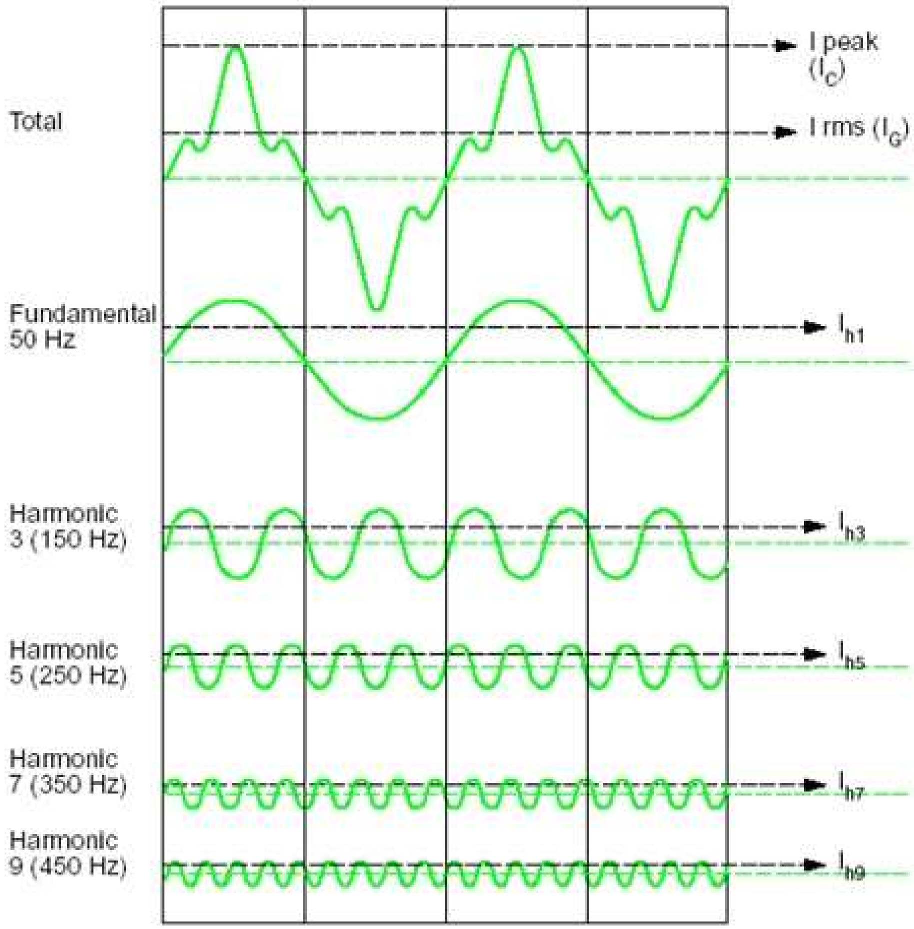
Example for input of a 3-phase AC drive





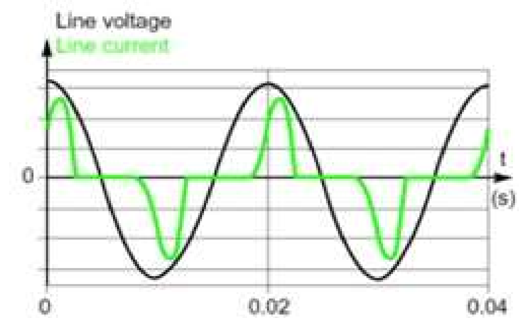
THD, Harmonics

Example for single phase AC drive without DC choke

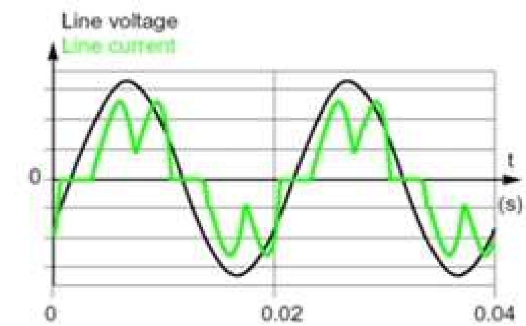


example of a current containing harmonics and expansion of the overall current into its harmonic orders 1 (fundamental), 3, 5, 7 and 9

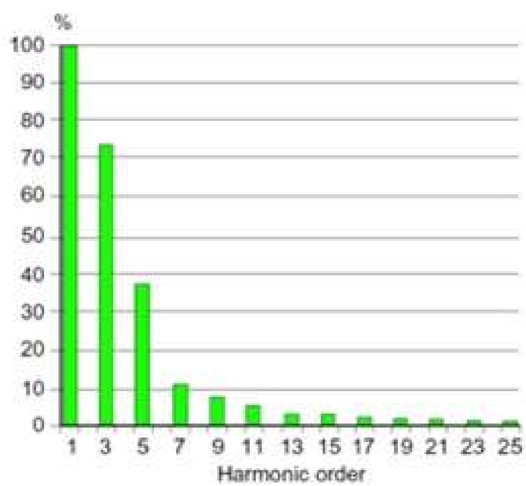
Example for inputs of single and three phase AC motor drive

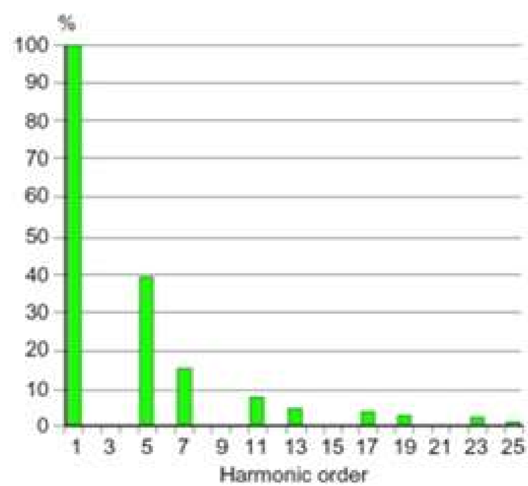


current drawn and phase voltage of the line supply (single-phase power supply).



current drawn and phase voltage of the line supply (3-phase supply).





THD, Harmonics

Power factor and THD

- The Power Factor $\cos\varphi$ is the ratio between Real Power P in kW and Apparent Power in kVA.

- Harmonics reduce the Power Factor

$$THDi = \frac{\sqrt{I_2^2+I_3^2+\cdots+I_n^2}}{I_1}$$

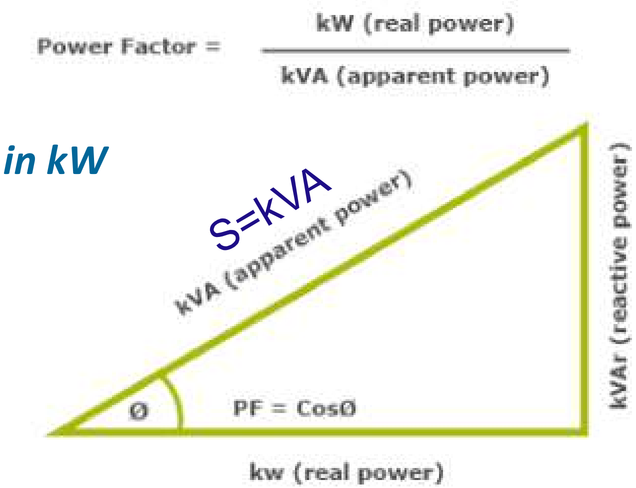
where I_n is n^{th} harmonic current, I_1 is fundamental current.

$$D = \frac{Cos\varphi}{\sqrt{1+THDi^2}}$$

In a 3-phase system:

$$P = U * I_{RMS} * \sqrt{3} * D$$

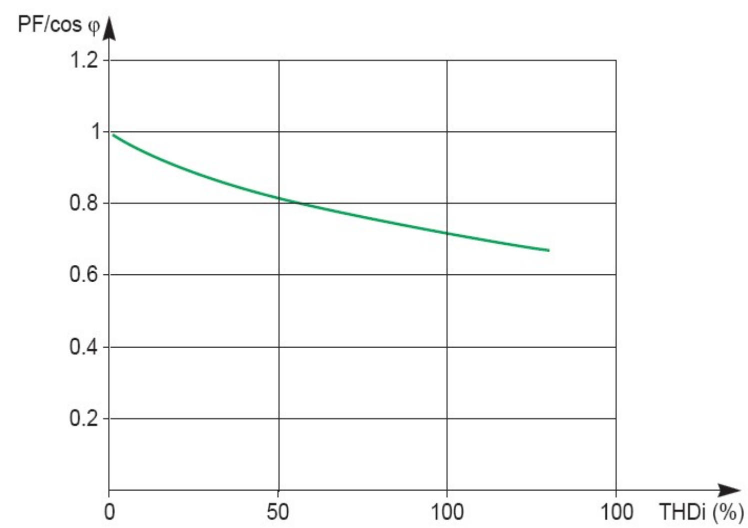
- If THDi = 0 (no harmonics) D=$\cos\varphi$.
- More harmonics (higher THDi) give lower D and thus lower Power.



S=kVA

Q=kVAR (nonwork producing)

P= kW (work producing)



THD, Harmonics

Calculation of I_{RMS} and THDi in % at 3-phase AC Motor Drive input

$$I_{RMS} = \sqrt{I_1^2 + I_2^2 + \cdots + I_n^2}$$

$$I_{RMS} = \sqrt{48^2 + 12.4^2 + 5.33^2 + 3.44^2 + 2.44^2 + 1.63^2 + 1.33^2}$$

$$I_{RMS} = 51A$$

$$THDi\% = \frac{\sqrt{I_2^2 + I_3^2 + \cdots + I_n^2}}{I_1} * 100\%$$

$$THDi\% = \frac{\sqrt{12.4^2 + 5.33^2 + 3.44^2 + 2.44^2 + 1.63^2 + 1.33^2}}{48} * 100\%$$

$$THDi\% = 30\%$$

Motor

Power [kW]	30
Current [A]	60
Frequency [Hz]	50

Mains

Voltage [V]	400
Current [A]	51
THD [% of I1]	30

Harmonics	Ih	Ih/I1
	[A]	[%]
I1	48.0	100.0
I5	12.4	25.8
I7	5.33	11.1
I11	3.44	7.2
I13	2.44	5.1
I17	1.63	3.4
I19	1.33	2.8
I23	0.989	2.1
I25	0.817	1.7
I29	0.627	1.3
I31	0.542	1.1
I37	0.351	0.7
I41	0.310	0.6

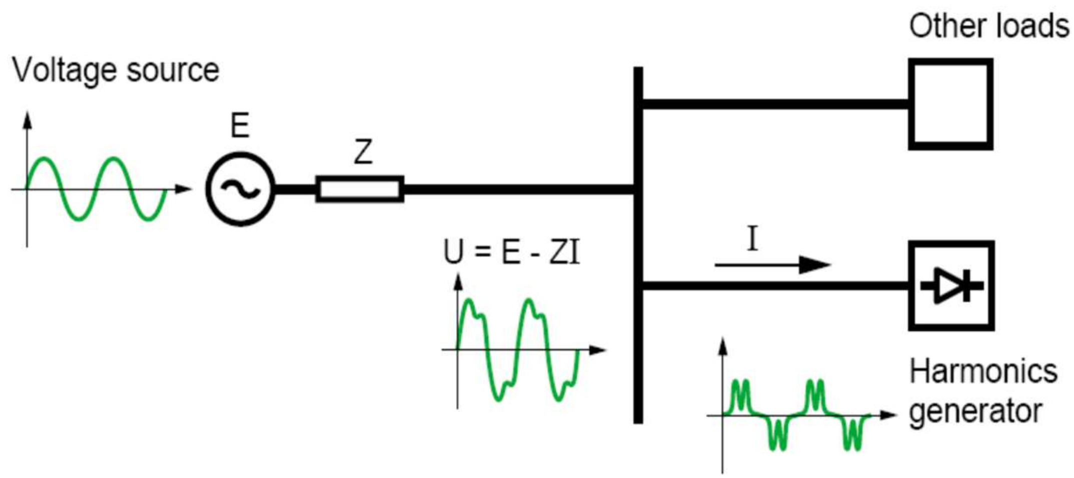
Measured values

THD, Harmonics

Voltage Total Harmonic Distortion THDU

- ***Harmonic currents distort the voltage.***
- ***Harmonic current and voltage are proportional.***
- ***High impedance gives high THDU values.***

$$U_{hn} = Z_{hn} \cdot I_{hn}$$



Things to remember

- *The RMS current with THDi overloads the transformer, cables and other components on the supply side.*
- *Voltage harmonics THDU can disturb sensitive equipment.*
- *The frequency of the harmonics can cause resonance in capacitor banks.*
- *Harmonic currents cause extra losses in cables and the mains transformer.*

- *The IEEE 519 standard mentions the total harmonic distortion at full load on the PCC (Point of Common Coupling).*
  In most cases the PCC is at the input of the mains transformer.

THD, Harmonics

Standards

There are two standards regarding AC drives and THD

- *IEC/EN 61800-3*
  International standard for Power drives system
  Reference to IEC61000-3-2, IEC61000-3-4 and IEC61000-3-12

	Residential directly connected onto the public network				Industrial MV/LV transformer
	Professional equipment		Non professional		
I line Drive	Standard	THDI	Standard	THDI	
<= 16A	IEC 61000-3-12	<=48%	IEC 61000-3-2	<5%	No requirement
16A < I <= 75A	IEC 61000-3-12	<=48%	IEC 61000-3-12	<=48%	No requirement
>=75A	IEC 61000-3-4	<=48%	IEC 61000-3-4	<=48%	No requirement

- *IEEE 519*
  Recommended and required THD control in Electrical Power Systems

Low-Voltage System Classification and Distortion Limits

	Special Applications[1]	General System	Dedicated System[2]
THD (voltage)	3%	5%	10%

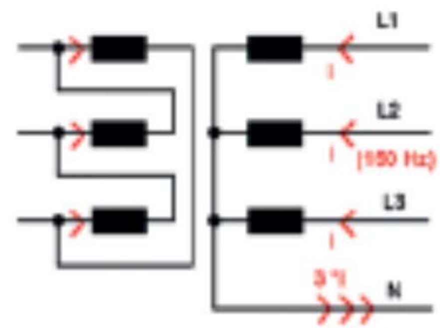
1 Special applications include hospitals and airports
2 A dedicated system is exclusively dedicated to the converter load

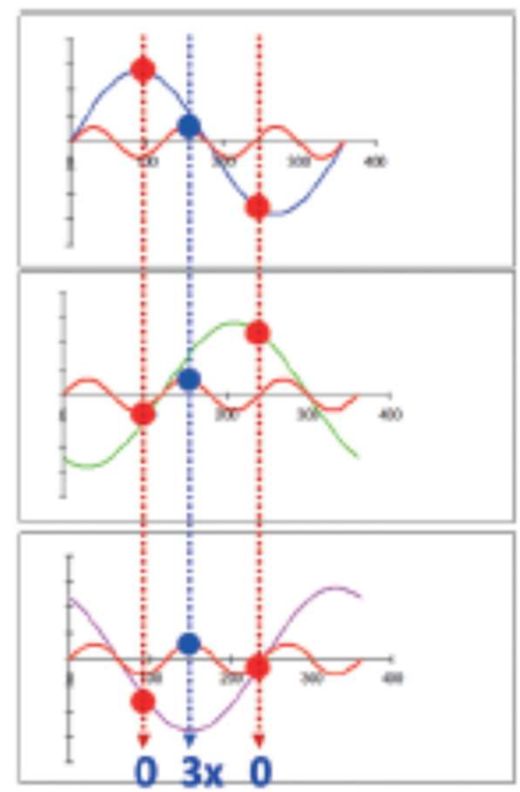
Effects of harmonic distortion.

- *Overload of the neutral.*

  Example:
  Many switched mode power supplies (lighting) on a 3 phase mains net with neutral. The 3rd harmonic is large.
  The sum of the fundamental currents in neutral are 0 at any moment, provided the phase currents are equal.
  The sum of the 3rd harmonic is not zero and much larger than expected.

  Example:
  The fundamental current in each phase is 10A.
  The 3rd harmonic current in each phase is 60% (= 6A).
  That means in the neutral a current of 18A!
  This applies also to multiple of the 3rd harmonic (9, 15, 21 etc.)





Effects of harmonic distortion.

- ***Unexpected tripping of safety devices.***
  Devices are calculated on the actual power.
  Harmonics cause distortion of the reactive power (heats up bimetals in safety devices.)

- ***Overloading cables.***
  - ***Extra reactive power → extra heat losses in the cable.***
  - ***Skin effect: High frequency currents become distributed to the surface of the wire, reducing the available wire section and increasing the effective resistance.***
    This results in higher heat losses .

Effects of harmonic distortion.

- ***Overloading transformers***
  - More copper and Eddy current losses ➔ more heat
  - Also skin effect in the windings.
  - De-rating transformers, can be used till 85% of the rated power, so bigger transformers needed.

- ***Overloading capacitors (in capacitor banks)***
  Lower impedance at higher frequencies ($Z_C = {}^{1}/_{2\pi f C}$) causing higher currents.

- ***Extra heating up of DOL motors***
  - Higher Eddy currents
  - Higher harmonics voltage ➔ different speed (or direction)

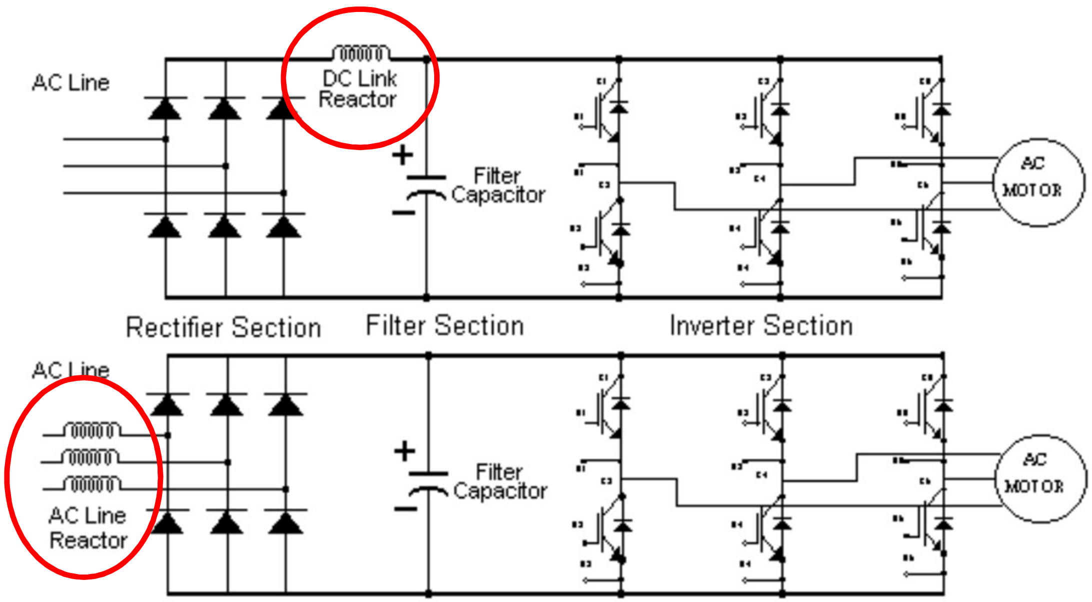
Solutions to reduce harmonics in drives:

- AC or DC reactors
- Multi pulse rectifiers
- Passive filtering
- Active filtering
- Active Front End (AFE)

THD, Harmonics

DC or AC reactor

An AC drive, fitted with a 6-diode full wave rectifier, feeding an uncontrolled DC link capacitor, will generate no even or triple harmonics, only odd harmonics from the 5th upwards.
The magnitude depends on the internal impedance of the system. By adding AC or DC reactors with higher impedance at higher (harmonics!) frequencies, the magnitude of the harmonics is reduced.



- ***Without DC and AC reactors, THDi=80% approximately.***
- ***With DC or AC reactor, THDi= 30-40%, depending on the reactor impedance (proportional to mH inductance).***

THD, Harmonics

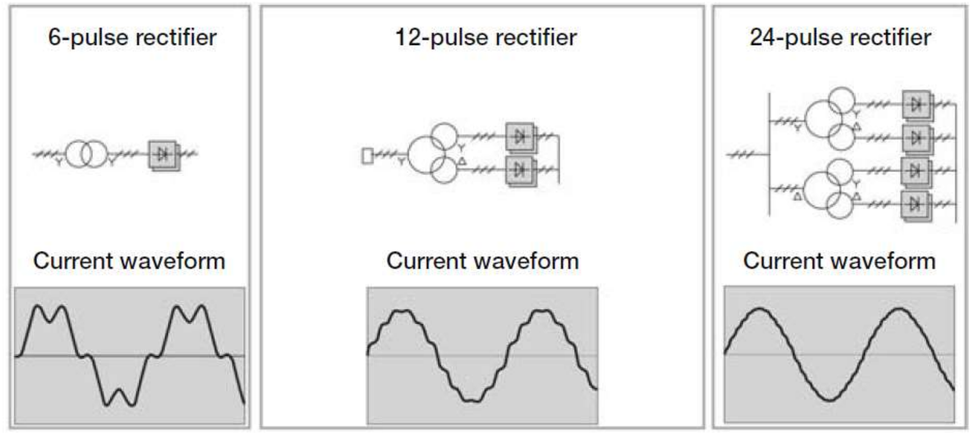
Multi pulse rectifiers

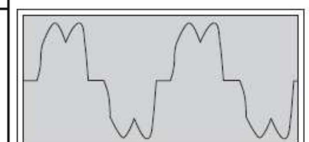
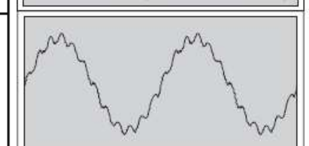
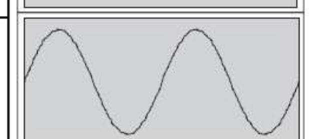
Harmonic migration by phase shifting between bridges.

Phase shifting is done in the secondary windings of the transformer (more expensive!).

The phase shift angle between each secondary winding is 360°/number of rectifier pulses.

Multi-pulse rectifiers generate only odd harmonics from (n-1) upwards (n= pulse number)



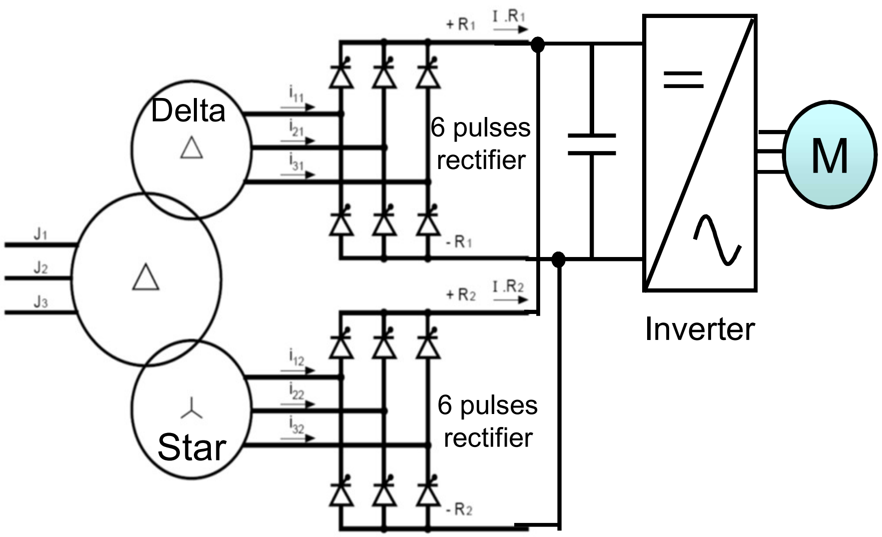
Supply type	Current TDH (%)	Voltage TDH (%) RSC=20	Voltage TDH (%) RSC=100	Current waveform
6-pulse rectifier	30	10	2	
12-pulse rectifier	10	6	1.2	
IGBT supply unit	4	8	1.8	

Distortion is in% of RMS values

THD, Harmonics

12 pulse rectifier

- The transformer must have a phase shift angle of 30° between the two secondary transformer windings.
- This topology creates a phase shift between the 5^{th} and 7^{th} harmonic, and they level each other out
- THDi value approx. 12%

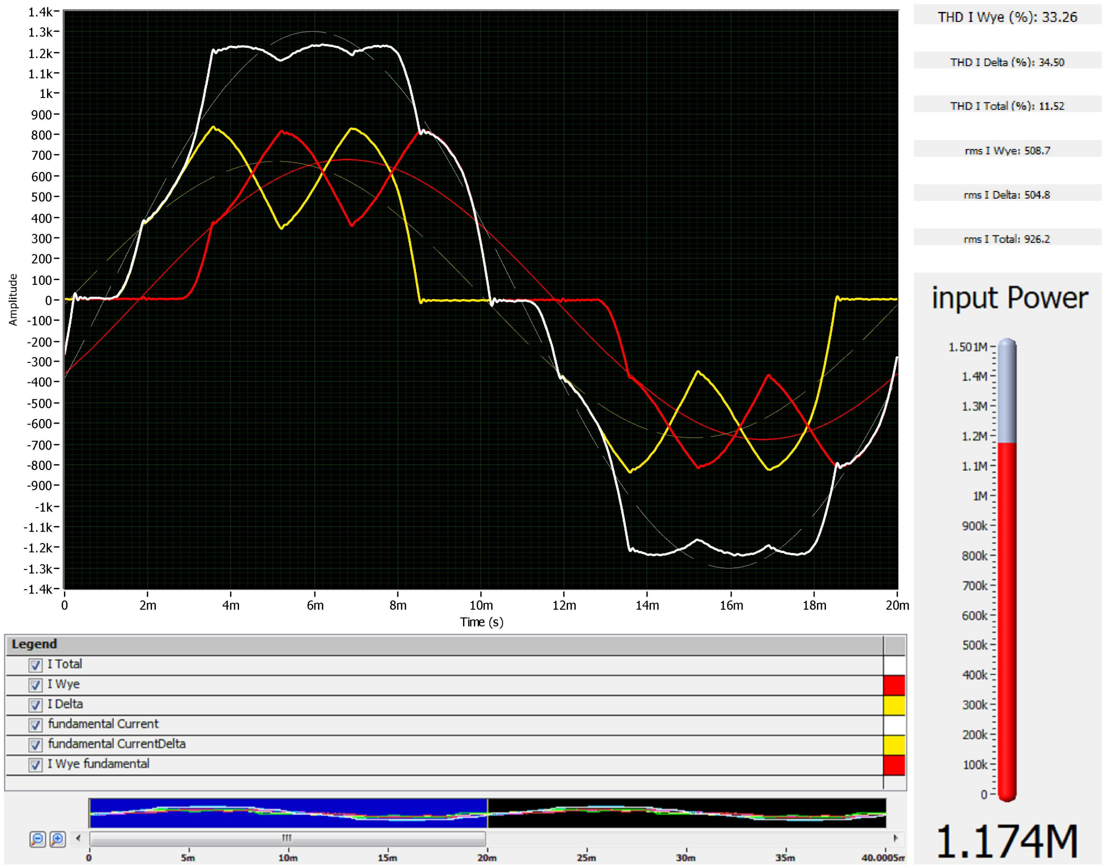


Delta drives:

12 pulse rectifier only possible in C/CP2000 Frame G & H, because these drives have standard double diode bridges at the input.

THD, Harmonics

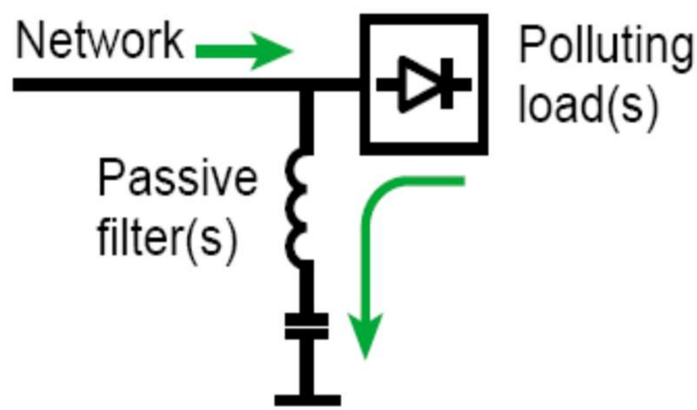
Example:12 pulse supply, THDi value approx. 12 %



- **THD I Star 33.26%**
- **THD I Delta 34.50%**
- **THD I total 11.52%**
- **I_{RMS} Star 509A (red)**
- **I_{RMS} Delta 505A (yellow)**
- **$I_{RMS, total}$ 926A (white)**

Passive filtering

- *Calculated acc. to drive power and current.*
- *These kind of filters are designed for frequency drives to significantly lower the 5th and the 7th harmonic.*
- *There is a little distortion at the input and a significant amount of current and voltage distortion at the output stage of this filter.*
- *Can only be used with non-linear loads.*
- *Voltage boosting will occur under no load conditions due the presence of shunt capacitors and reactors.*

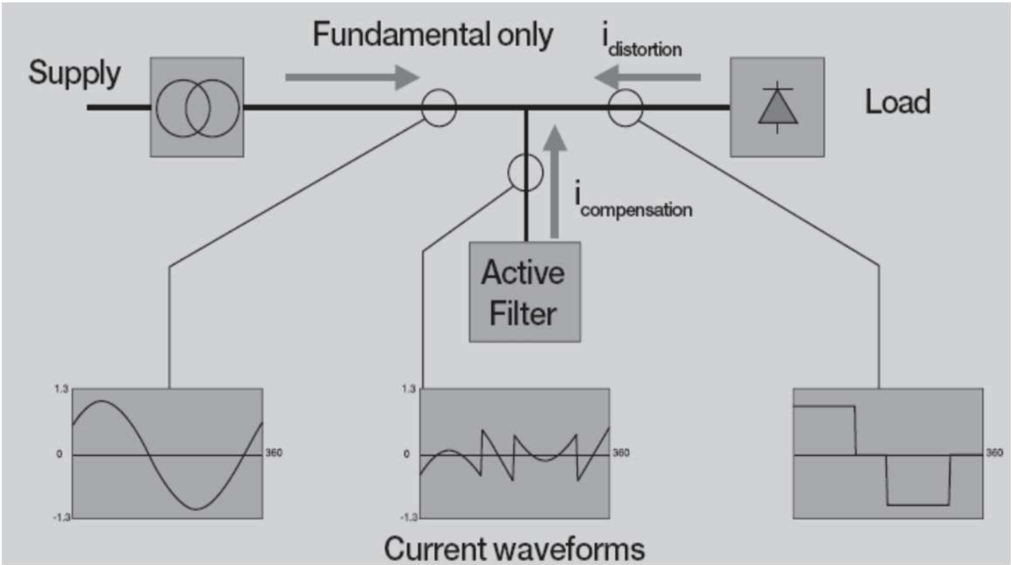


- *THDi value approx. 5-16 % at full load (THDi filtering depending on load)*

Active filtering

An active filter monitors the load currents of a system, filters out the fundamental frequency, analyzes the harmonic frequencies and their magnitude and injects the appropriate inverse currents to cancel the individual harmonics.
Active filters will normally cancel harmonics up to the 50th harmonic.

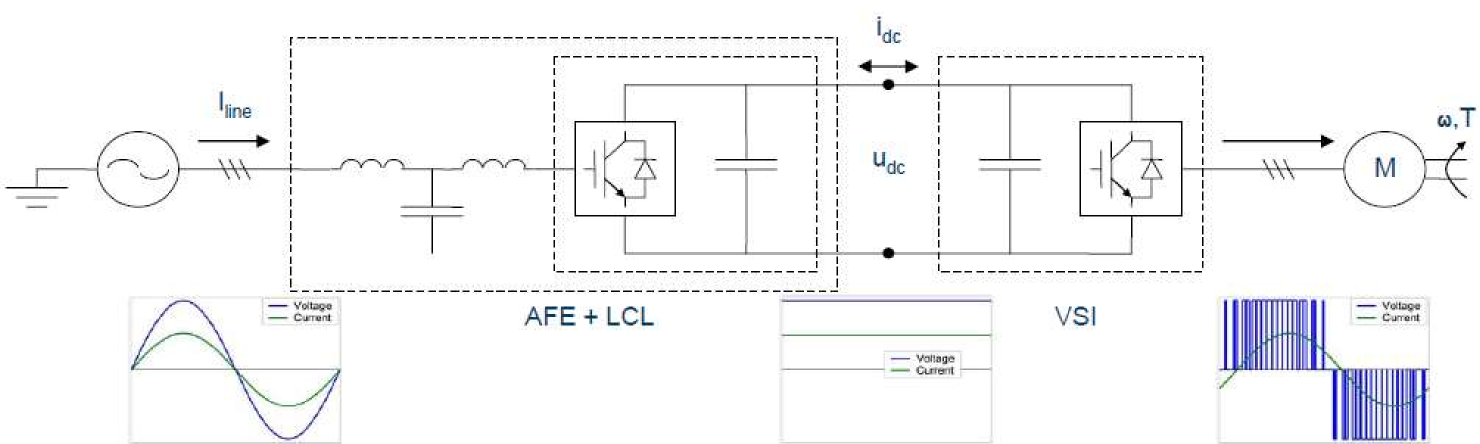
THDi value approx. 5 % or less



Active Front End

Has IGBTs at the input, with a passive filter against higher harmonics in the current and voltage.
The input current waveform will be monitored and re-shaped to a sinusoidal form by active control of the input IGBTs.

THDi value < 5 %



THD, Harmonics

Summary

Solutions	Reactor 4%	Passive filter	12 pulse	Active front end	Active filter
Current distortion THDI	**<30%-35%**	**<5%-16%**	**<5%-10%**	**<5%**	**<5%**
Meet IEEE519 gen. app.	to be evaluated	yes	yes (18p)	yes	yes
Meet IEC 61000 3-12	yes	yes	yes	yes	yes
Meet IEC 61000 3-2	no	no	no	yes	yes
Drop voltage	yes	yes	no	yes	no
Power factor no/full load	0.75-0.95	0.75-1	0.90-0.99	0.8-1	0.90-0.99
Load influence on THDI	yes	yes	no	no	no
Efficiency	97%	98%	96%	96%	96%
Reliabilty	High	Good	High	Medium	Medium
EMC	Good	Good	Good	Poor	Medium
Influence on VSD perf.	weak	no	no	no	no
Resonance risk	weak	yes	no	no	no
Cost effectiveness	good	<100kW	>400kW	If regen needed	for installation
Price ratio /drive cost	100%	150%-200%	200%-250%	250%	250%
Foot print ration/drive	100%	200%	200%	200%-250%	200%

Delta Power Quality Solutions

THD, Harmonics

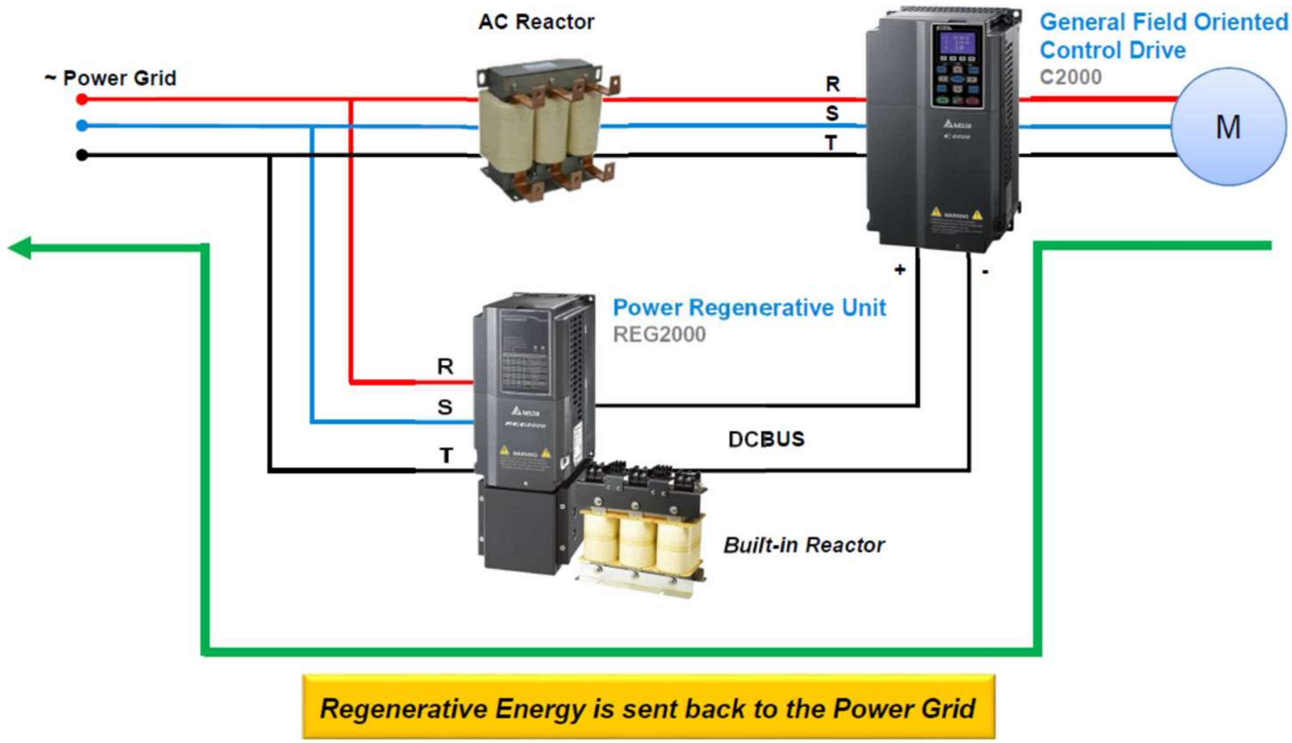
Power Regenerative unit (REG2000)

Replaces traditional brake resistors and provides power regeneration functions.

- *Compact design, easy to install. (Reactor included)*
- *Replaces traditional brake resistors, energy savings*
- *Improves motor braking capability.*
- *Modbus RS485 communication monitors kWh and cost in real-time*
- *Compatible with DC-bus of inverters and servo drives*
- *Parallel (max 4 units) connection possible for larger powers.*
- *Communication option cards available: Modbus TCP, CANopen, Profibus, Devicenet, Ethernet IP*

THD, Harmonics

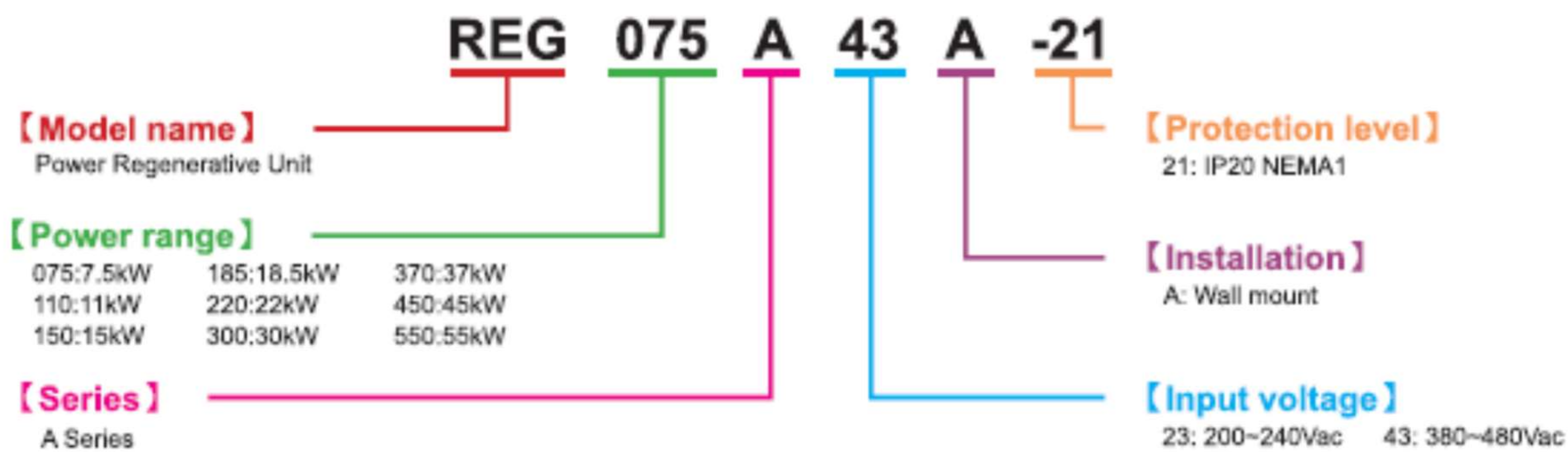
Power Regenerative unit (REG2000)



THD, Harmonics

Power Regenerative unit (REG2000)

Model Name



THD, Harmonics

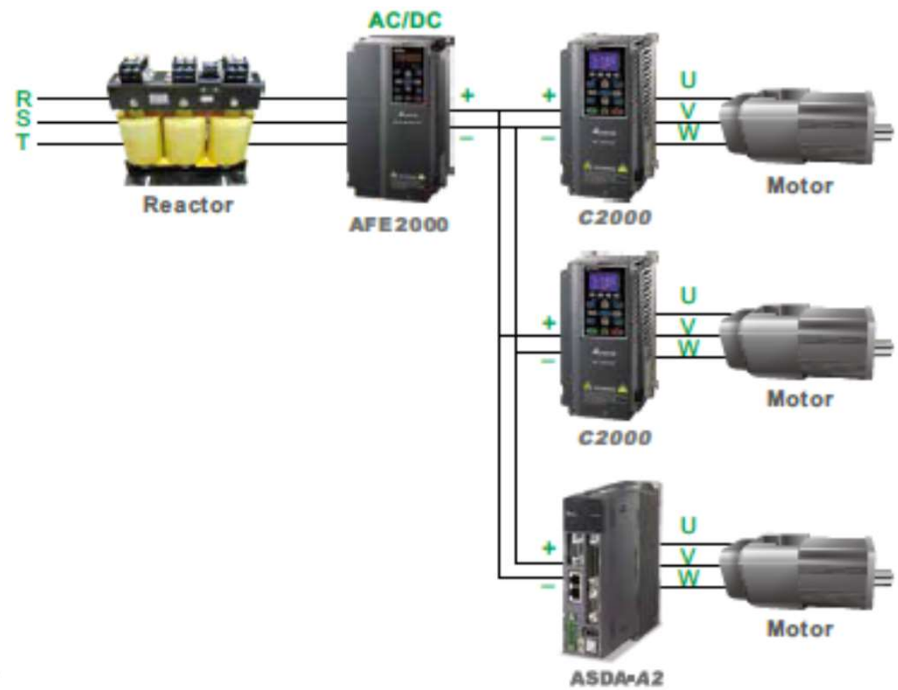
Active Front End

- Controlled rectifier with IGBTs
- Power exchange between AC and DC and regenerating re-usable energy to the mains.
- Power factor is corrected up to 1
- AFE eliminates high order harmonics, THDI < 5%
- Output connectable to multiple frequency drives.
- Option input reactor mandatory.

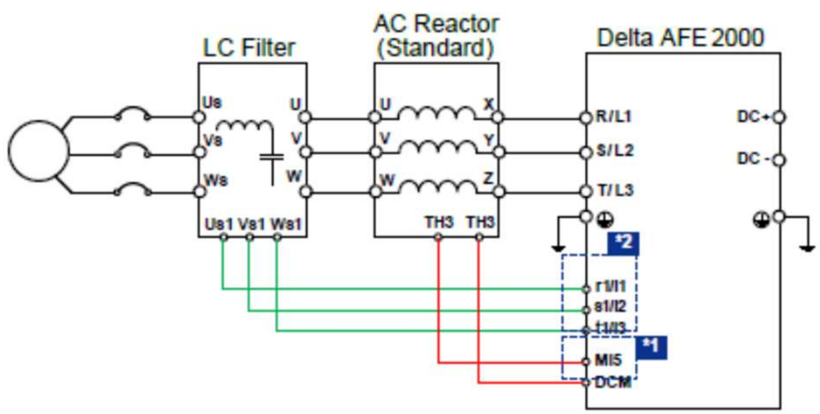
Active Front End (AFE2000)

AFE with one Frequency drive

AFE with multiple Frequency drives

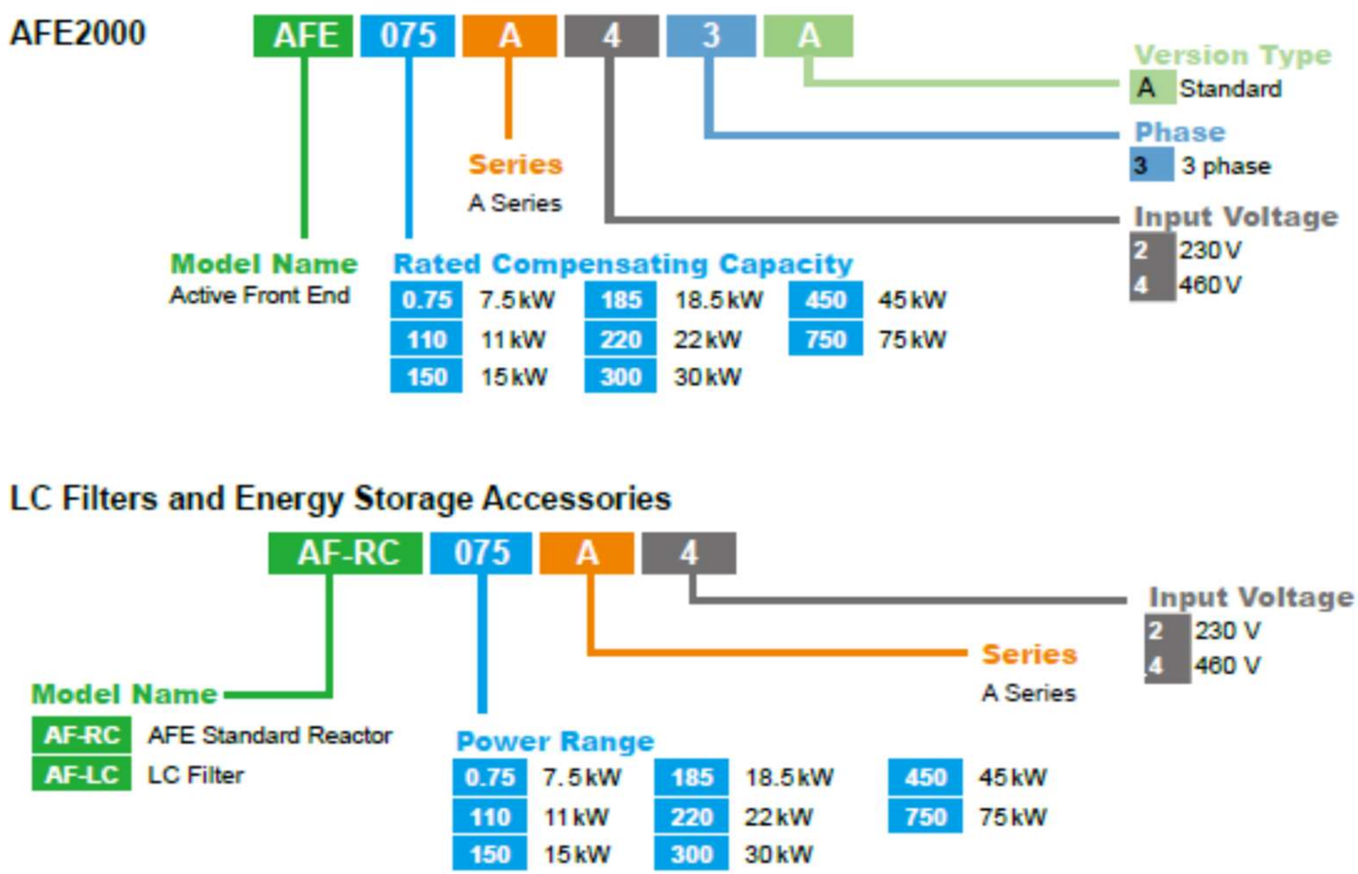


Solutions with additional LC filter



Active Front End (AFE2000)

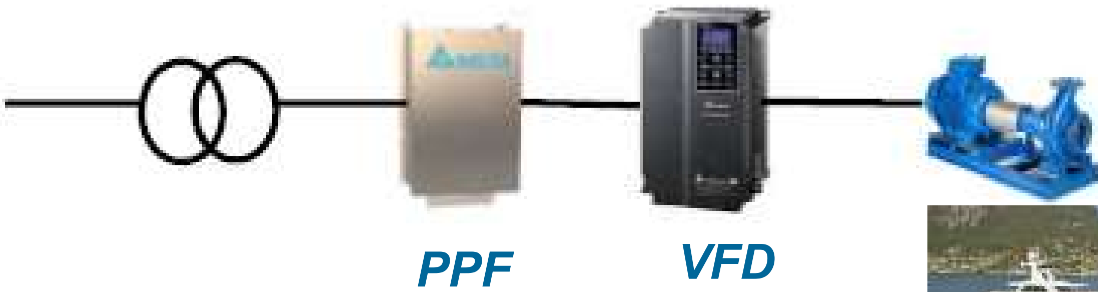
Model Name

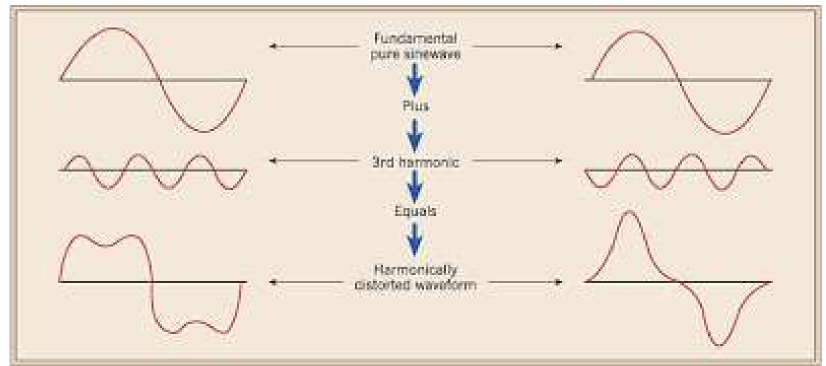


THD, Harmonics

Passive Power Filter (PPF)

PPF with one Frequency drive.

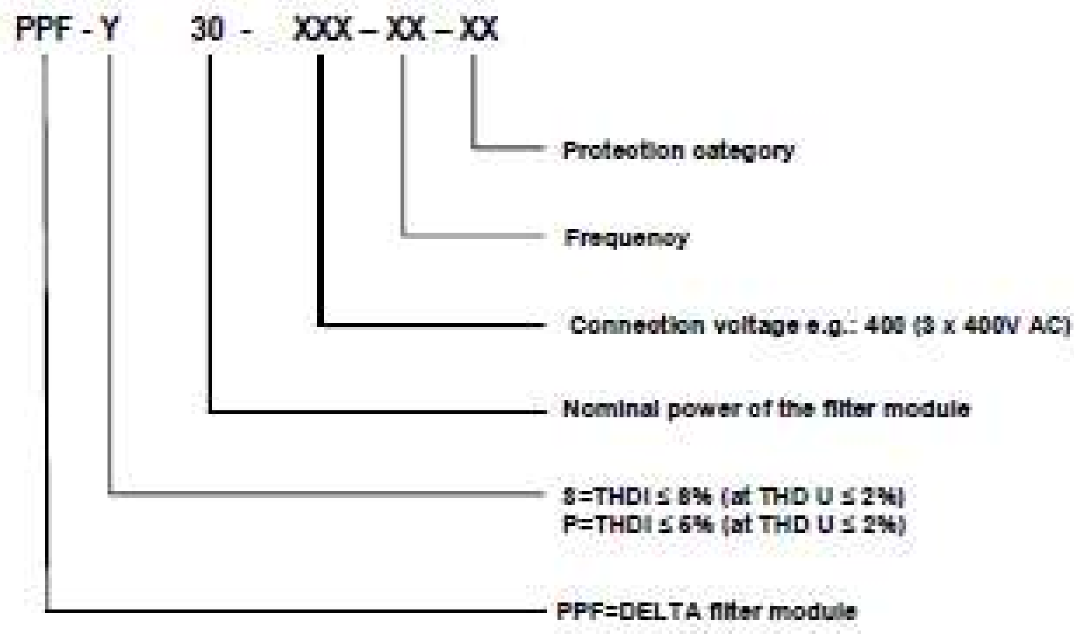




Also possible to combine one filter with more drives.

THD, Harmonics

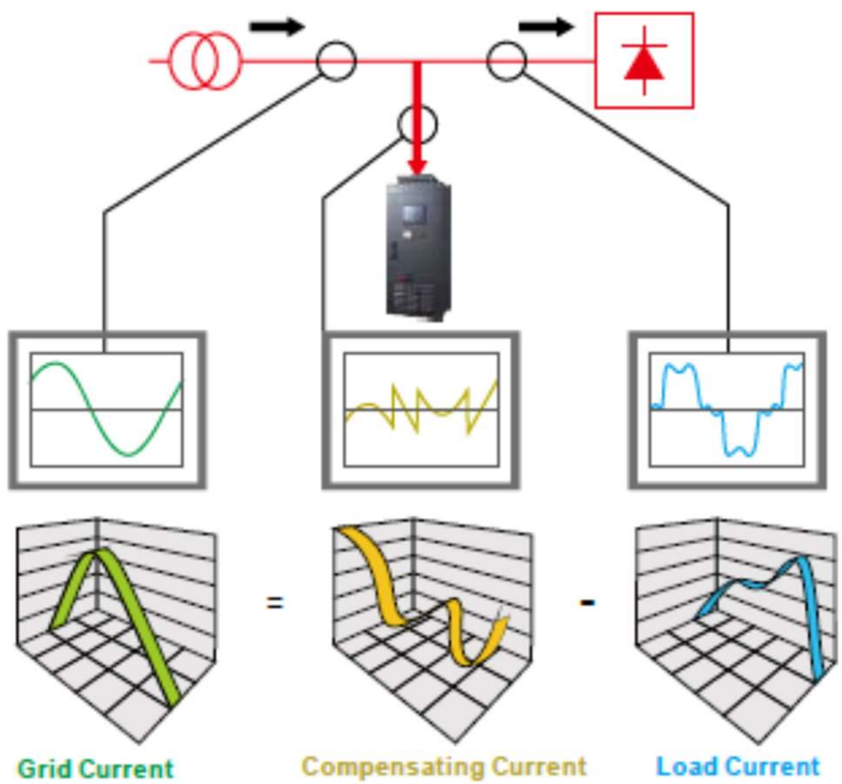
Passive Power Filter (PPF)



The PPF reduces the distortion of the mains current to a THDi significantly below 5% (PPF-P) or <8% (PPF-S) for a drive with DC reactor.

THD, Harmonics

Active Power Filter (APF2000)



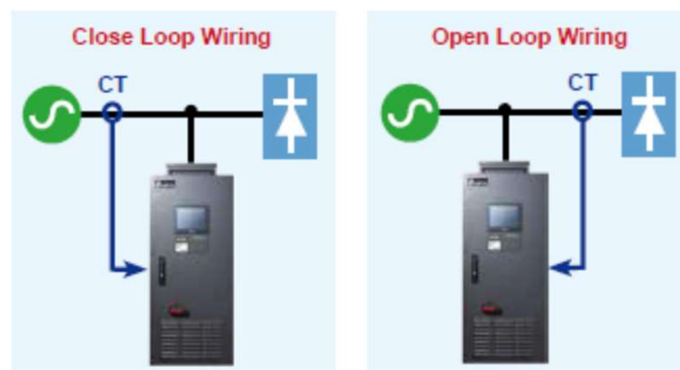
Compensation to Current, Harmonics and Power Factor

Features	Harmonics Compensation	Reactive Power Compensation	Note
Full Compensation			Under all operation modes, the "Unbalanced Compensation" functions compensate unbalanced loads[*1]
Harmonic Compensation			
Reactive Power Compensation			

Compensation priority: ▬ > ▬; No Compensation: ▬

*1 Verified derating ratio for different unbalanced loads.
Please contact technical engineers of Delta or distributors in your region.

Connection possibilities



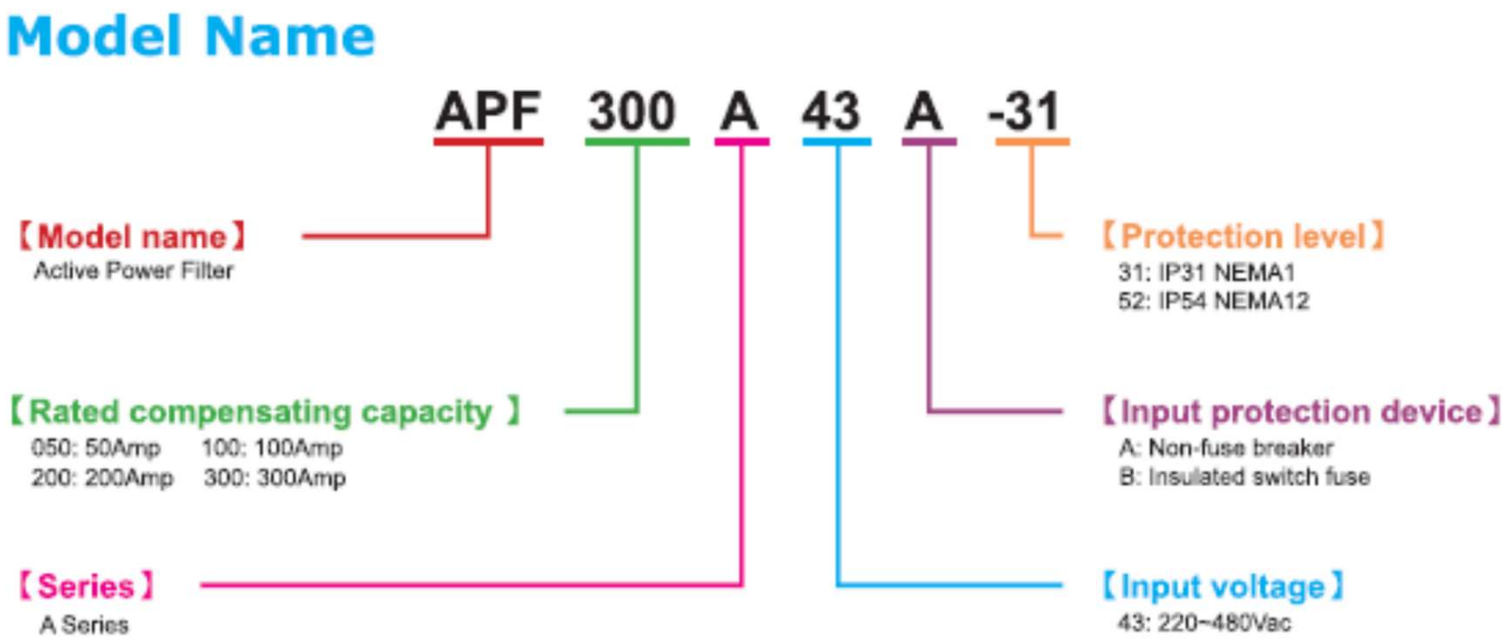
THD, Harmonics

Active Power Filter (APF2000)

- ***For cleaning the grid at connection point***
- ***Reduces voltage and current distortion, harmonic compensation till the 50th harmonic.***
- ***Unbalanced loads and reactive power compensation***
- ***Fast response time***
- ***Parallel connection possible for larger powers up till 6 units.***
- ***Communication option cards available: Modbus TCP, CANopen, Profibus, Devicenet,***

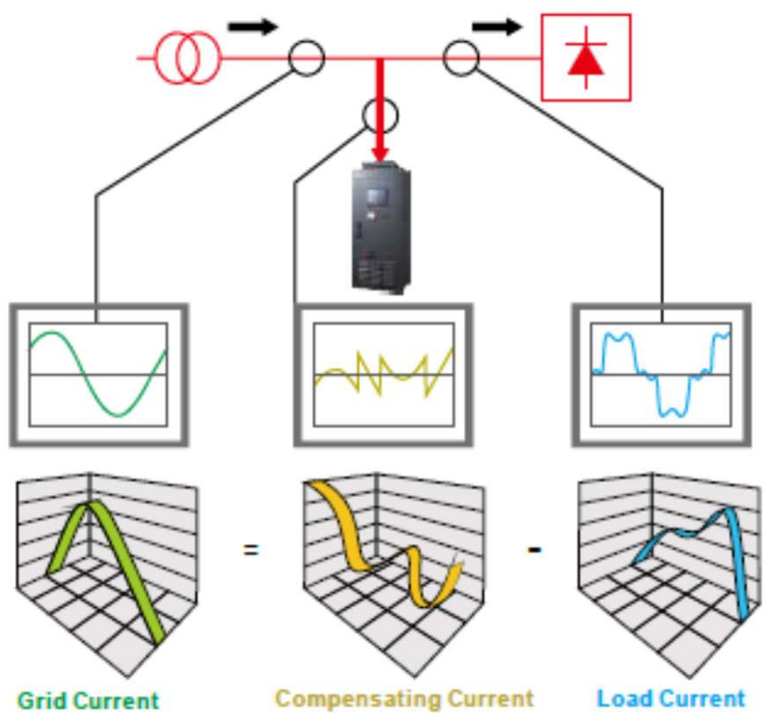
THD, Harmonics

Active Power Filter (APF2000)



Static Var Generator (SVG2000)

THD, Harmonics

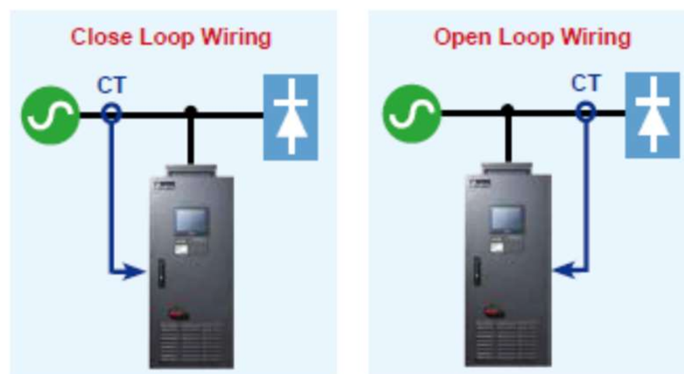


Compensation to Current, Harmonics and Power Factor

Features	Harmonics Compensation	Reactive Power Compensation	Note
Full Compensation	■ (green)	■ (dark green)	Under all operation modes, the "Unbalanced Compensation" functions compensate unbalanced loads[*1]
Harmonic Compensation	■ (dark green)	(no compensation)	
Reactive Power Compensation	(no compensation)	■ (dark green)	

Compensation priority: ■ (dark green) > ■ (green) ; No Compensation: ■ (light)

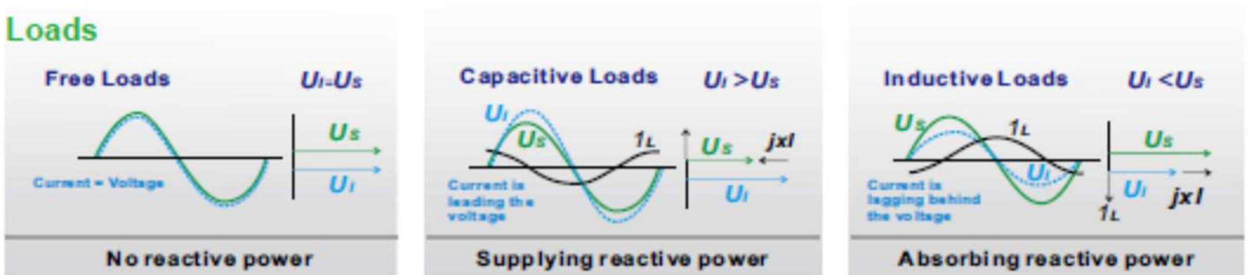
*1 Verified derating ratio for different unbalanced loads.
Please contact technical engineers of Delta or distributors in your region.



THD, Harmonics

Static Var Generator (SVG2000)

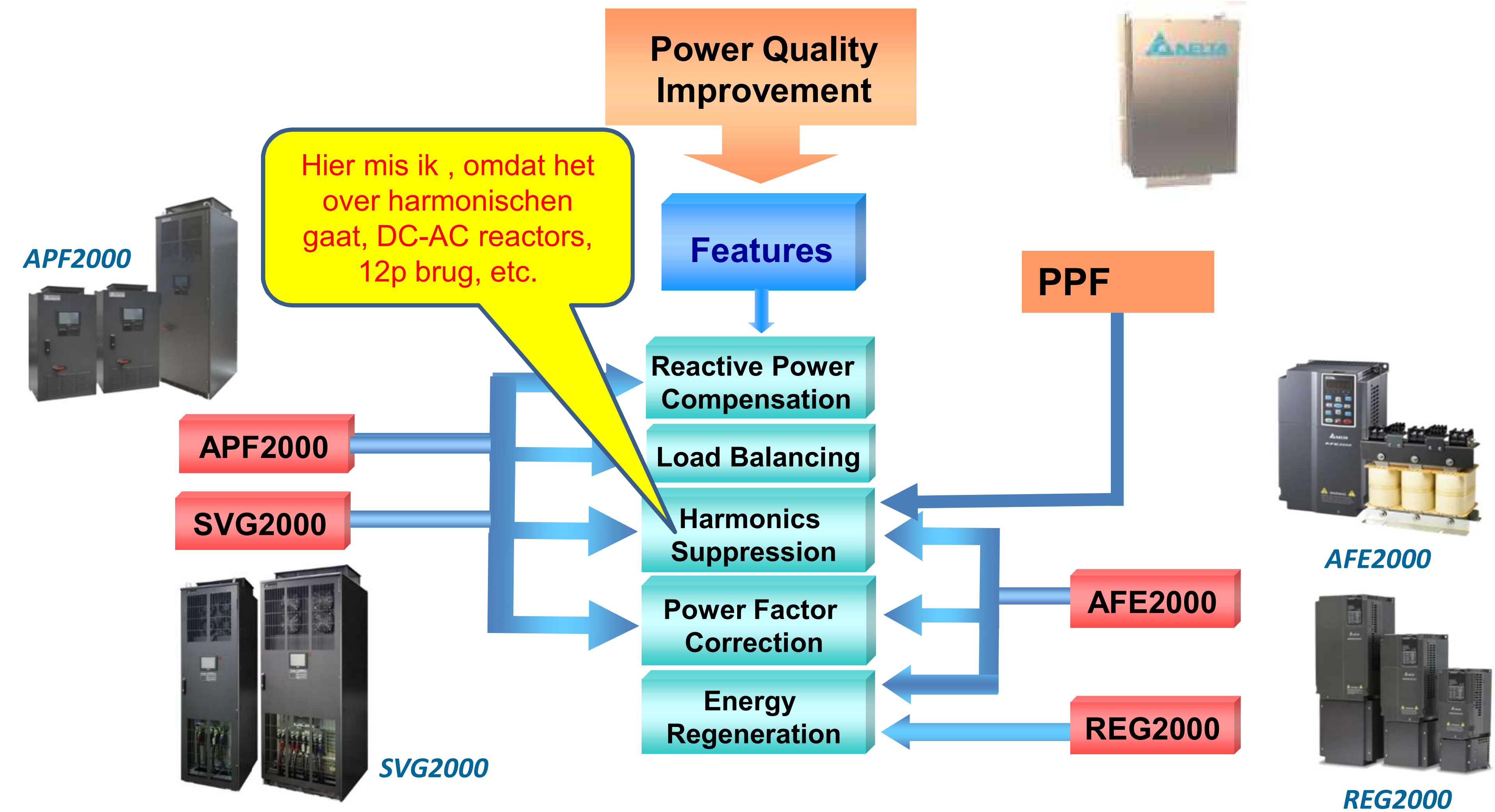
- *For compensating reactive powers on the grid*
- *Replaces traditional capacitor bank and LC filters*
- *Reduces current distortion, harmonic compensation till the 13th harmonic. (Only have 30% capacity to deal with the harmonic current)*
- *Unbalanced loads compensation*
- *Fast response time*
- *Modular design*
- *Parallel connections possible for larger powers up till 6 pcs.*
- *Communication option cards available: Modbus, Modbus TCP, CANopen, Profibus, Devicenet,*



Static Var Generator (SVG2000)

THD, Harmonics

Power Quality Improvement



Thank you

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