System Control and Power Quality in LVDC

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Contents

DC in Netherlands

Building and creating a serials of DC systems for industrial application

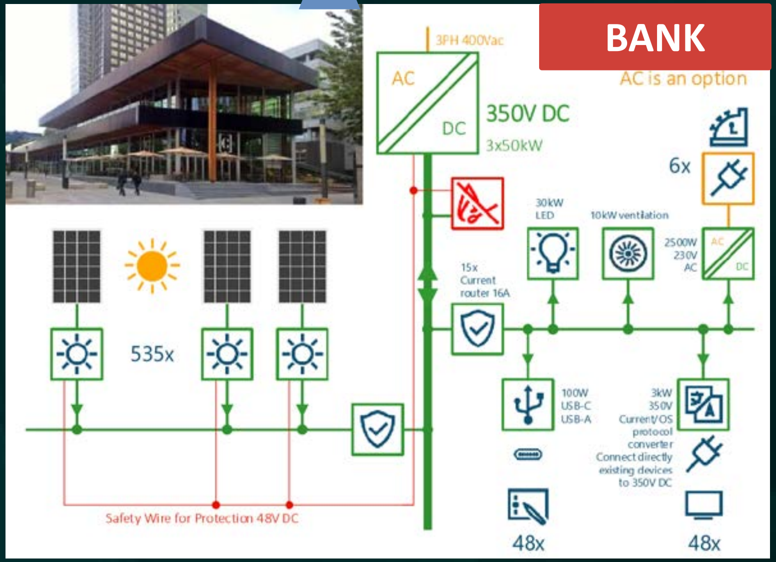
- For 350V and 700V DC grids
- In the range from 6kW … 1MW
- R&D on Safety, Protection, system dynamics, infrastructure, negative side effects, business cases, power electronics
- Buildings, Outdoor services, Distribution Grids, Greenhouses

HOUSE USE

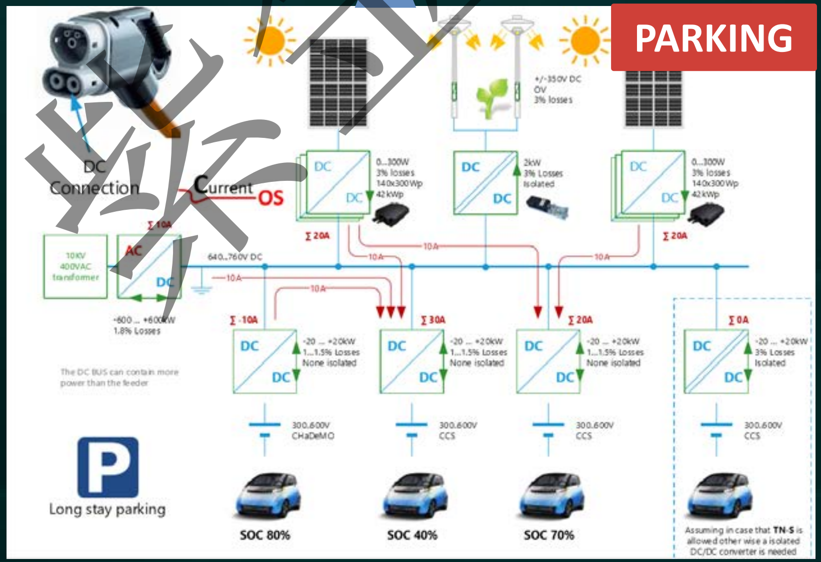
COMMERCIAL USE

PUBLIC USE

BANK



PARKING



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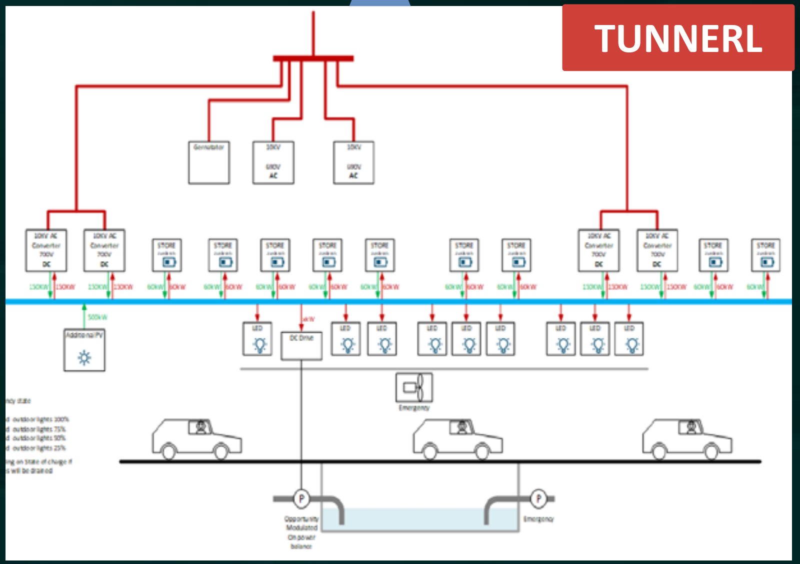
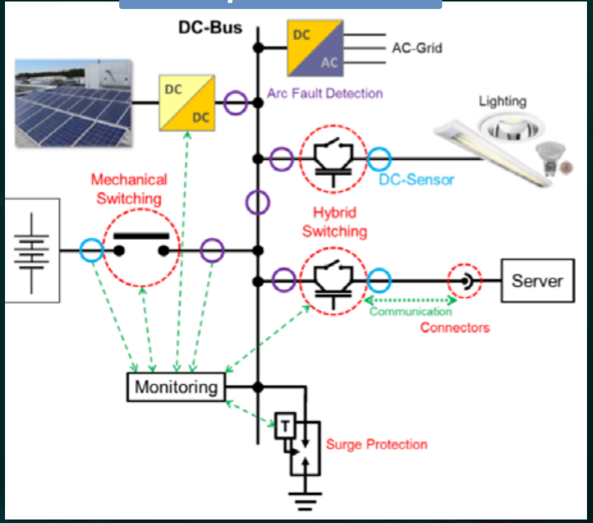


DC in Germany

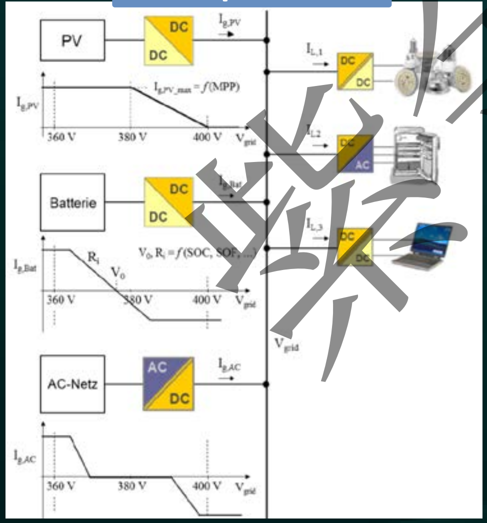
Building application platform for LVDC systems

- New protection strategies and solutions that couple smart markets with the physical system
- Design modular topologies for meshed dc distribution smart grids (±380V / ±750V)
- Create models and intelligent algorithms for congestion management and autonomous operation

DC protection



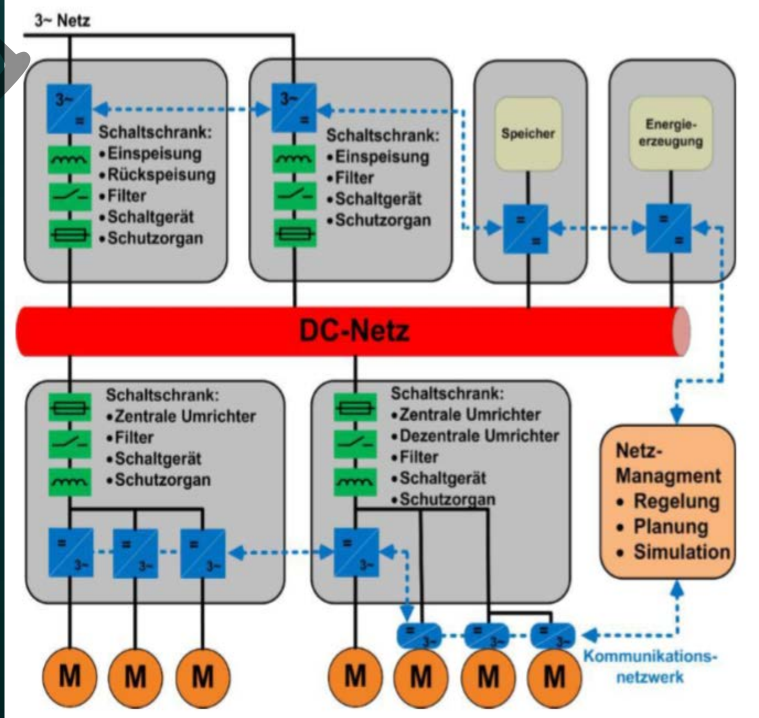
Droop control



Power Module

Research field

DC INDUSTRIAL BMWi Research Project



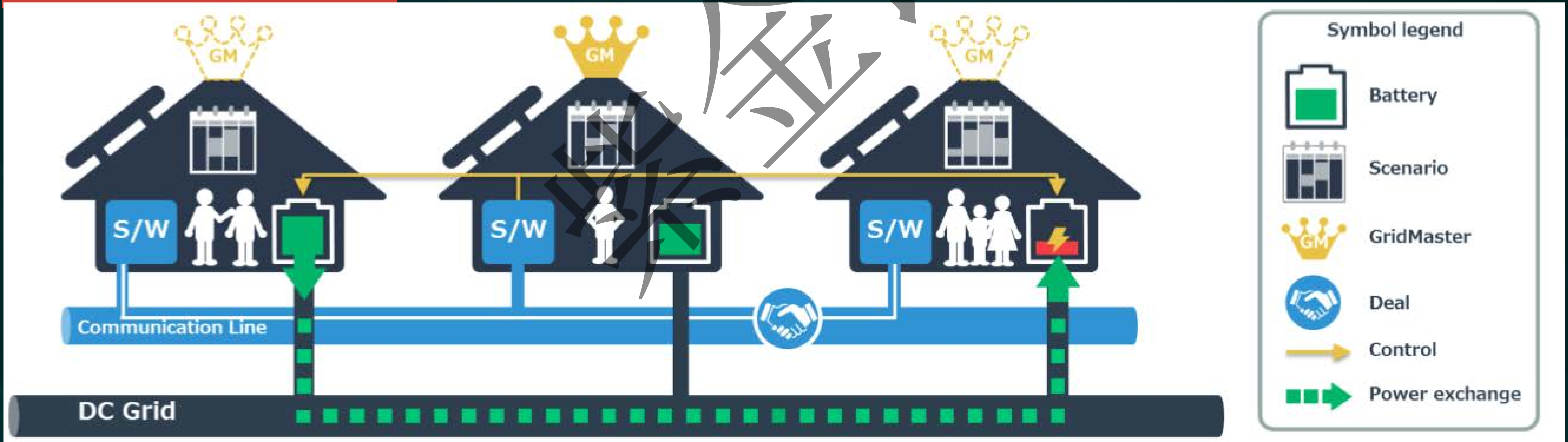
- 👍 Increasing industrial plant energy efficiency by **10 %**
- 👍 Reducing cost for devices up to **20 %**

DC in Japan

Pure P2P energy sharing technology

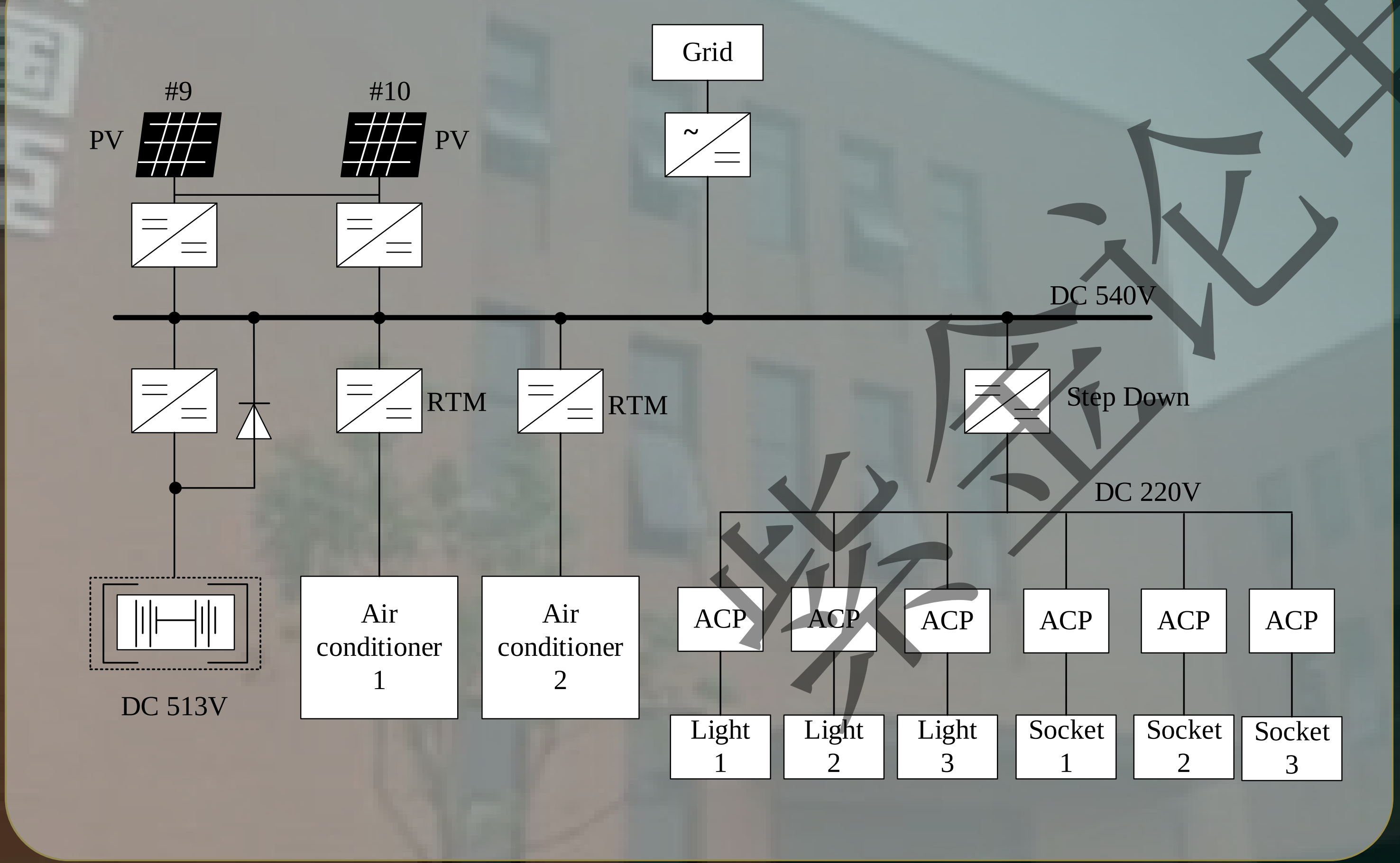
- Installed bi-directional P2P energy exchange function.
- Realized that each node can be a power provider or a power user.
- Enabled multiple energy exchanges activity between nodes by sharing DC bus.
- Bi-directional DC-DC converter and ACU (Autonomous Control Unit) are connected through standardized I/F(RS-485 or CAN) to the battery system.

PureP2P energy exchange



DC in China

Golden cooperate LVDC building

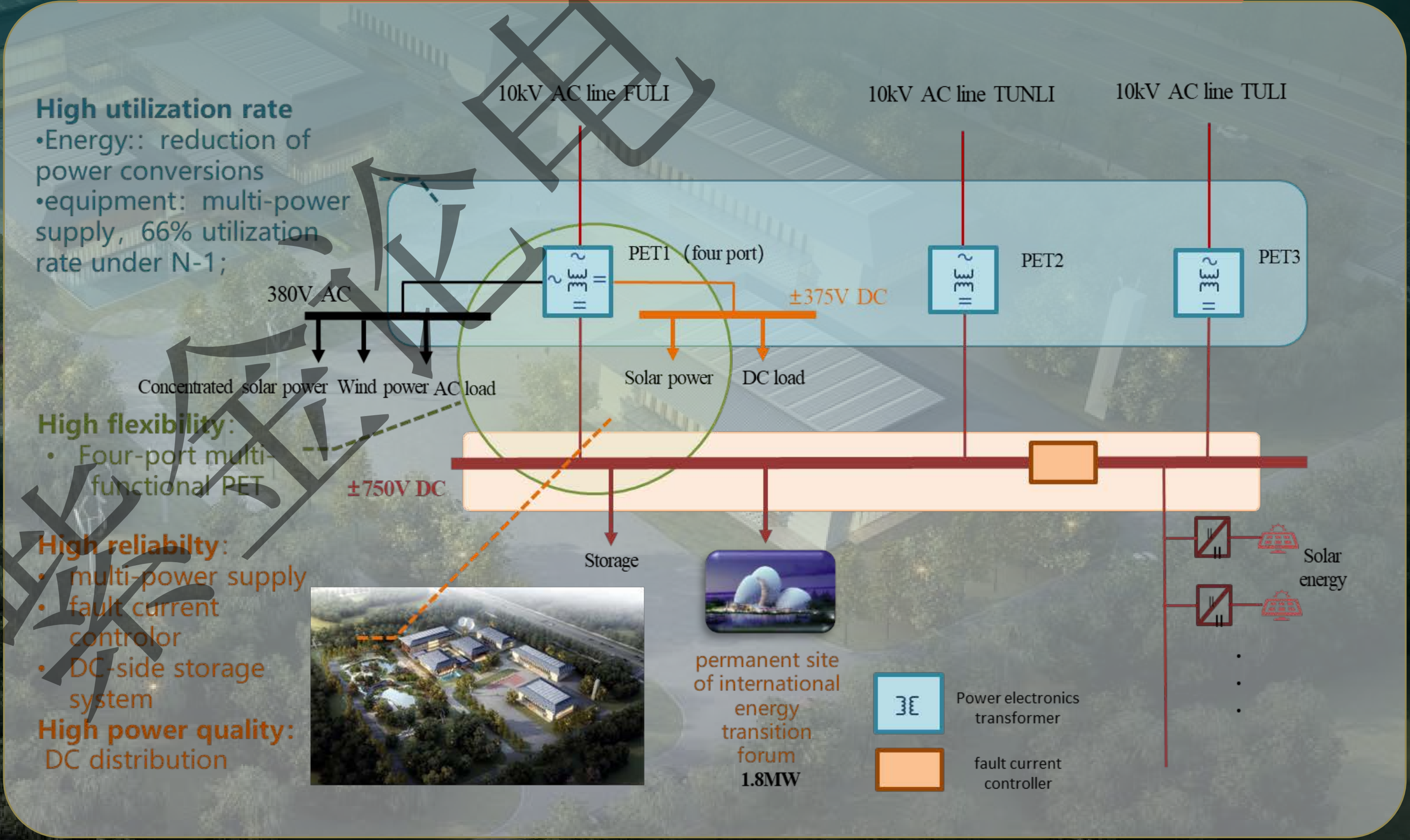


- **Configuration**
  - 600V all DC system
  - Air conditioners
- **Function**
  - Test for typical DC appliances in DC buildings.
  - Protection equipment and control strategy research
  - Power quality research in DC grid

DC in China

- **Function**
  - Research of flexible converter
  - Protection equipment and control strategy research
  - Operation study of DC load
- **Configuration**
  - Four-port multi-functional PET
  - DC-side storage system

National Key Project: Suzhou Tongli renewable energy town



High utilization rate
•Energy:: reduction of power conversions
•equipment: multi-power supply, 66% utilization rate under N-1;

High flexibility:
- Four-port multi-functional PET

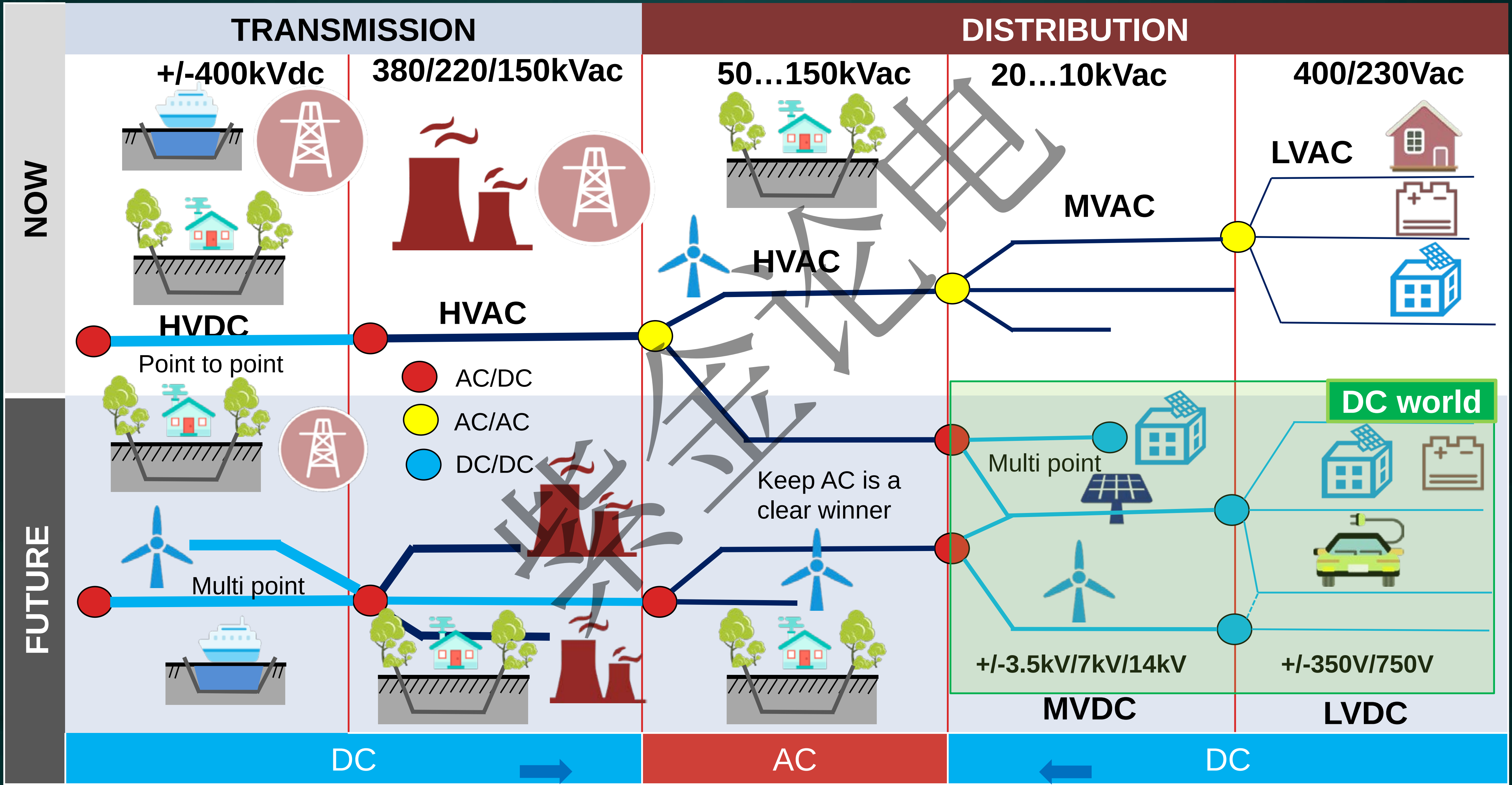
High reliabilty:
- multi-power supply
- fault current controlor
- DC-side storage system

High power quality:
DC distribution

permanent site of international energy transition forum

2017-2020 National key research project《AC / DC hybrid renewable energy technology based on power electronic transformer》

Transition is happening…



TRANSMISSION

DISTRIBUTION

NOW

FUTURE

+/-400kVdc

380/220/150kVac

50…150kVac

20…10kVac

400/230Vac

HVDC

Point to point

HVAC

HVAC

MVAC

LVAC

● AC/DC

● AC/AC

● DC/DC

Multi point

Keep AC is a clear winner

DC world

Multi point

+/-3.5kV/7kV/14kV

+/-350V/750V

MVDC

LVDC

DC

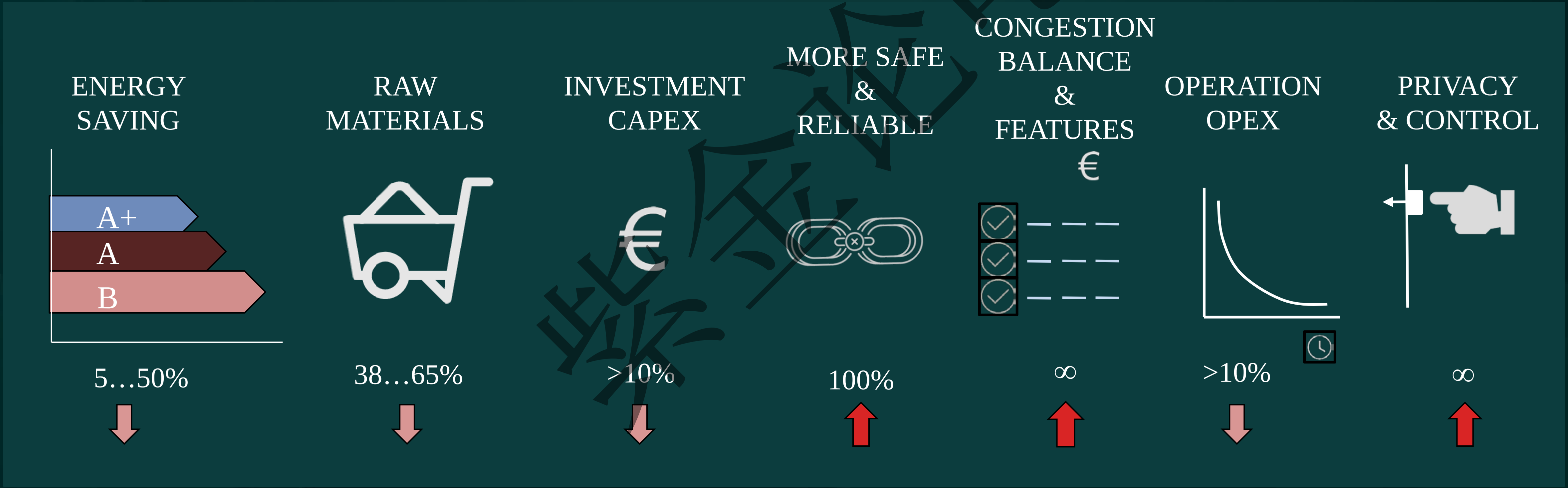
AC

DC

Why DC Now ?

Everything is also possible in AC

But it makes more sense to do this in DC because

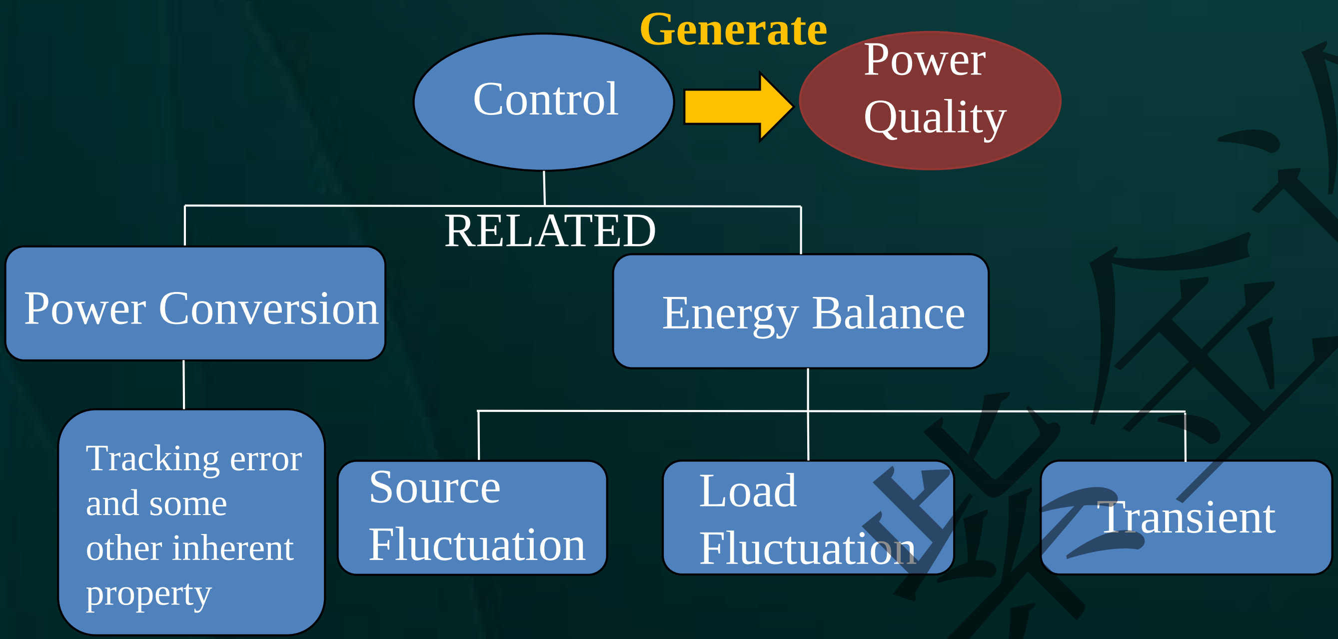


ENERGY SAVING	RAW MATERIALS	INVESTMENT CAPEX	MORE SAFE & RELIABLE	CONGESTION BALANCE & FEATURES	OPERATION OPEX	PRIVACY & CONTROL
5…50%	38…65%	>10%	100%	∞	>10%	∞
⬇	⬇	⬇	⬆	⬆	⬇	⬆

WE ARE ALREADY LIVING IN A DC WORLD WITHOUT REALIZING IT

Contents

2.1 Control and Power Quality



Control

Generate

Power Quality

RELATED

Power Conversion

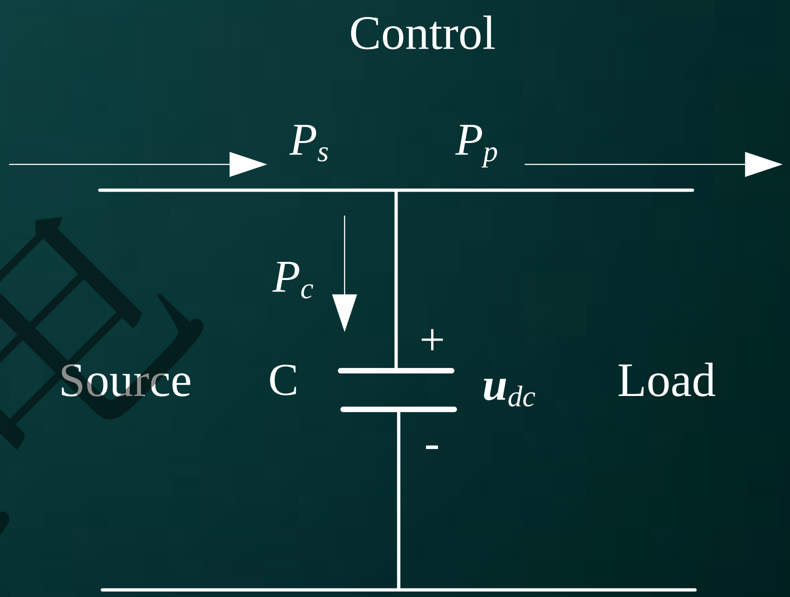
Energy Balance

Tracking error and some other inherent property

Source Fluctuation

Load Fluctuation

Transient



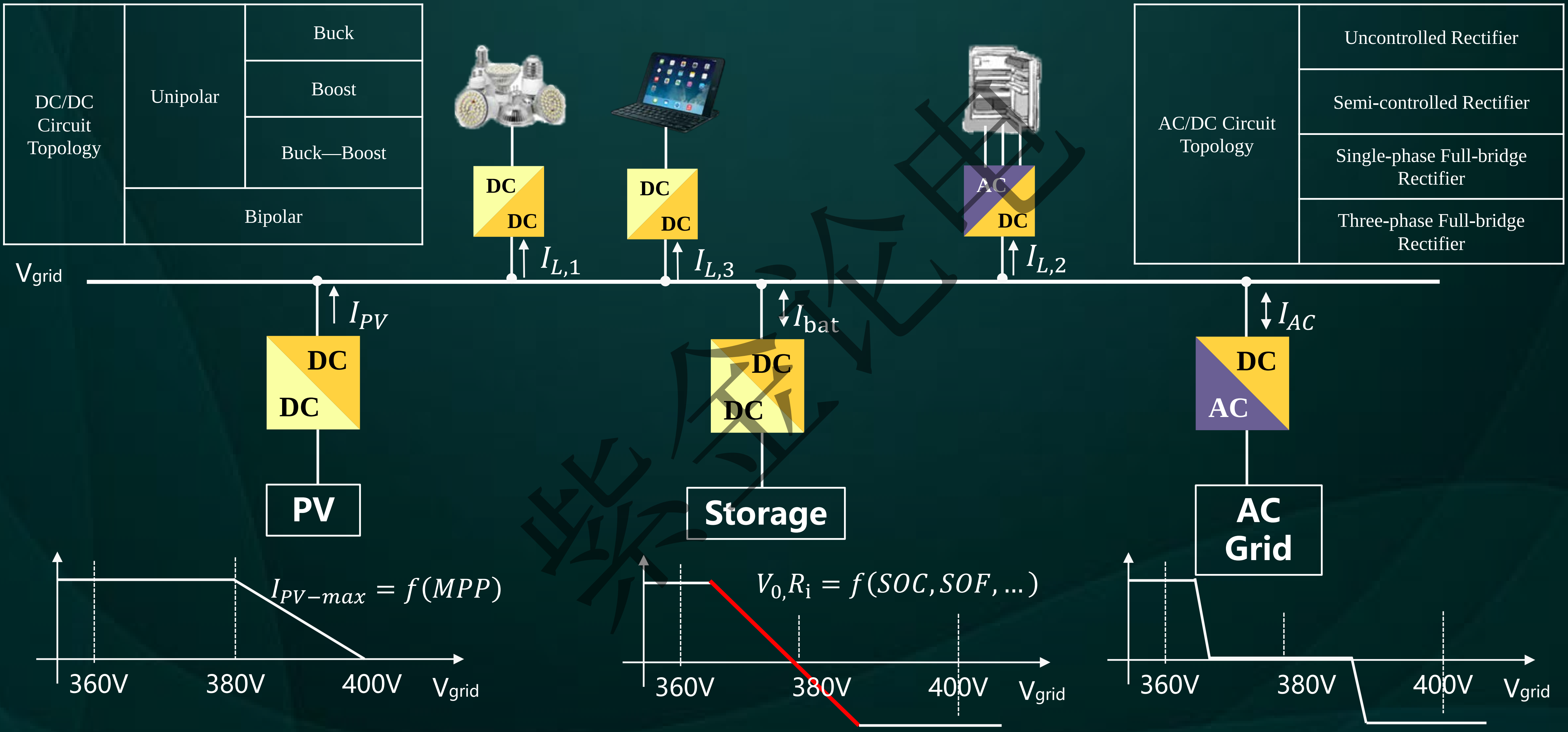
The control of LVDC:

Active power balance → Voltage balance

$$P_s=P_p+P_c$$

$$U_{dc}(dU_{dc}/dt)=(P_s-P_p)/C$$

2.2 Power Electronics Interface in LVDC

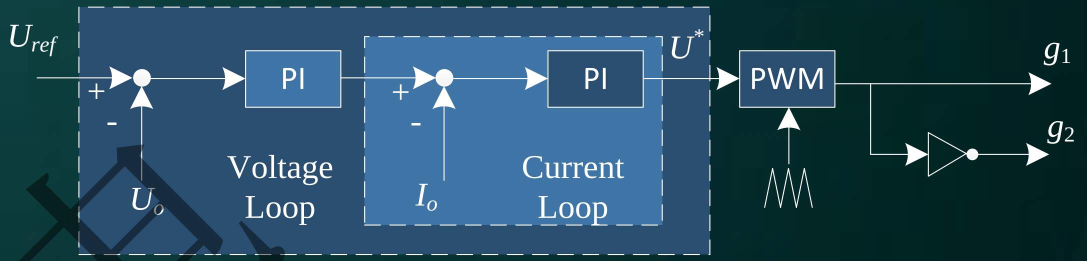


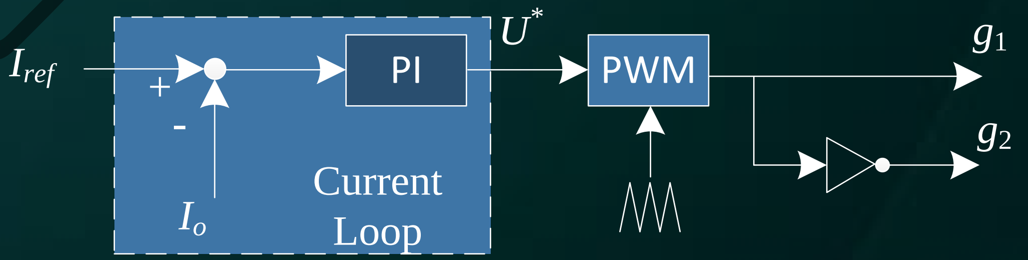
DC/DC Circuit Topology	Unipolar	Buck
		Boost
		Buck—Boost
	Bipolar	

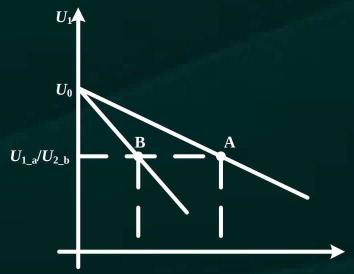
AC/DC Circuit Topology	Uncontrolled Rectifier
	Semi-controlled Rectifier
	Single-phase Full-bridge Rectifier
	Three-phase Full-bridge Rectifier

2.3 Power Electronic Converter Control

- Power Electronic Converter Control
  - Master-slave Control
    - Main Source Voltage Control
    - Slave Source Power Control
  - Peer-to-peer Control
    - Droop Control



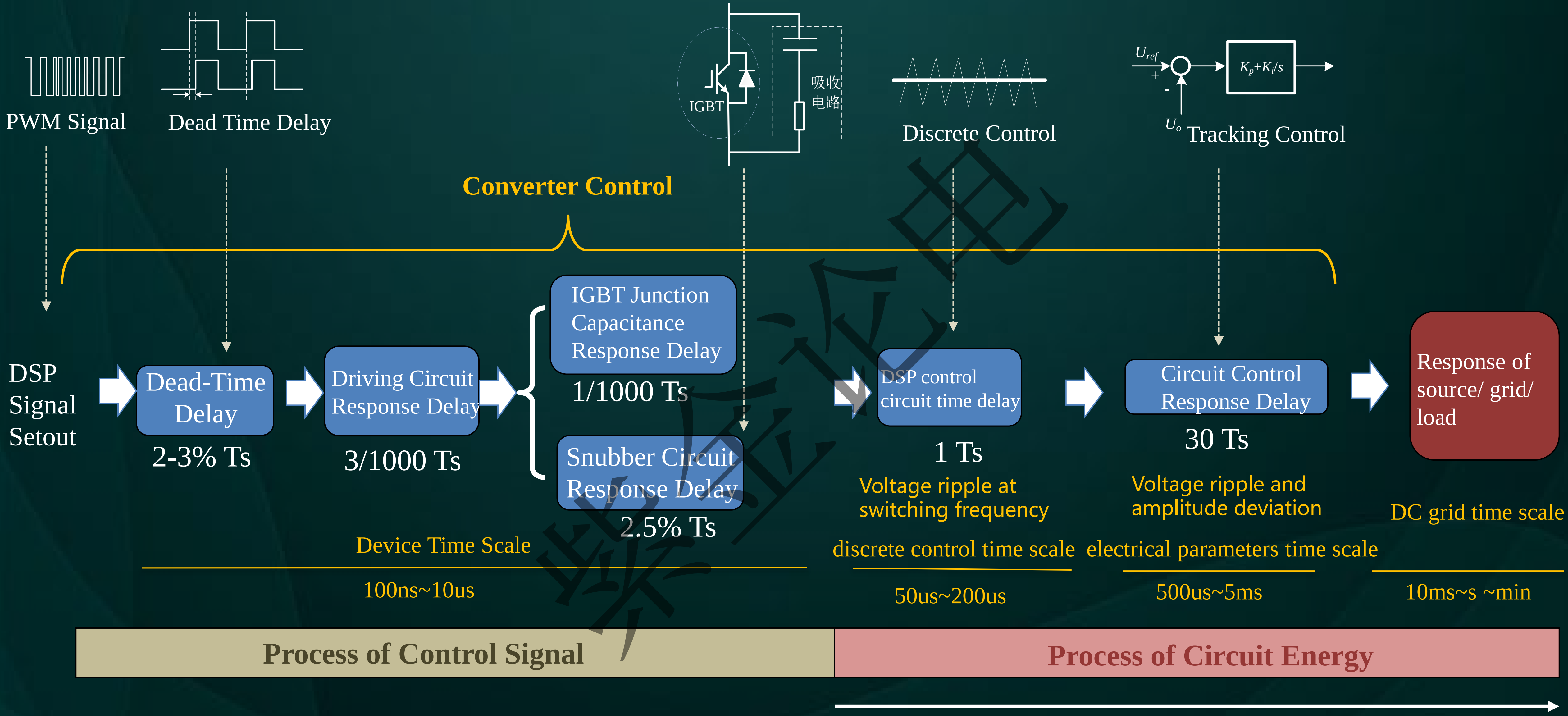




Voltage Current Dual-Loop Control

Coordinated control of the converter leads to more complex power quality problems.

2.4 Control Effects with Different Time Scales



PWM Signal

Dead Time Delay

Discrete Control

Tracking Control

Converter Control

DSP Signal Setout

Dead-Time Delay

2-3% Ts

Driving Circuit Response Delay

3/1000 Ts

IGBT Junction Capacitance Response Delay

1/1000 Ts

Snubber Circuit Response Delay

2.5% Ts

DSP control circuit time delay

1 Ts

Voltage ripple at switching frequency

Circuit Control Response Delay

30 Ts

Voltage ripple and amplitude deviation

Response of source/ grid/ load

DC grid time scale

Device Time Scale	discrete control time scale	electrical parameters time scale	
100ns~10us	50us~200us	500us~5ms	10ms~s ~min

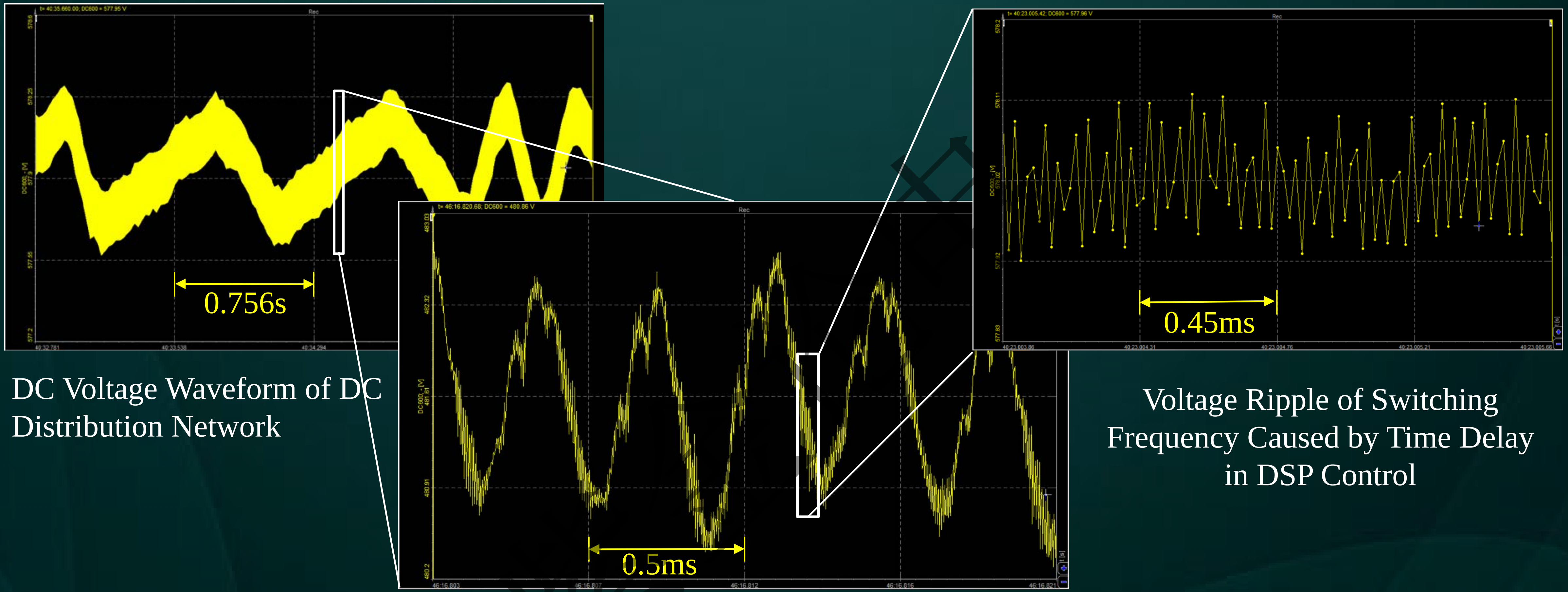
Process of Control Signal

Process of Circuit Energy

The start point of power quality phenomena

Ts： **switching period**

2.4 Control Effects with Different Time Scales



DC Voltage Waveform of DC Distribution Network

Voltage Ripple of Switching Frequency Caused by Time Delay in DSP Control

Voltage Ripple Caused by Circuit Control Response Delay

Response of source/ grid/ load

Time scale of DC power grid

10ms~s ~min

Circuit Control Response Delay

Time scale of electrical parameters

500us~5ms

DSP control circuit time delay

Time scale of discrete control

50us~200us

Contents

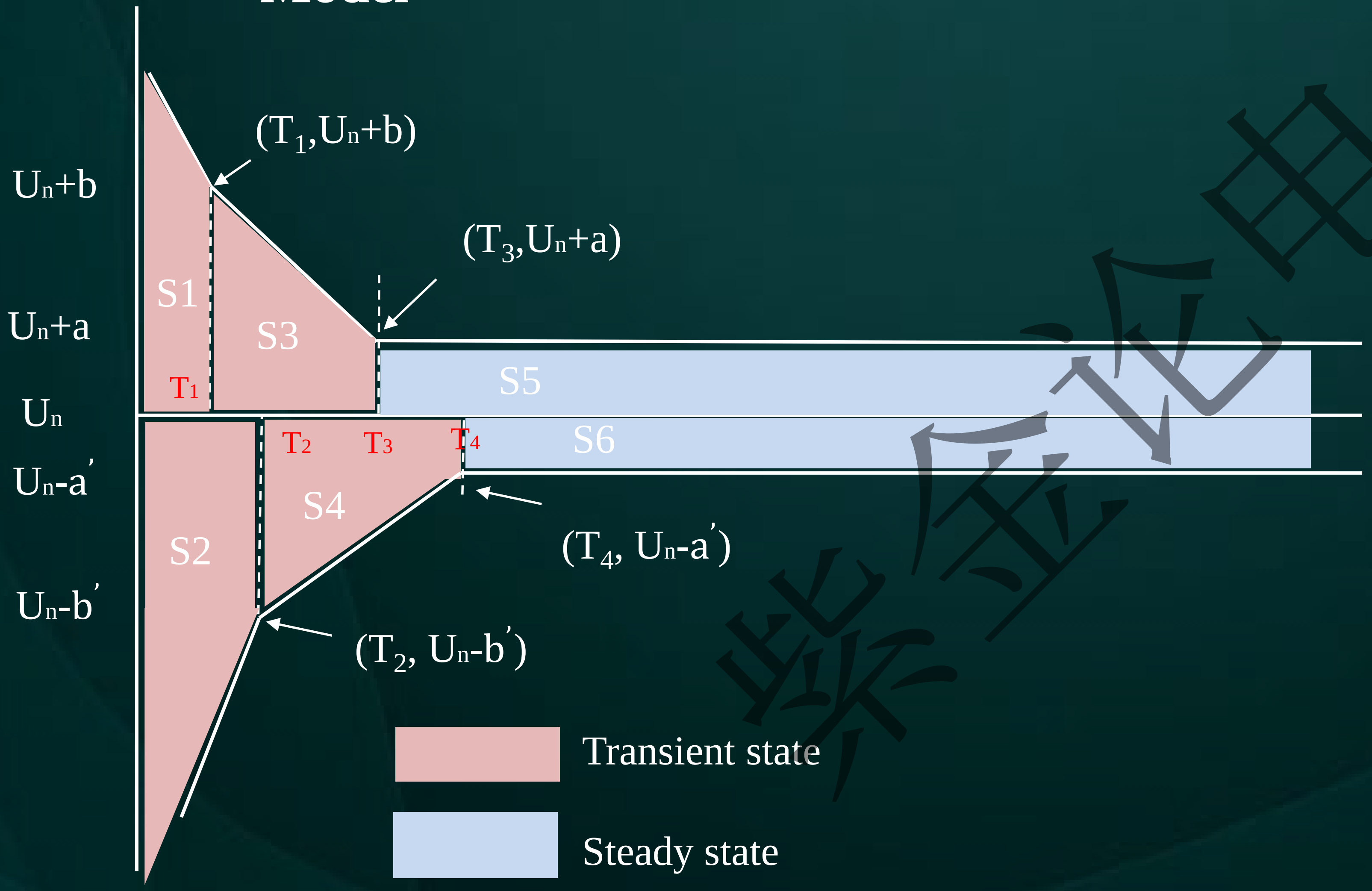
3.1 Power Quality in LVDC

Classification

Steady state	Transient state
Voltage Amplitude	
Voltage Deviation	Voltage Sag or Swell Voltage Interruption Voltage Transient
Voltage Ripple	▨
Bipolar Imbalance	

3.2 Voltage Amplitude

Model



S1&S2 - overvoltage suppression devices voltage band for transient overvoltage protection

S3&S4 - operating voltage band for protection and switching devices

S5&S6 - rated voltage for normal operation (power transmission from one point of the installation to another),

3.2 Voltage Amplitude

3.2.1 Voltage Level Selection

Questions need to be answered for selecting the correct voltage level The voltage

The voltage level including the droop ranges is defined by the:

- Grounding system
- Direct touch protection
- Distribution efficiency
- Full replacement of existing AC solutions in many pplications
- Must work in all applications, with compatibility
- Clearness in hybrid systems
- Arcing
- Corrosion
- And many more small items that are common overlooked

Source：Bernd Wunder, Germany

3.2 Voltage Amplitude

3.2.1 Voltage Level Selection

Research & Development Direct Current BV	VOLTAGE CLASS		DIRECT TOUCH PROTECTION 3ms		NO AC VOLTAGE LEVEL	APPLICATION																													Maximal cable length 1% drop @ 6A/mm^2. For biopolar system is balanced	Maximal cable power @6A/mm^2 power per 1mm^2 copper	Number of wire excluding PE
						HOMES <20kW							OFFICES <200kW							WAREHOUSE >100kW					GREENHOUSE 500kW~2MW						DISTRUBUTION 500kW~1MW							
NOMINAL DC Voltage	SELV	LVDC	W/O DROOP	INCL DROOP		USB-C	LIGHTING	VENTILATION	HEATPOMP	SOLAR>10kW	KITCHEN	EV CHARGING	USB-C	LIGHTING	VENTILATION	HEATPOMP	SOLAR>100kW	KITCHEN	EV CHARGING	LIGHTING	VENTILATION	HEATPOMP	SOLAR>200kW	DRIVES	LIGHTING	VENTILATION	PUMPS	DRIVES	HPS GEN	SOLAR>1M	LAST MILE	PUBLIC LIGHTING	EV CHARGING	PUMPS	TELECOM			
12V	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	0,6m	72W	2
24V *)	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	1,2m	144W	2
48V 2)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟧	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	2,4m	288W	2
60V	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	2,9m	360W	2
120V	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	5,9m	720W	2
190V	⬜	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	9,3m	1140W	2
200V	⬜	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	9,8m	1200W	2
250V	⬜	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟧	🟩	🟩	🟧	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	12,3m	1500W	2
300V	⬜	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	14,7m	1800W	2
350V	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	17,2m	2100W	2
380V *)	⬜	🟩	🟩	🟧	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	18,6m	2280W	2
±190V *)	⬜	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	18,6m	2280W	3
400V	⬜	🟩	🟧	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	19,6m	2400W	2
±200V	⬜	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	19,6m	2400W	3
500V	⬜	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	24,5m	3000W	2
±250V	⬜	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	24,5m	3000W	3
600V	⬜	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟥	🟥	🟩	🟧	🟥	🟥	🟥	🟥	🟥	🟧	🟥	29,4m	3600W	2
±300V	⬜	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟥	🟥	🟩	🟧	🟥	🟥	🟥	🟥	🟥	🟧	🟥	29,4m	3600W	3
700V	⬜	🟦	🟥	🟥	🟦	🟥	🟥	🟥	🟦	🟦	🟦	🟦	🟥	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟥	🟥	🟦	🟥	34,3m	4200W	2
±350V	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟥	🟥	🟦	🟦	🟦	🟦	🟦	34,3m	4200W	3
750V	⬜	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟧	🟧	🟧	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟥	🟩	🟧	🟥	36,8m	4500W	2
760V	⬜	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟧	🟩	🟩	🟩	🟥	🟧	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟧	🟧	🟧	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟥	🟩	🟧	🟥	37,3m	4560W	2
±380V	⬜	🟩	🟩	🟧	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	37,3m	4560W	3
800V	⬜	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟧	🟧	🟧	🟥	🟥	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟧	🟧	🟩	🟩	🟥	🟩	🟧	🟥	39,2m	4800W	2
±400V	⬜	🟩	🟧	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	39,2m	4800W	3
1000V	⬜	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟥	🟥	🟥	🟥	49,0m	6000W	2
±500V	⬜	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	49,0m	6000W	3
1200V	⬜	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟥	🟥	🟥	🟥	58,8m	7200W	2
±600V	⬜	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟧	🟩	🟥	🟥	🟩	🟥	58,8m	7200W	3
1400V	⬜	🟦	🟥	🟥	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟦	🟦	🟥	🟥	🟥	🟥	68,6m	8400W	2
±700V	⬜	🟦	🟥	🟥	🟦	🟥	🟥	🟥	🟦	🟥	🟥	🟥	🟥	🟦	🟥	🟥	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟥	🟦	🟥	🟦	🟦	🟥	68,6m	8400W	3
1500V	⬜	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟥	🟥	🟥	73,5m	9000W	2
±750V	⬜	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟧	🟧	🟩	🟩	🟩	🟧	🟥	🟩	🟩	🟥	🟥	🟧	🟥	73,5m	9000W	3

🟦 Advised proposal by Direct Current BV ⬜ NA 🟩 Possible 🟧 Possible but on the limit 🟥 Not advisable

*) Emerge Alliance standard US

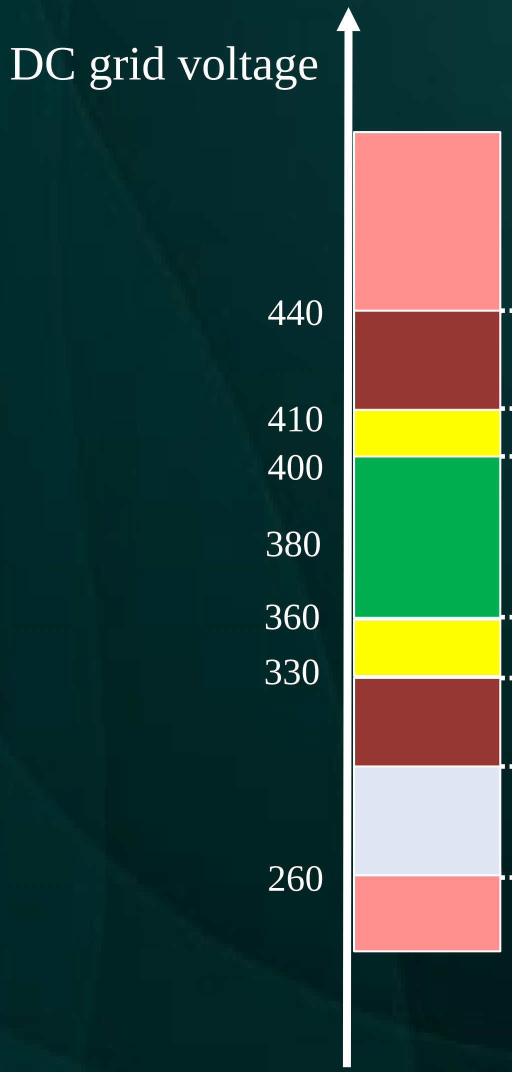
1) As an application, but no distribution

2) Used by Direct Current for auxiliaries and safety wire

Source：Harry Stokman，Netherlands

3.2 Voltage Amplitude

3.2.2 Voltage Band



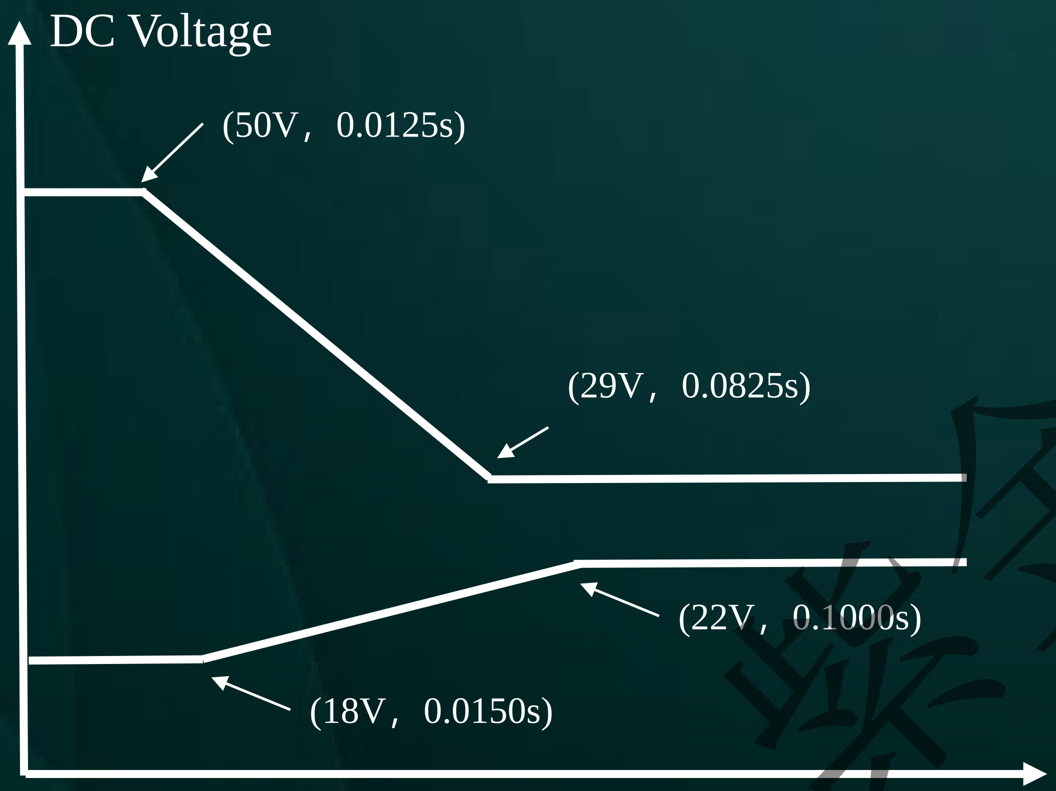
Voltage band	Behavior of device and components
Self-protection	Switch-off for self-protection allowed
Transient over-voltage	Transient operation with limited functionality and power derating
Stationary over-voltage	Operation with full functionality, power derating allowed
Nominal voltage range	Operation with specified functionality
Stationary under-voltage	Operation with full functionality, power derating allowed
Transient under-voltage	Transient operation with limited functionality and power derating
Special function range	To be used for various protection and safety functions

Source：Bernd Wunder, Germany

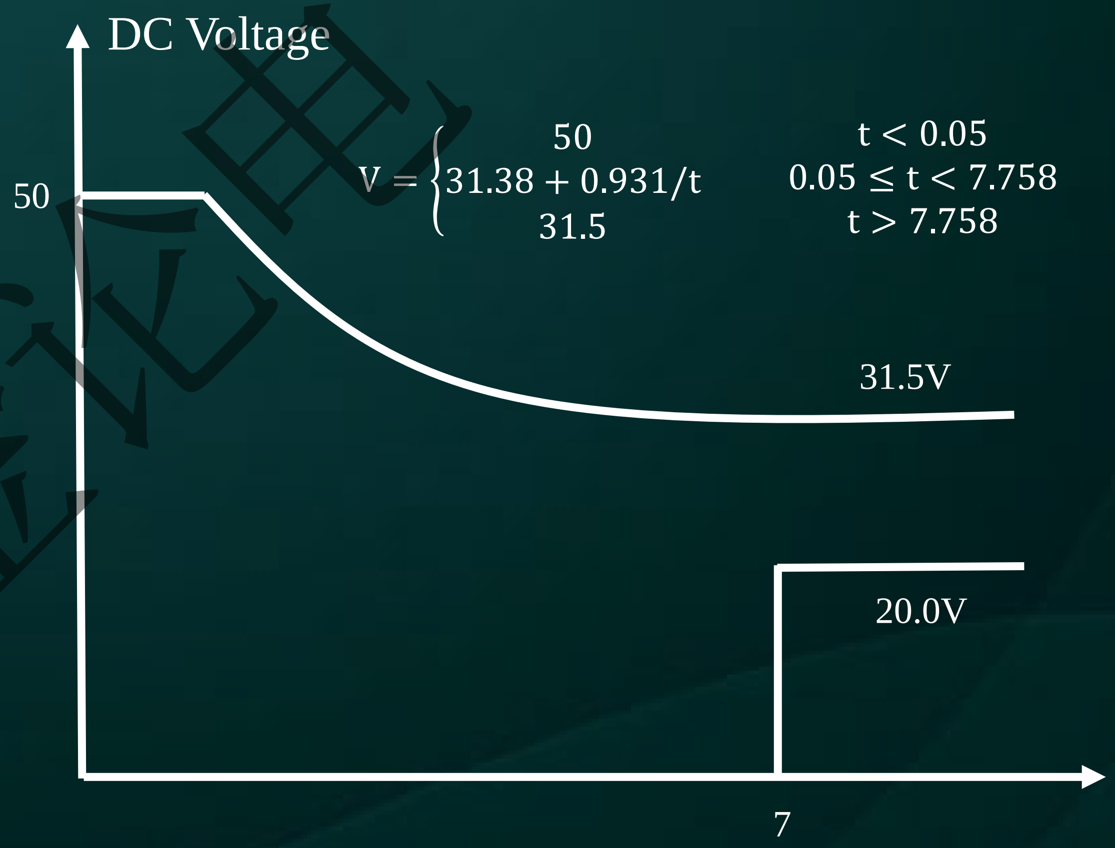
3.2 Voltage Amplitude

3.2.2 Voltage Band

Source：MIL-STD-704



Maximum distortion spectrum for 28 volts DC sysytem



$$V = \begin{cases} 50 & t < 0.05 \\ 31.38 + 0.931/t & 0.05 \leq t < 7.758 \\ 31.5 & t > 7.758 \end{cases}$$

Limits for overvoltage and undervoltage for 28 volts DC system

A transient is a changing value of a characteristic that usually occurs as a result of normal disturbances such as electric load change and engine speed change.

Abnormal operation. Utilization equipment shall be permitted a degradation or loss of function unless otherwise specified in its detail specification. Utilization equipment shall not suffer damage or cause an unsafe condition. Utilization equipment shall automatically resume full performance when normal operation of the electrical system is restored.

3.2 Voltage Amplitude

3.2.3 Voltage Devitation

(1) Voltage deviation caused by load

P=UI

Energy Conservation:

$$P_{Source} = P_{Load} + P_{Loss}$$

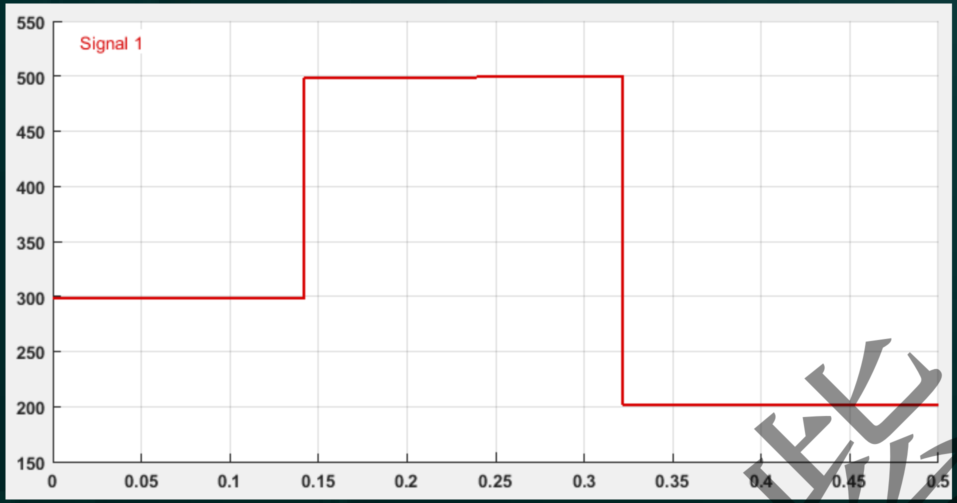
Source and load are connected through converter

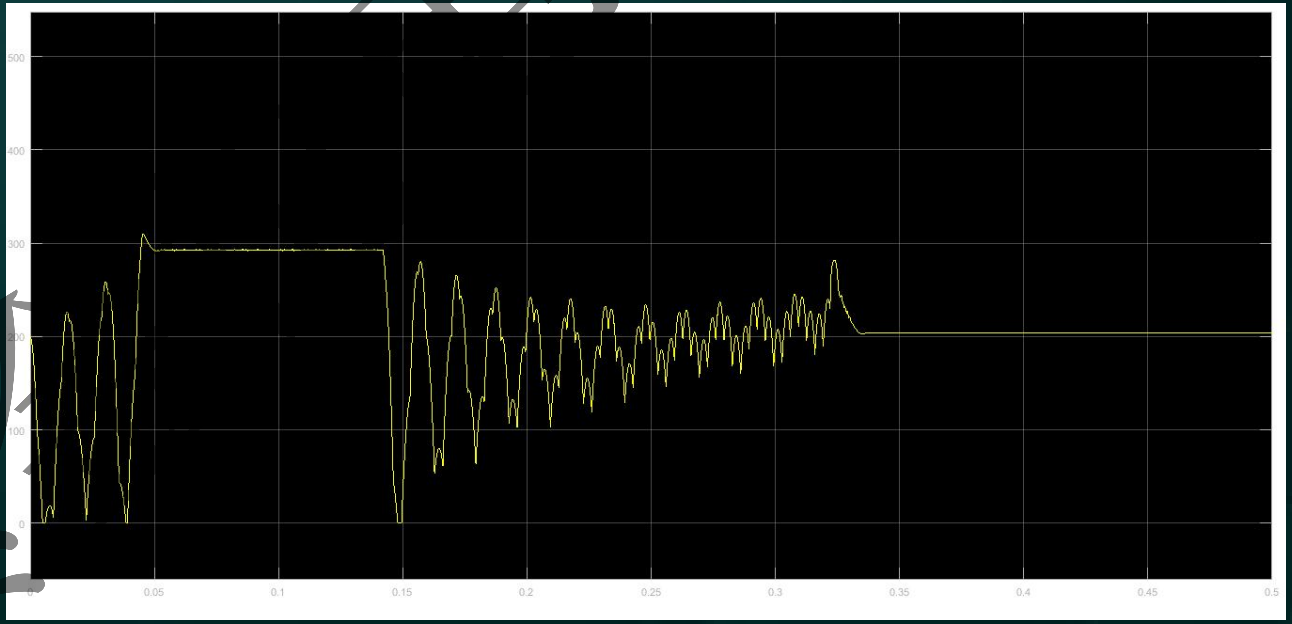
$$\sum U_{Source} I_{Source} = \sum U_{Load} I_{Load} + P_{Loss}$$

3.2 Voltage Amplitude

3.2.3 Voltage Band

(2) Voltage deviation caused by system control tracking error

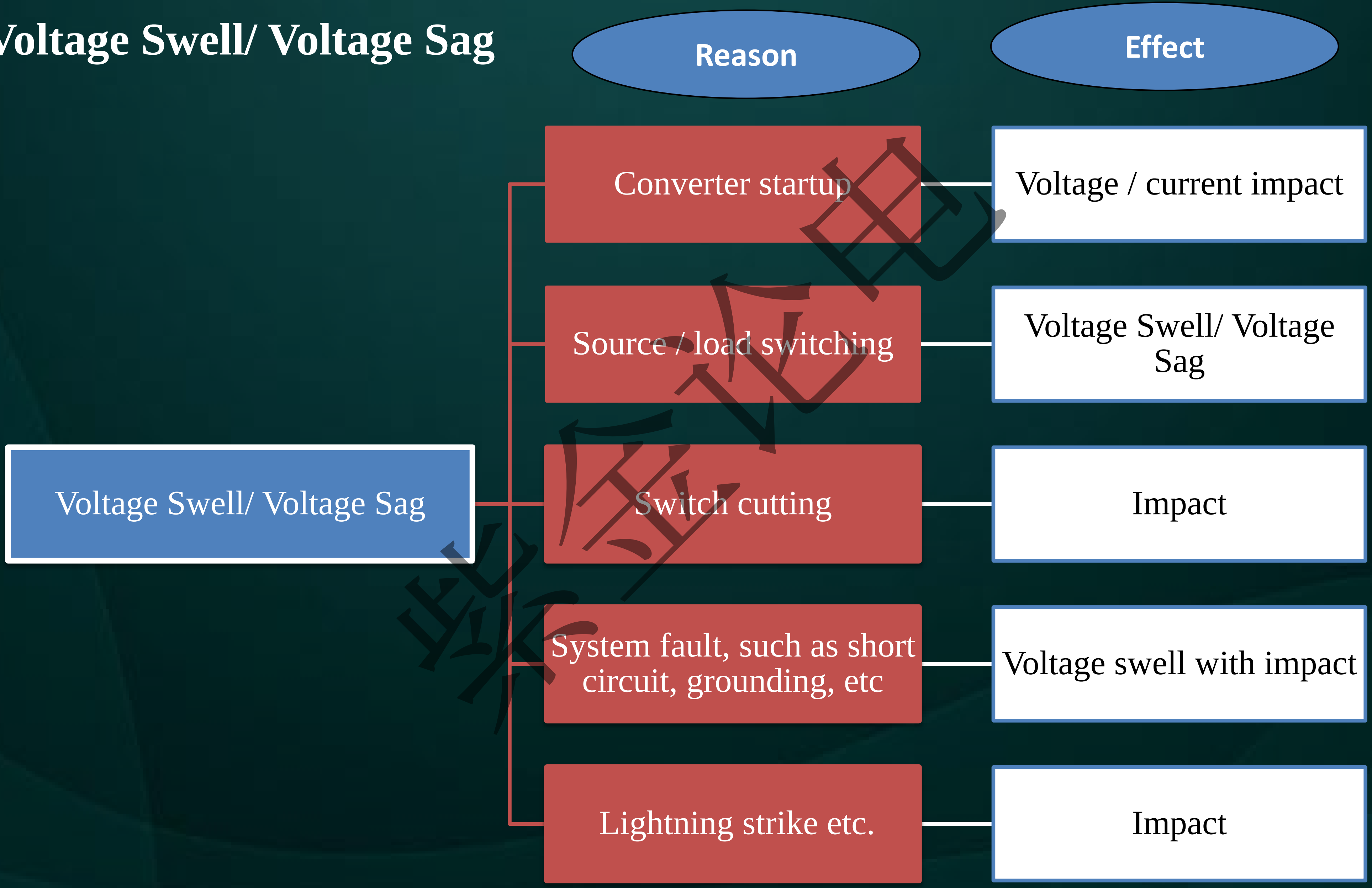




In Matlab/Simulink, the tracking target is set as 500V. Because of control deviation, the voltage remains 500V, resulting in voltage deviation.

3.2 Voltage Amplitude

3.2.4 Voltage Swell/ Voltage Sag



Voltage Swell/ Voltage Sag

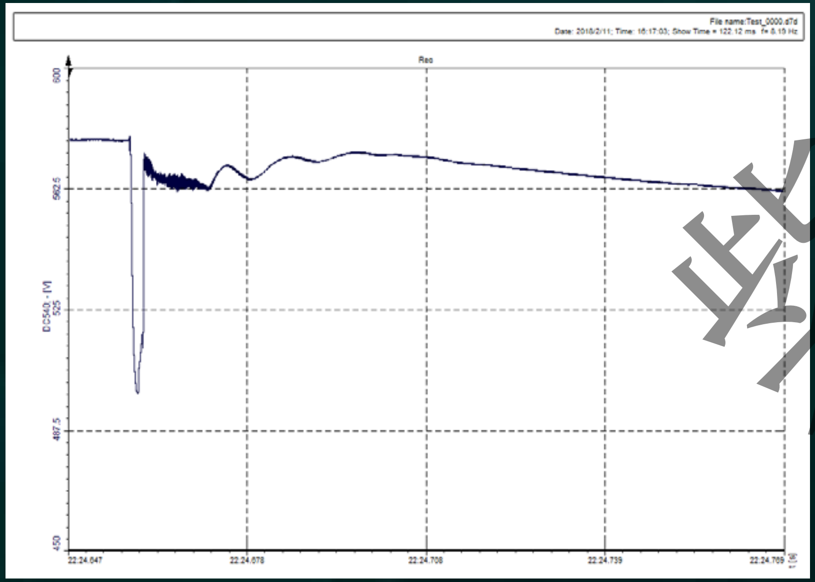
Reason	Effect
Converter startup	Voltage / current impact
Source / load switching	Voltage Swell/ Voltage Sag
Switch cutting	Impact
System fault, such as short circuit, grounding, etc	Voltage swell with impact
Lightning strike etc.	Impact

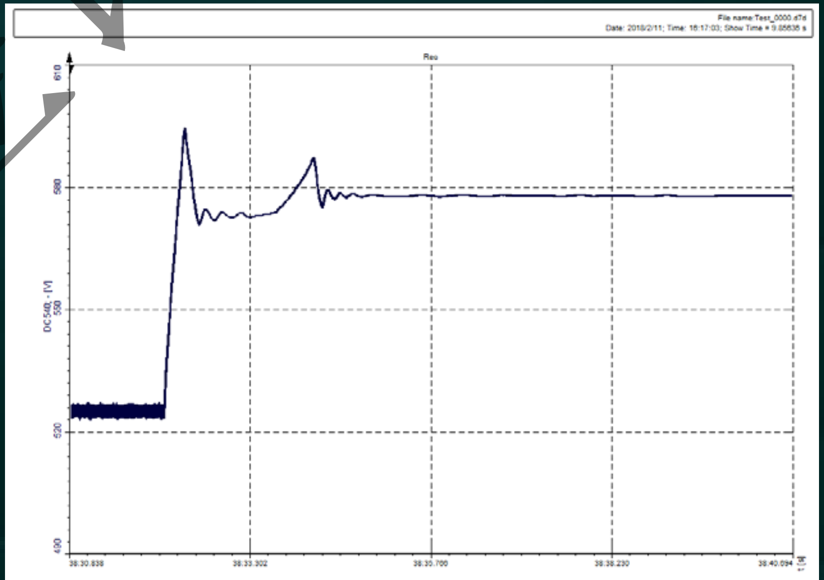
3.2 Voltage Amplitude

3.2.4 Voltage Swell/ Voltage Sag

Voltage Sag: DC system faults, power electronic converter or sudden change of load (such as starting of high-power machine).

Voltage Swell: System faults, such as ground fault and short circuit; Shutdown of high-power machine.





3.3 Voltage Ripple

3.3.1 IEC Standard

Ripple Content: alternating component, the quantity derived by removing the direct component from a pulsating quantity. **(IEC 60050_161_0225)**

Ripples affect the reliable operation of DC-powered equipment in factories, residential and commercial environments.

R.M.S.-Ripple Factor (IEC 60050_161_02_27):

The ratio of the r.m.s. value of the ripple content to the absolute value of the direct component of a pulsating quantity

$$q = \frac{U_{\mathrm{ac,\ rms}}}{|U_{\mathrm{dc}}|}$$

3.3 Voltage Ripple

3.3.1 IEC Standard

Peak-ripple Factor (IEC 60050_161_02_26)：

The ratio of the peak-to-valley value of the ripple content to the absolute value of the direct component of a pulsating quantity

$$q=\frac{U_{\text{max}}-U_{\text{min}}}{|U_{\text{dc}}|}$$

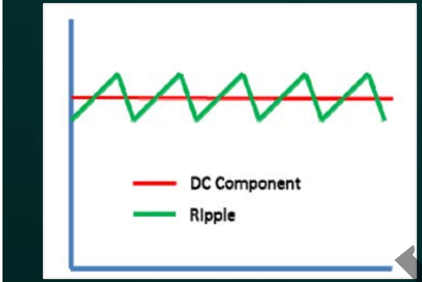
Half peak ripple factor(IEC 61180-1_6.12, IEC 60034-1_3.29)：

The ripple content is half of the difference between the maximum and the minimum, and the ripple factor is the ratio of the ripple content to the average value of the arithmetic in one cycle.

$$q=\frac{U_{\text{max}}-U_{\text{min}}}{2U_{\text{av}}}$$

3.3 Voltage Ripple

3.3.2 Factor

	Main Factors	**Characterizations**
Voltage Ripple 	Three phase unbalance	100Hz
	Uncontrolled rectifier	Three phase uncontrolled rectifier DC side 300Hz, single-phase uncontrolled rectifier DC side 100Hz
	Circuit control response delay	250Hz~5500Hz
	Switching frequency	Ts（3kHz~10kHz）

3.3 Voltage Ripple

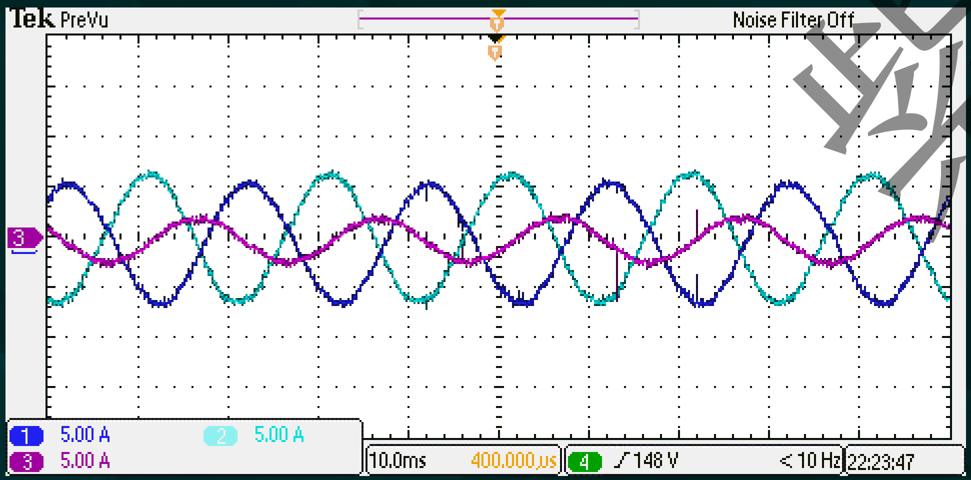
3.3.2 Factor

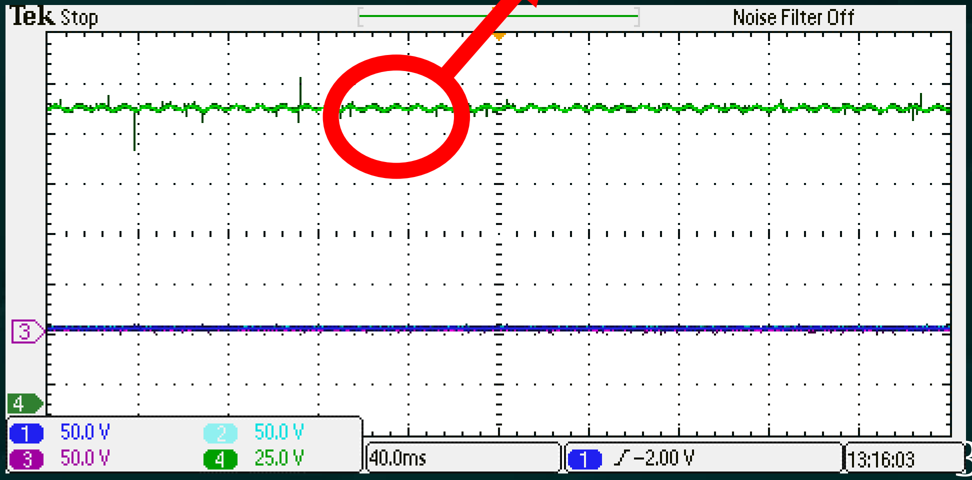
Three phase unbalance

With the three-phase unbalanced on the AC side, the transmission power has double frequency component. According to energy conservation, the DC-side voltage has a double frequency ripple.

double frequency ripple（100Hz)

Three phase unbalance





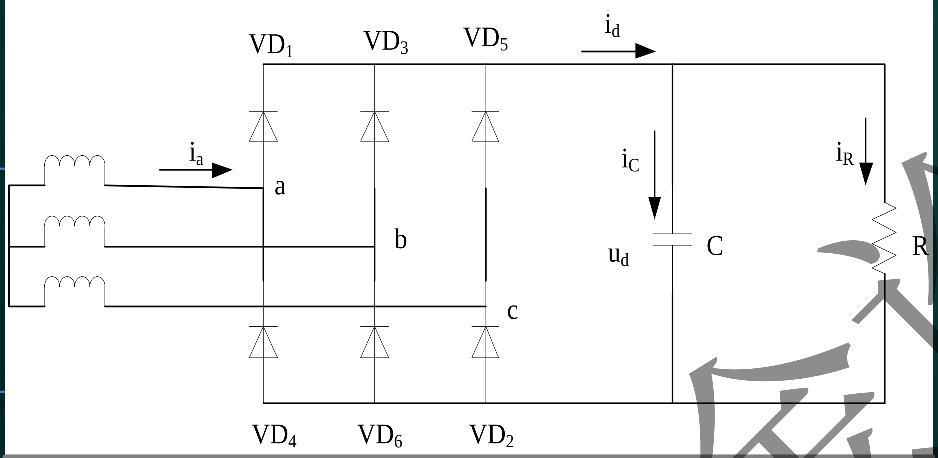
3.3 Voltage Ripple

3.3.2 Factor

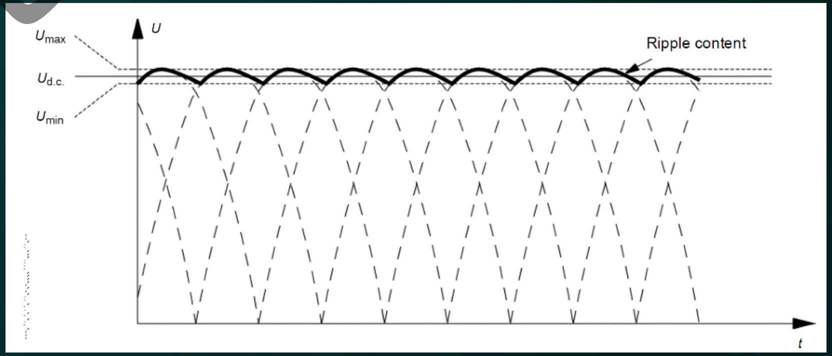
Uncontrolled rectifier

DC voltage is the envelope of the AC voltage in the positive half cycle; the three-phase uncontrolled rectifier DC side voltage contains 6k times low frequency ripple, and the single phase uncontrolled rectifier DC side voltage contains 2k times low frequency ripple.

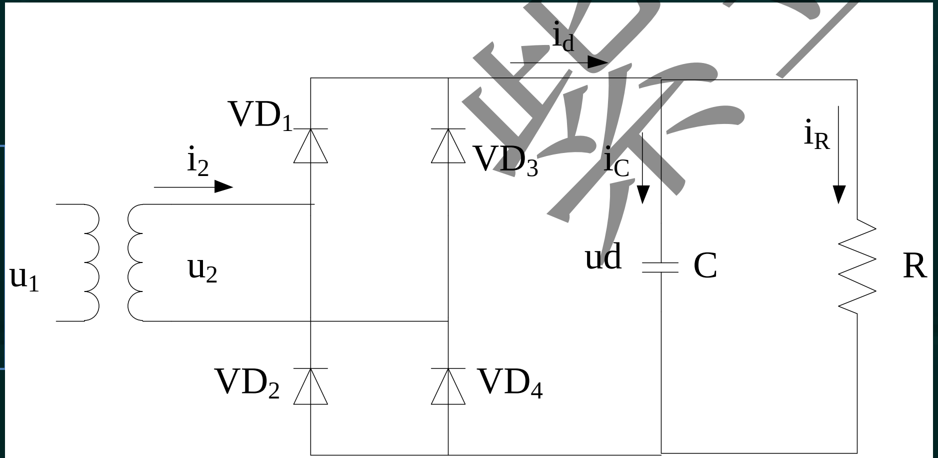
Widely used in large power uncontrolled rectifier



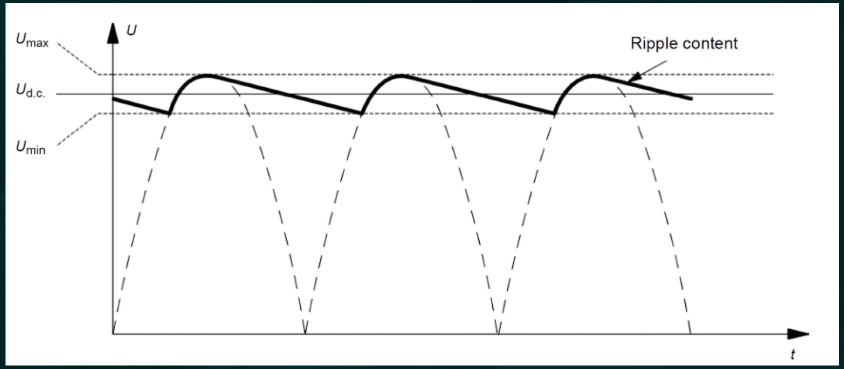
Three-phase uncontrolled rectifier



Widely used in small and medium-sized uncontrolled rectifiers



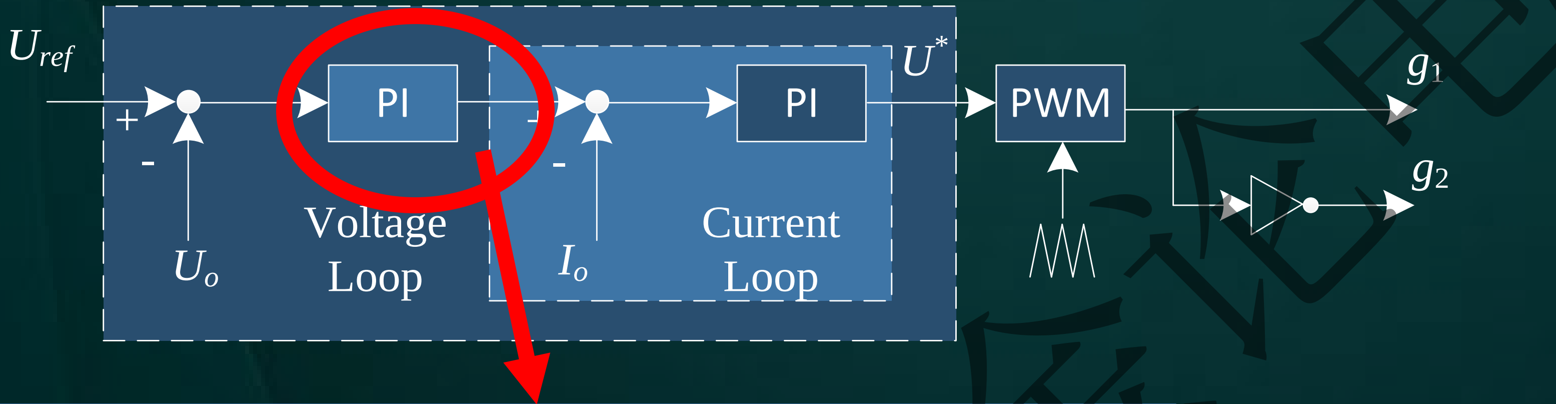
Single-phase uncontrolled rectifier

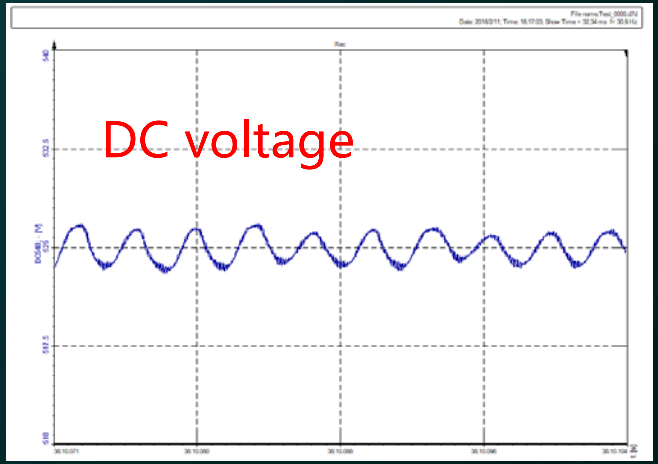


3.3 Voltage Ripple

3.3.2 Factor

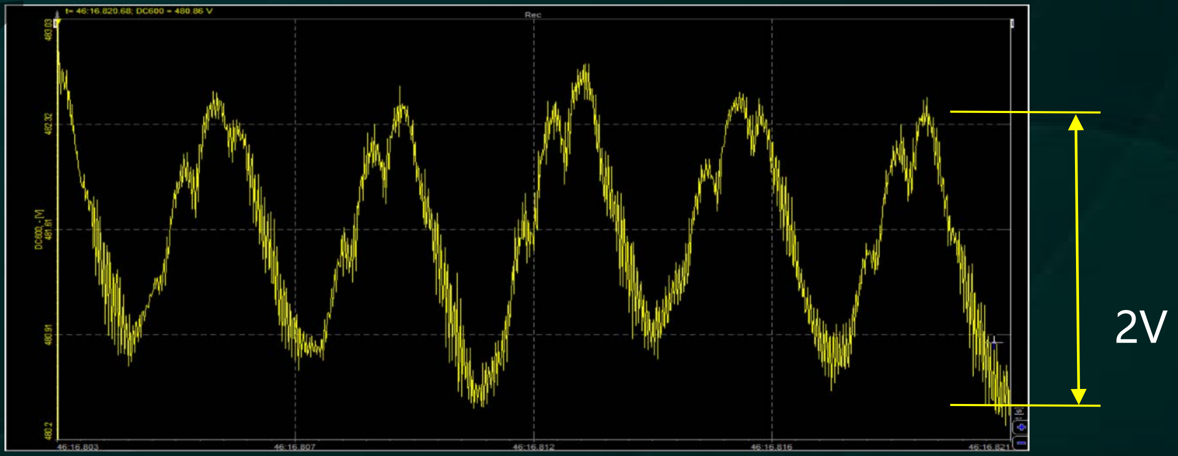
Circuit control response delay





Regardless of the chosen control strategy, the U_{ref} needs to be tracked and controlled by the voltage outer loop. The choice of PI parameters has a direct impact on the DC voltage.

Note: In DC, PI controller can achieve no static error tracking according to the internal model principle. However due to the discrete controller, it is impossible to realize no static tracking.



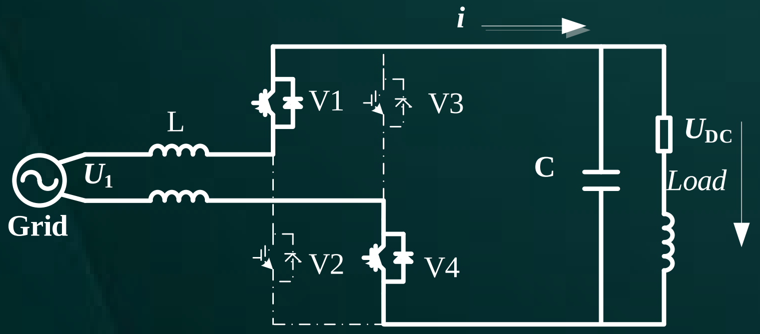
250Hz~5500Hz

3.3 Voltage Ripple

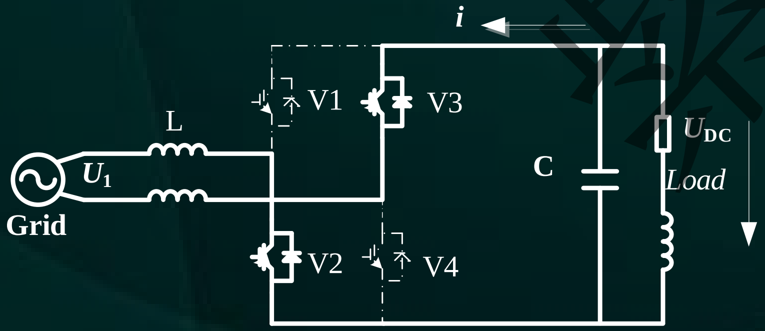
3.3.2 Factor

Switching frequency

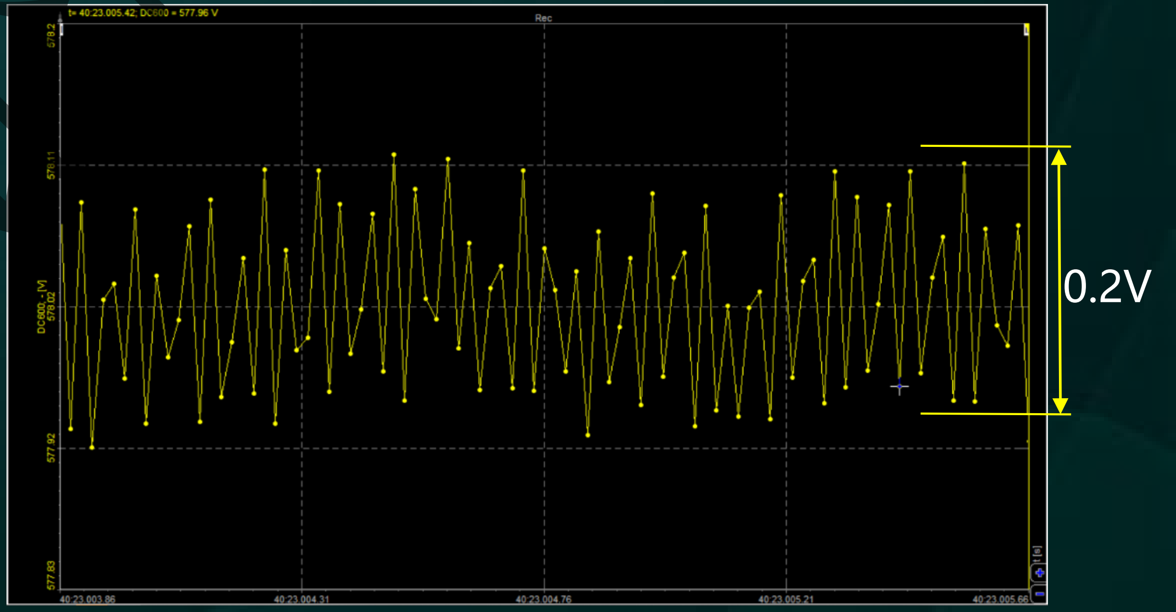
The ripple frequency is an integer multiple of the IGBT switching frequency and cannot be eliminated due to discretization.



- V1,V4 on, forward ac votlage



- V2,V3 on, reverse AC voltage



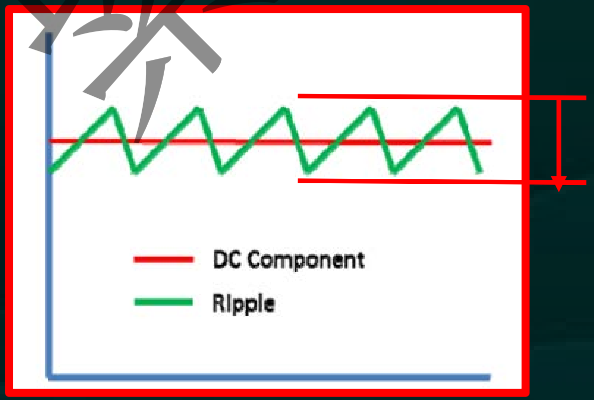
Ts（3kHz~10kHz）

3.3 Voltage Ripple

3.3.3 Limit

DC distortion factor: the ratio of DC distortion to steady-state DC voltage.。（28V DC system is set to3.5%，270V DC system is set to 1.5%）。 (MIL-STD-704F)

Pulsation amplitude: Ripple is the variation of voltage about the steady state DC voltage during steady state electric system operation（28V DC system is set to 1.5V，270V DC system is set to 6V）。(MIL-STD-704F_3.25)



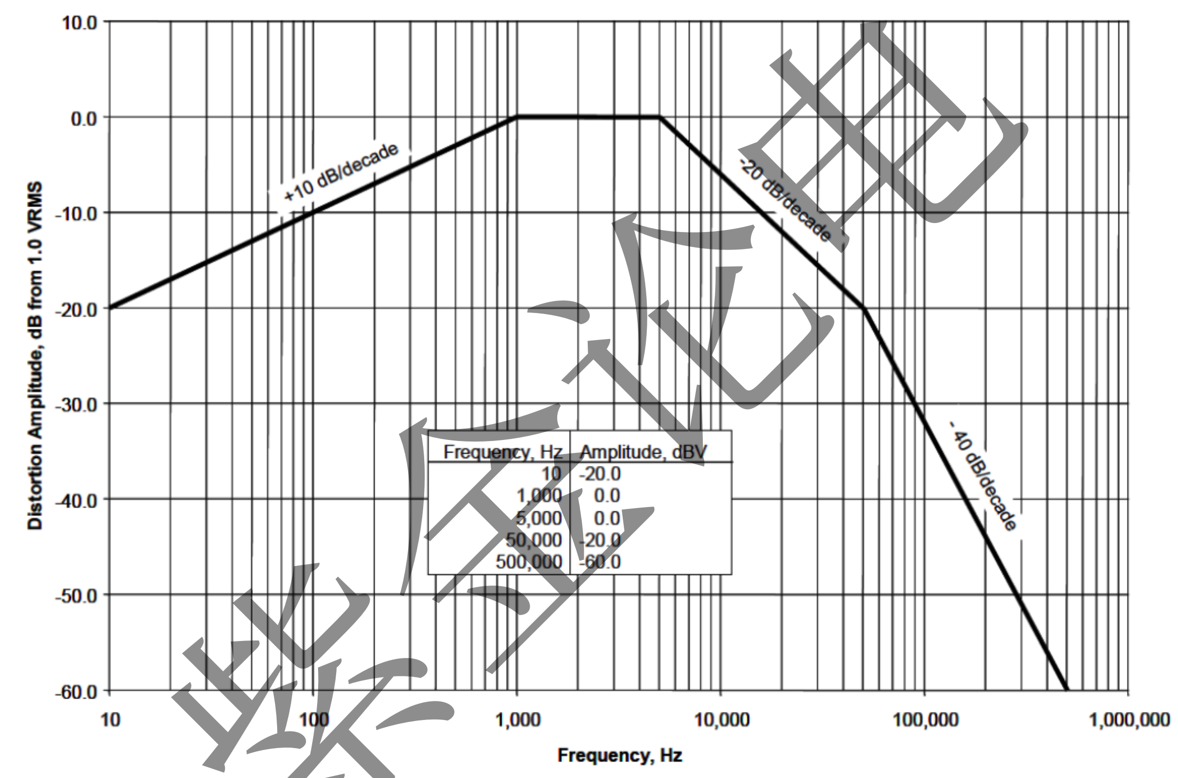
Pulsation amplitude

3.3 Voltage Ripple

3.3.3 Limit

Source：MIL-STD-704

Distortion Spectrum



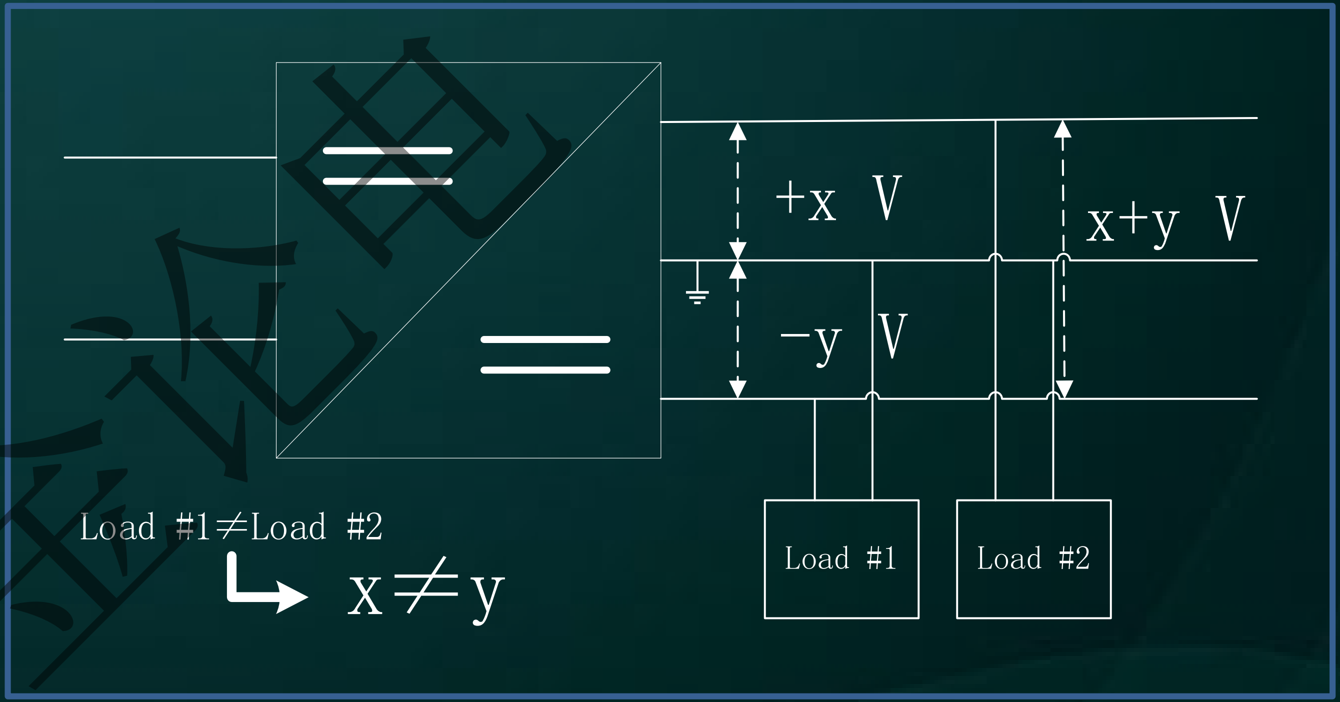
Frequency, Hz	Amplitude, dBV
10	-20.0
1,000	0.0
5,000	0.0
50,000	-20.0
500,000	-60.0

FIGURE 15. Maximum distortion spectrum for 28 volts DC system.

Frequency Range: 10Hz~500kHz
Spectrum limit curve：28V DC system is set to 1 V; 270V DC system is set to 3.16V.

3.4 Bipolar Imbalance

The voltage imbalance of the bipolar DC system is mainly caused by the uneven load distribution of the two poles in the grid. In addition, the imbalance is constantly changing due to the uncertain operation of the load.

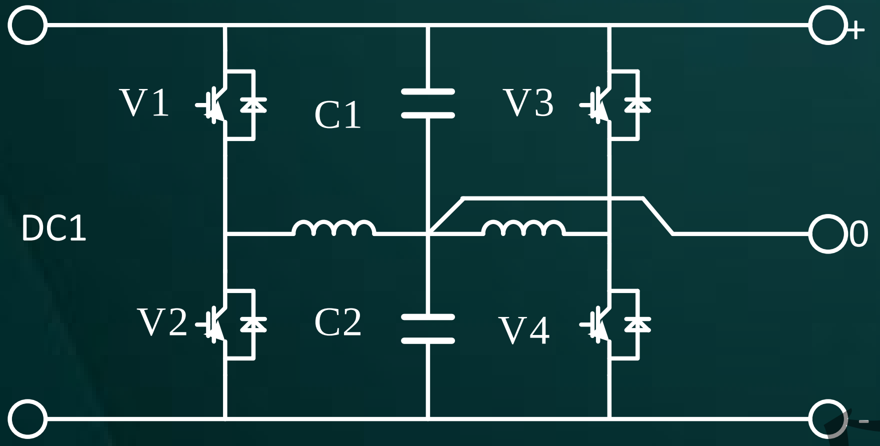


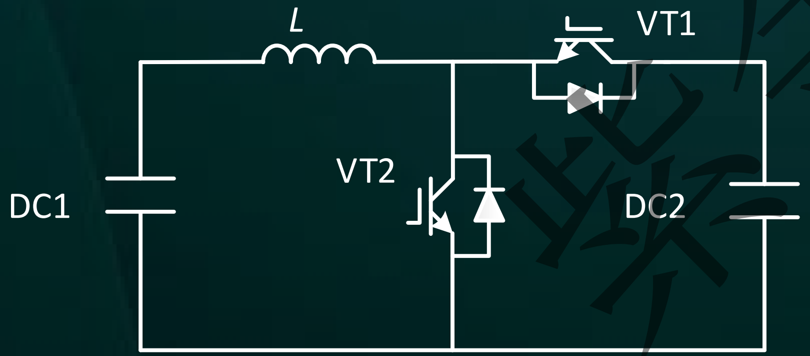
Load #1≠Load #2 → $x \neq y$

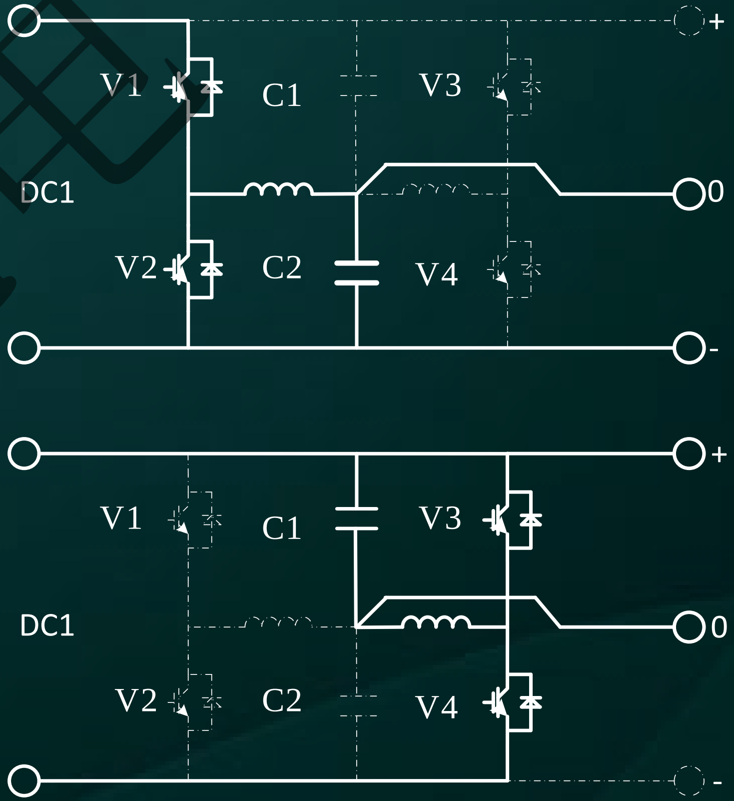
Effect

Unbalanced current due to voltage imbalance may reduce the operating efficiency of the converter;Voltage imbalance can degrade the performance of the converter and shorten the life of the converter.

3.4 Bipolar Imbalance

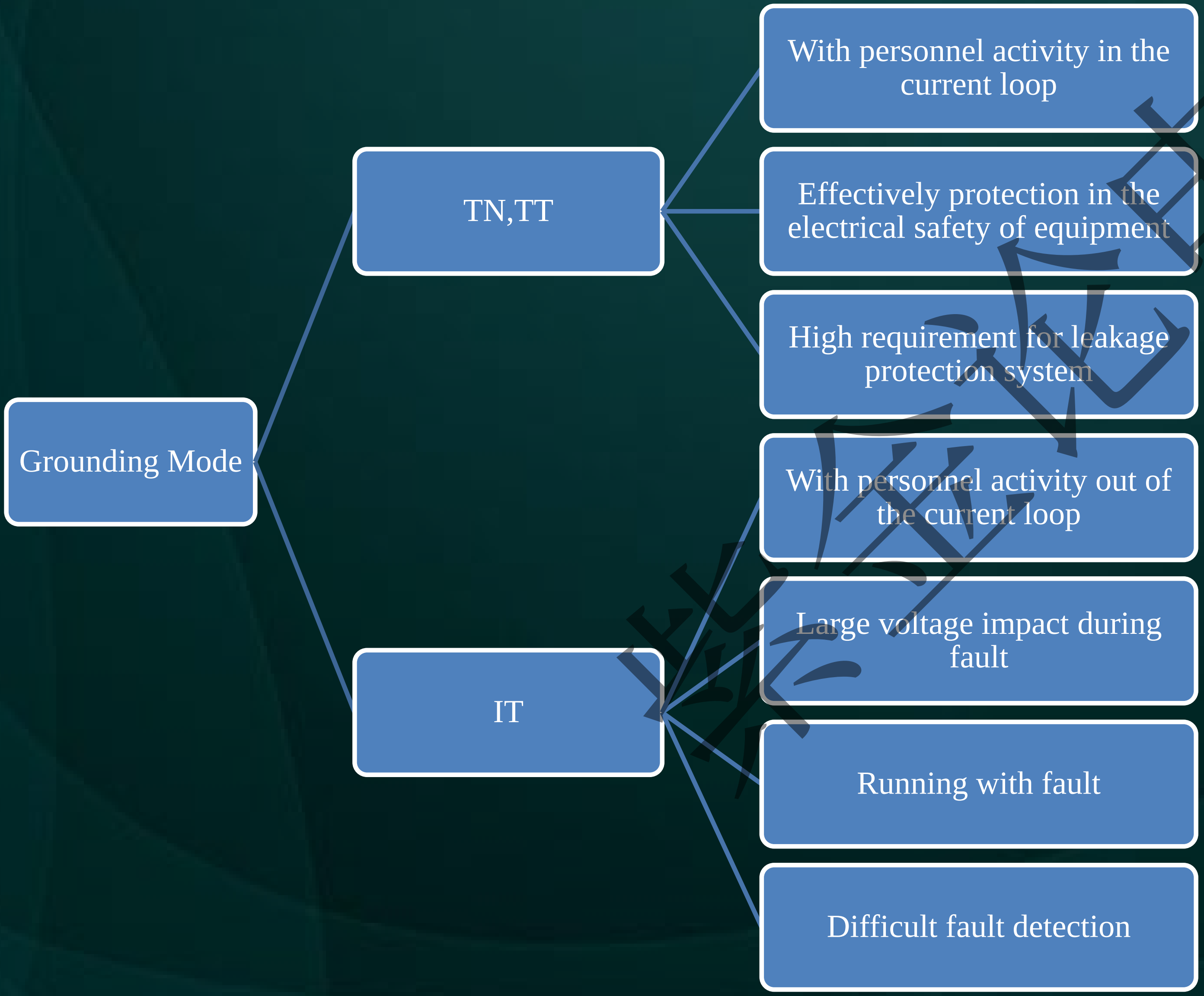






The topology is equivalent to two DC/DC circuits. When C1 and C2 are seriously unbalanced, such as more than 25%, the switch tube stress will exceed the set value

3.5 Grounding Mode



Grounding Mode

TN,TT

With personnel activity in the current loop

Effectively protection in the electrical safety of equipment

High requirement for leakage protection system

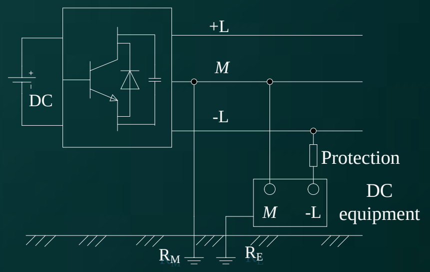
IT

With personnel activity out of the current loop

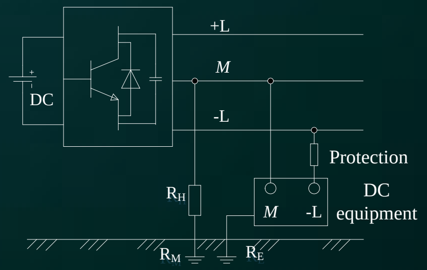
Large voltage impact during fault

Running with fault

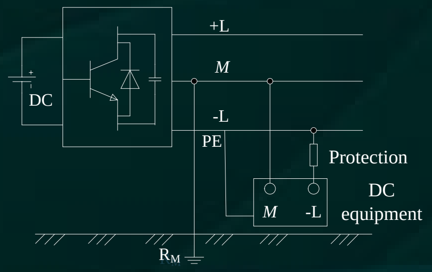
Difficult fault detection



(a) TT



(b) IT



(c) TN

Thanks!

Let's work together and contribute to LVDC standardization