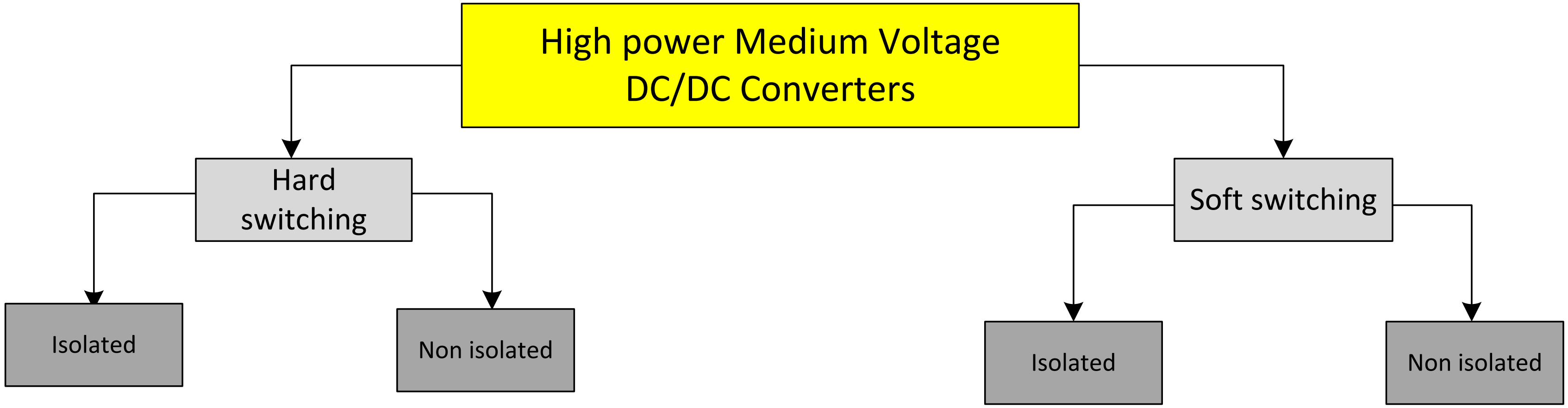
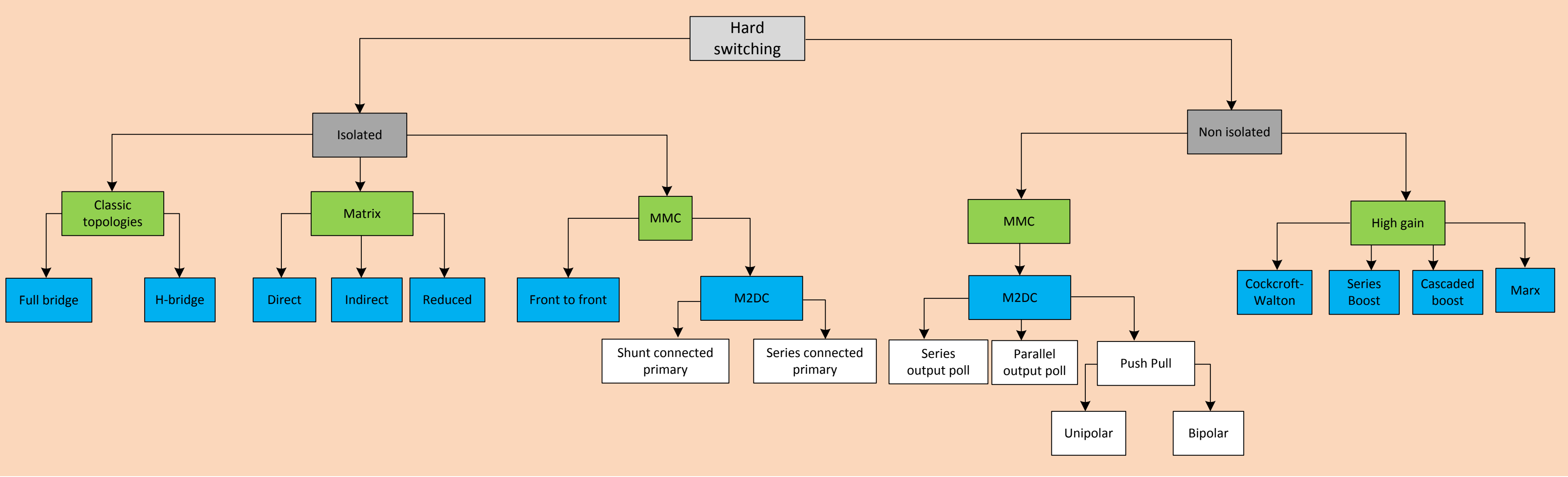
High power DC/DC Converter

Catalogue of circuits

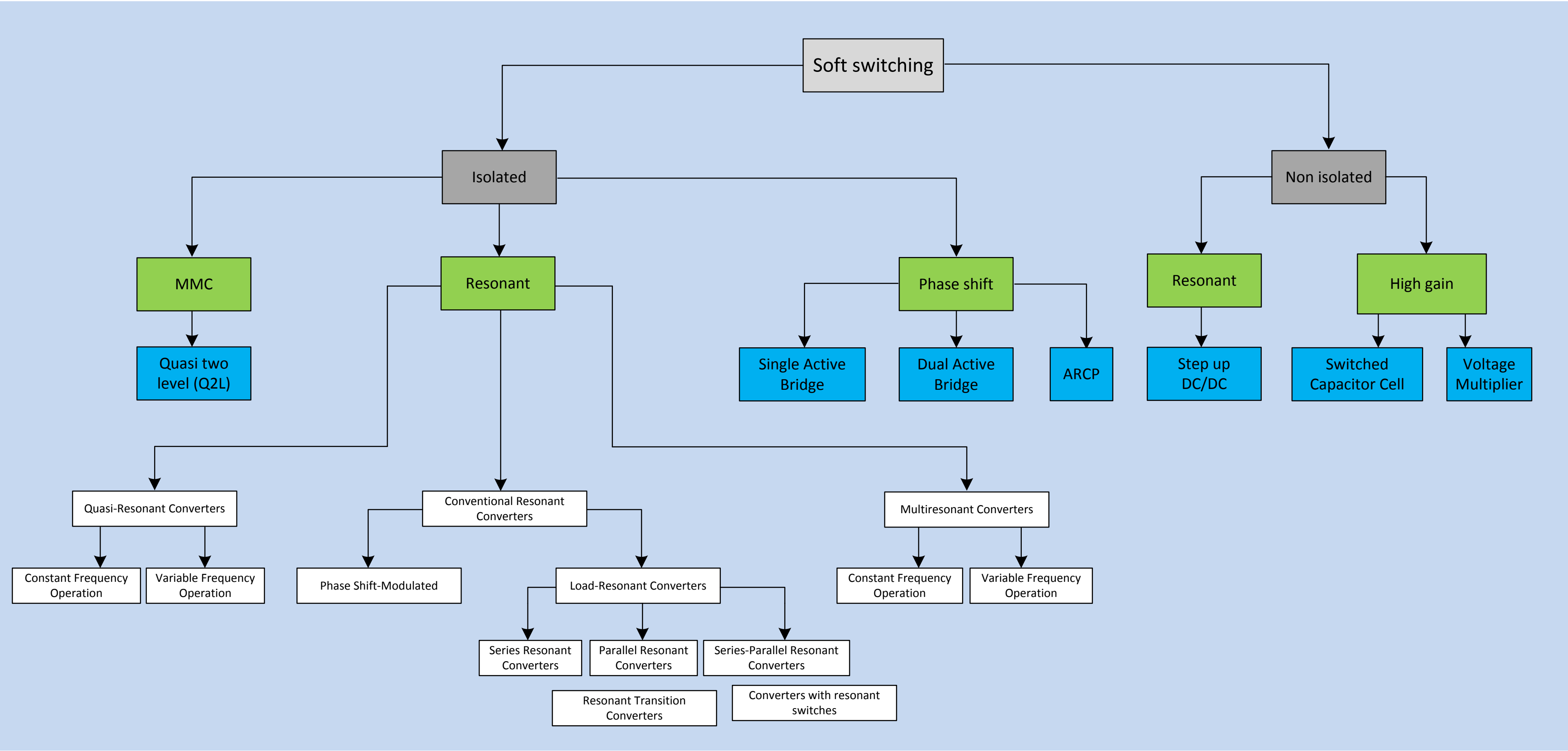
Catalogue of circuits



Catalogue of circuits
Hard Switching

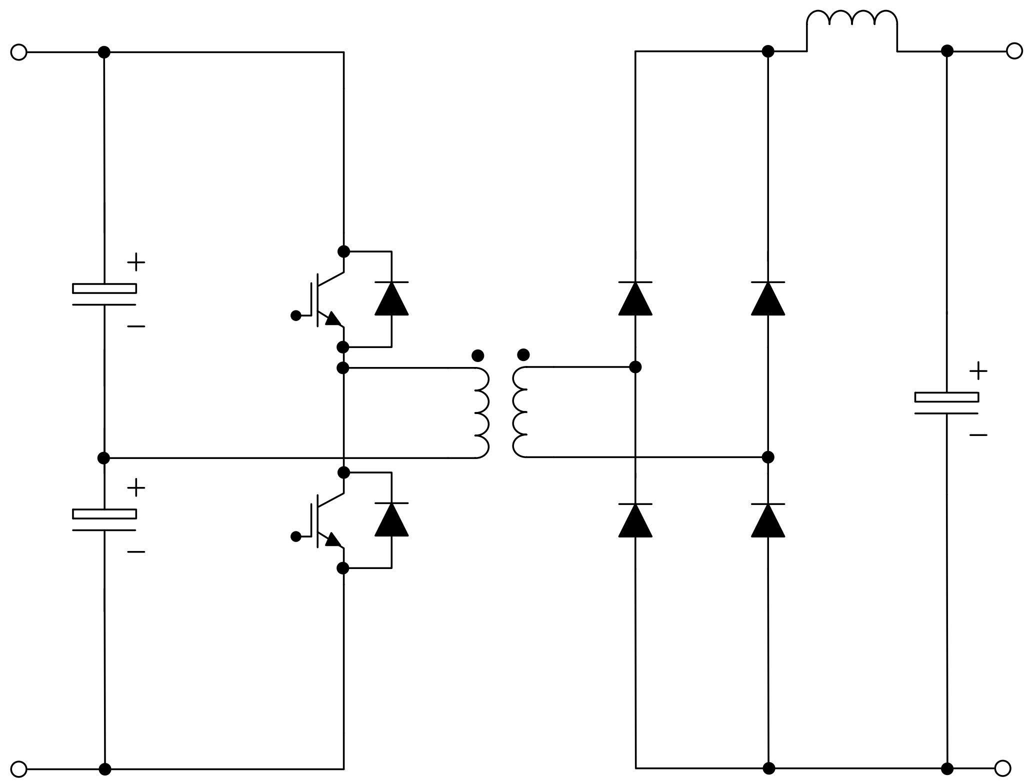


Catalogue of circuits
Soft Switching



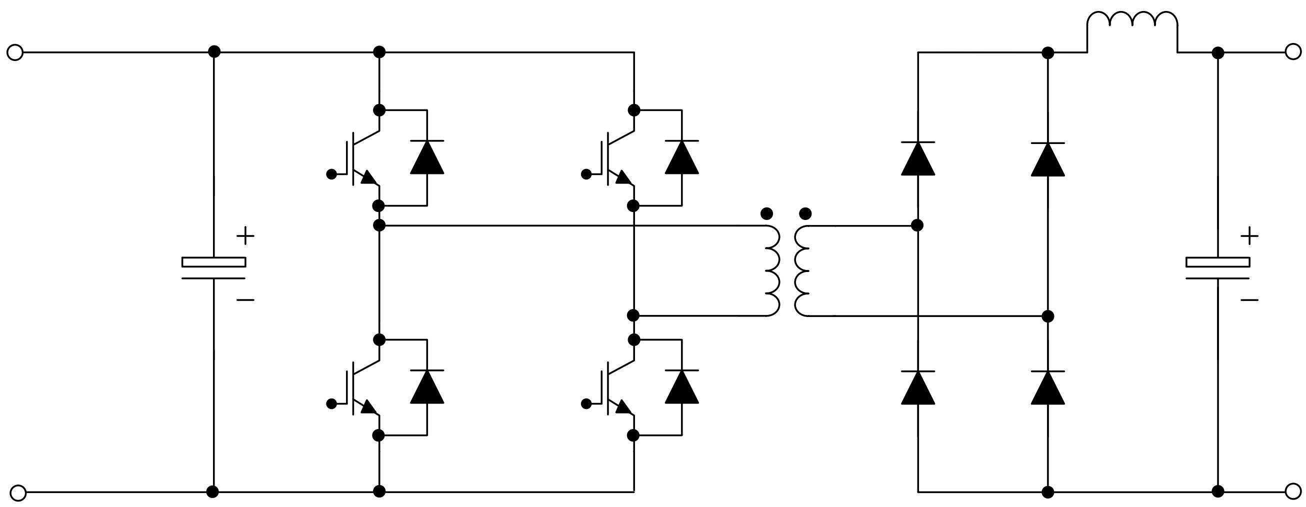
Hard switching-Isolated

1. Half Bridge



Hard switching-Isolated

2. Full Bridge



Hard switching-Isolated

Classic topologies

Advantages:

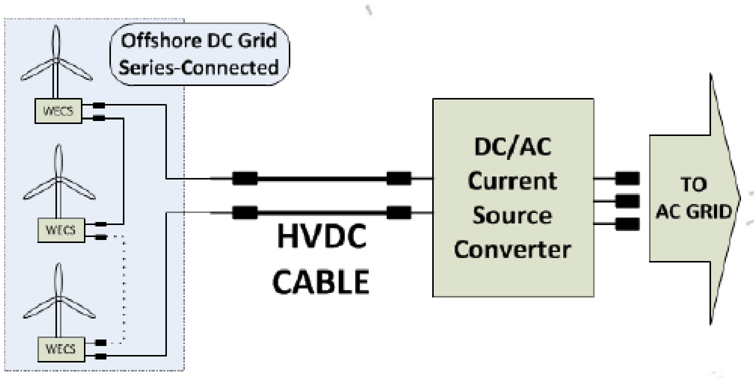
- No output filter required, as square wave voltage applied to the transformer
- Volume of transformer decreased to the higher operating frequency
- No additional snubbers or other components as compared to soft switching topologies
- Use of classic control concepts

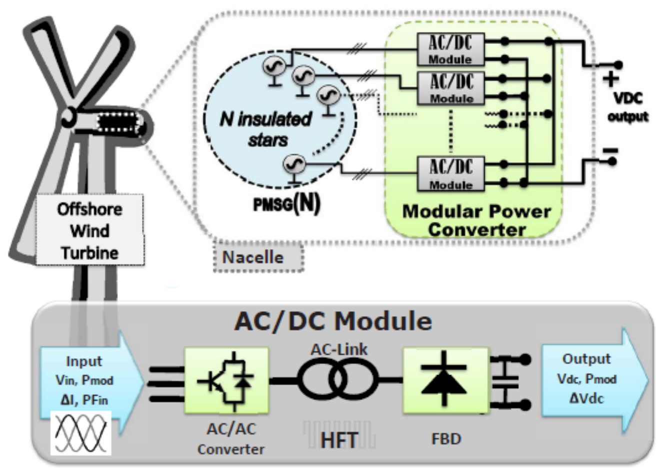
Disadvantages:

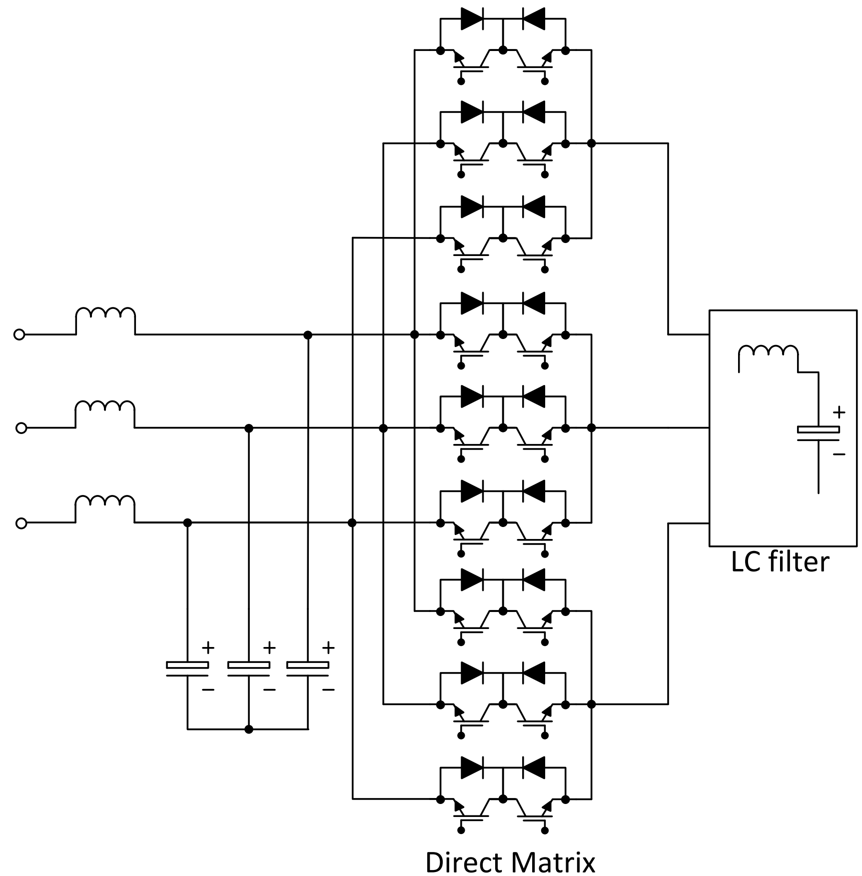
- Hard switching losses on semiconductors
- High transformer dv/dt
- Switching frequency limited to hundred of Hz,
- Transformer frequency limited to hundred of Hz

Hard switching-Isolated

3. Direct Matrix

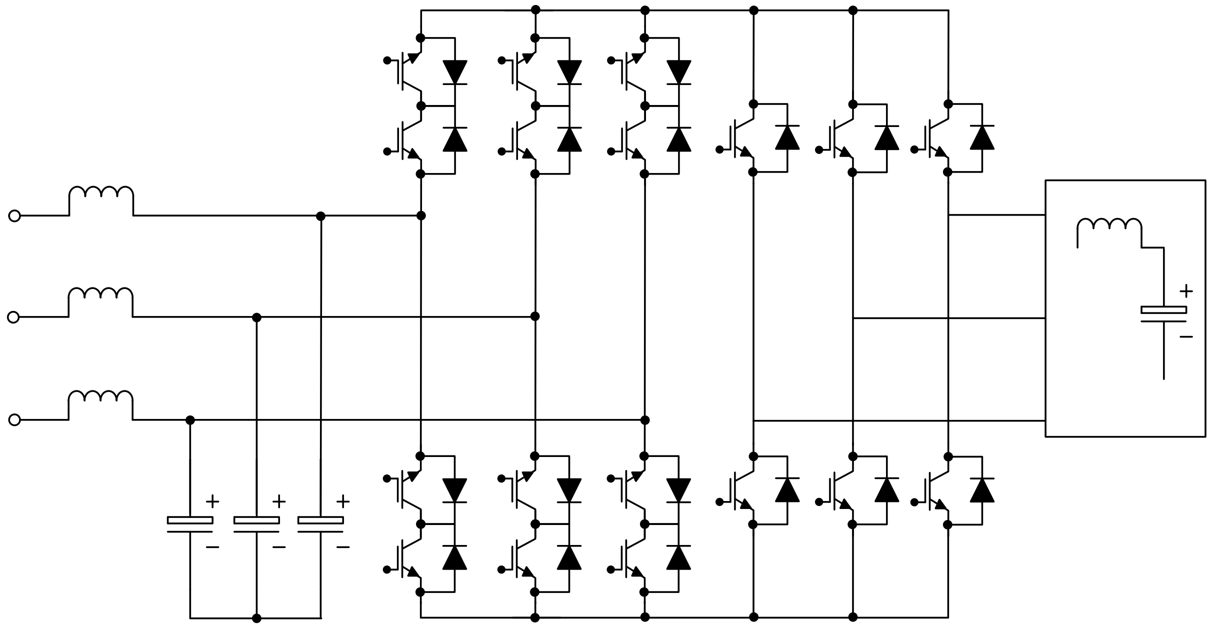






Hard switching-Isolated

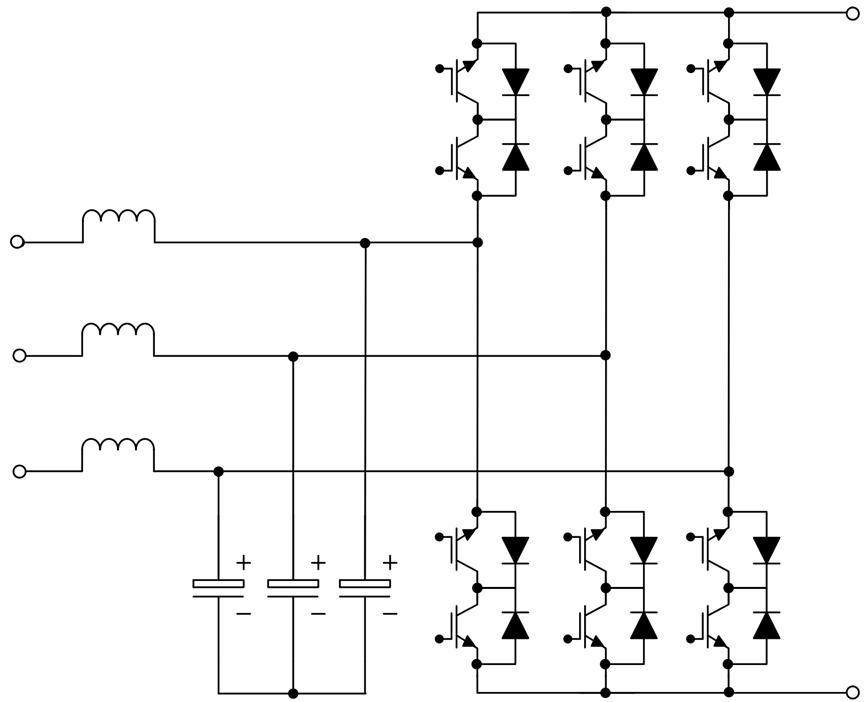
4. Indirect Matrix



Indirect Matrix

Hard switching-Isolated

5. Reduced Matrix



Reduced Matrix

Hard switching-Isolated Matrix converter

Advantages:

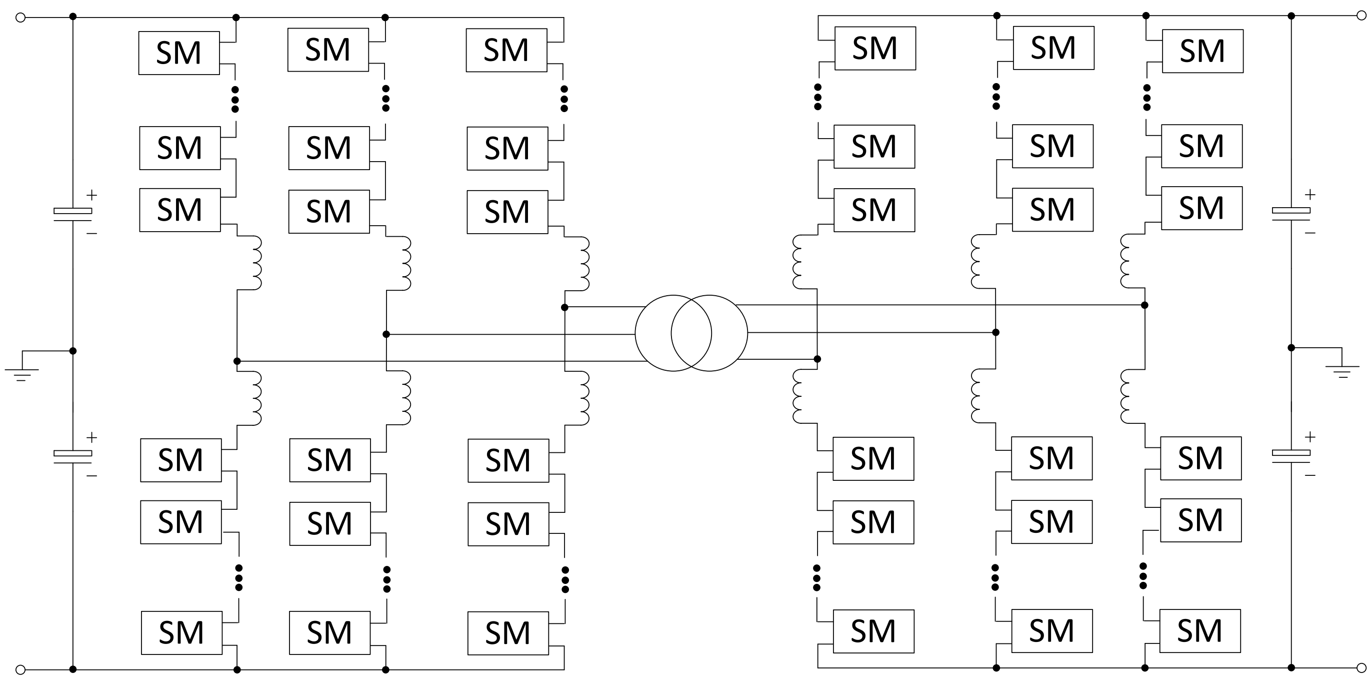
- 3 power stages
- Fewer switches, less switching and ON-state losses
- Smaller transformer due to higher frequency
- The best trade off between efficiency, power density and power to mass ration when the AC-AC converter topology is the direct matrix converter, the AC link frequency is selected around 1 kHz and the power per module is in the range of 2.5 to 4MW
- Compared to conventional 3AC-AC converter with DC Link, it was found that for range of transformer frequencies from 1khz to 20khz, the RMC topology has the most efficieny topology and the higherst power density
- No DC Link capacitors, saving space and components
- Higher efficiency than B2B topology, due to fewer converter stages

Disadvantages:

- All matrix topologies require a clamp circuit as they do not have natural freewheeling path
- The RMC needs to be protected against the overvoltages that might be destructive for semiconductors

Hard switching-Isolated

6. MMC-Front to front



Hard switching-Isolated

6. MMC-Front to front

Advantages:

- - low switching losses
- - Voltage across each module can be controlled separately
- - Easier voltage balancing across the switches
- - High voltage applications motivate the use of modular converter systems
- - Potential replacement for the cascaded multilevel converter in medium voltage applications
- - Fault tolerant operation
- - operation independent of ac side power factors and modulation indices
- - extendibility without capacitor voltage balancing problems.
- - Transformer winding can experience low dv/dt
- - The MMC can be controlled in a similar manner like the DAB, using phase shift switching actions
- - Able to interrupt power flow without using a circuit breaker
- - High efficiency for high powers >99.5%

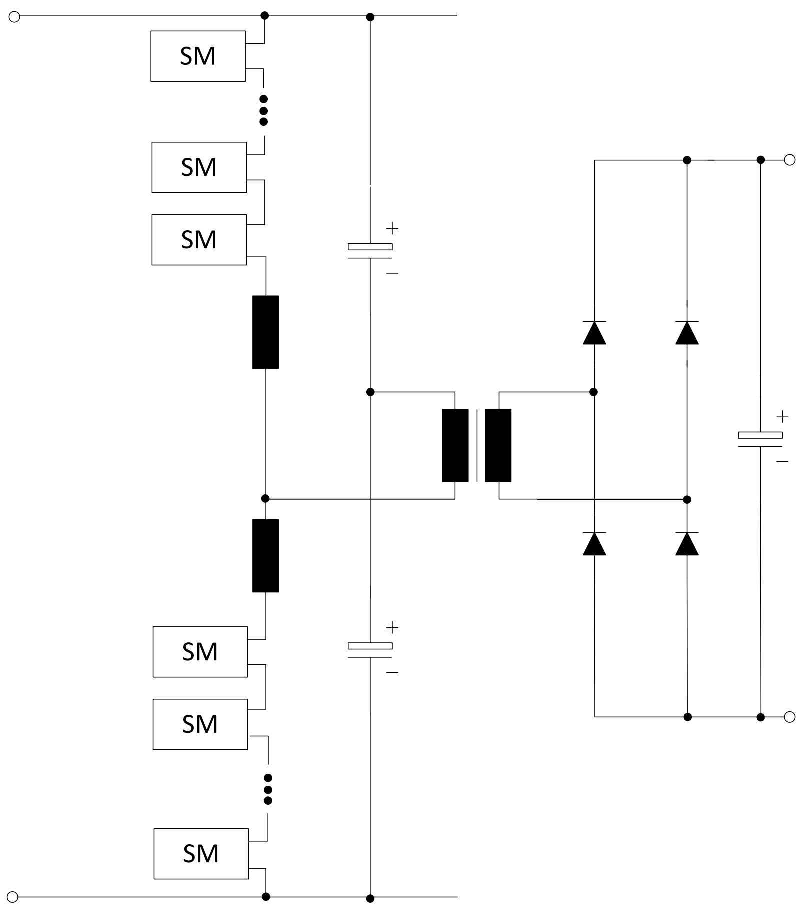
Disadvangages:

- - Capacitors occupy a large fraction of the volume
- - Increase in power circuit and control complexity

Hard switching-Isolated

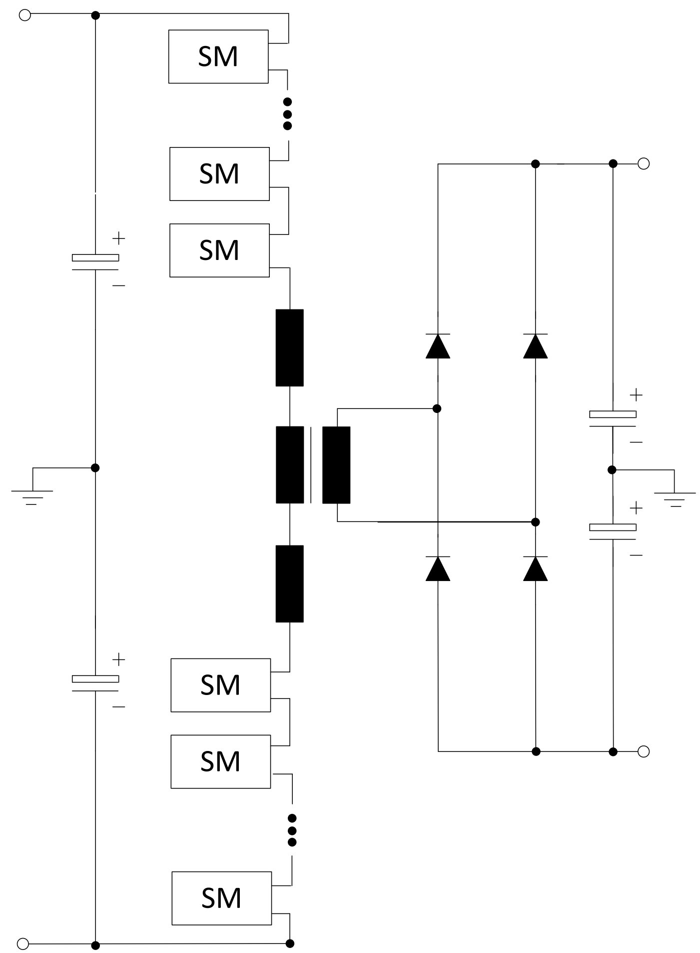
7.M2DC-Shunt connected Primary

M2DC with intermediate AC transformation and shunt connected primary



Hard switching-Isolated

8. M2DC Series Connected Primary



Hard Switching-Isolated M2DC

Advantages:

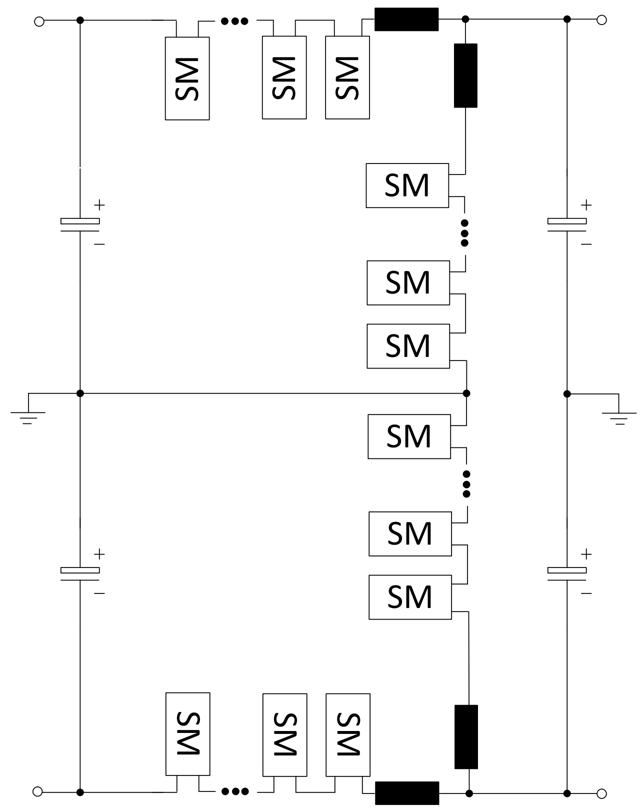
- Do not suffer from energy drift
- Full fault propagation prevention due to galvanic separation
- Main application for HVDC taps (500kV to 50kV)
- Lower power capacity factor than the direct conversion
- AC frequency can be optimized to achieve the most suitable trade off between transformer size and switching losses

Disadvantages:

- The transformer is a significant component in terms of volume and power losses
- Control complexity

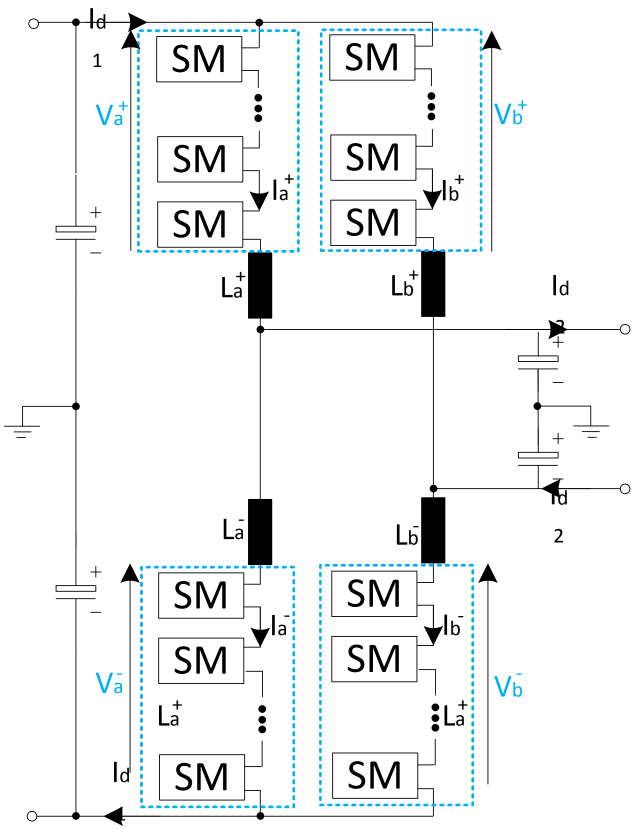
Hard switching-Non Isolated

9. M2DC Series Output Poll



Hard switching-Non Isolated

10. M2DC Parallel Output Pol



Hard switching-Non Isolated M2DC

Advantages:

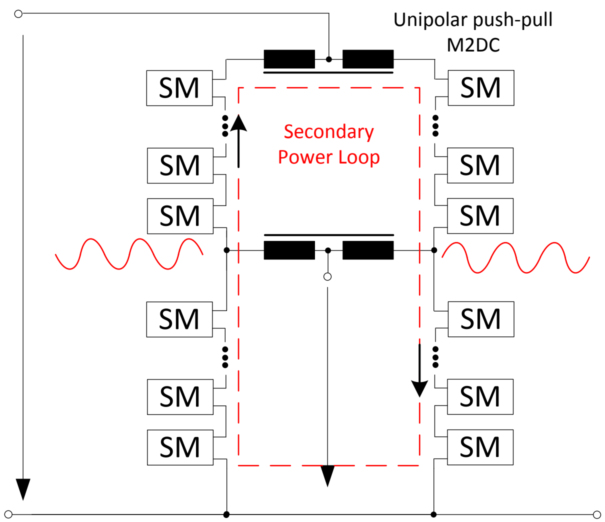
- - Suitable for direct connection
- - Suitable for connecting HVDC links of similar power but different nominal voltages
- - DC version of the MMC

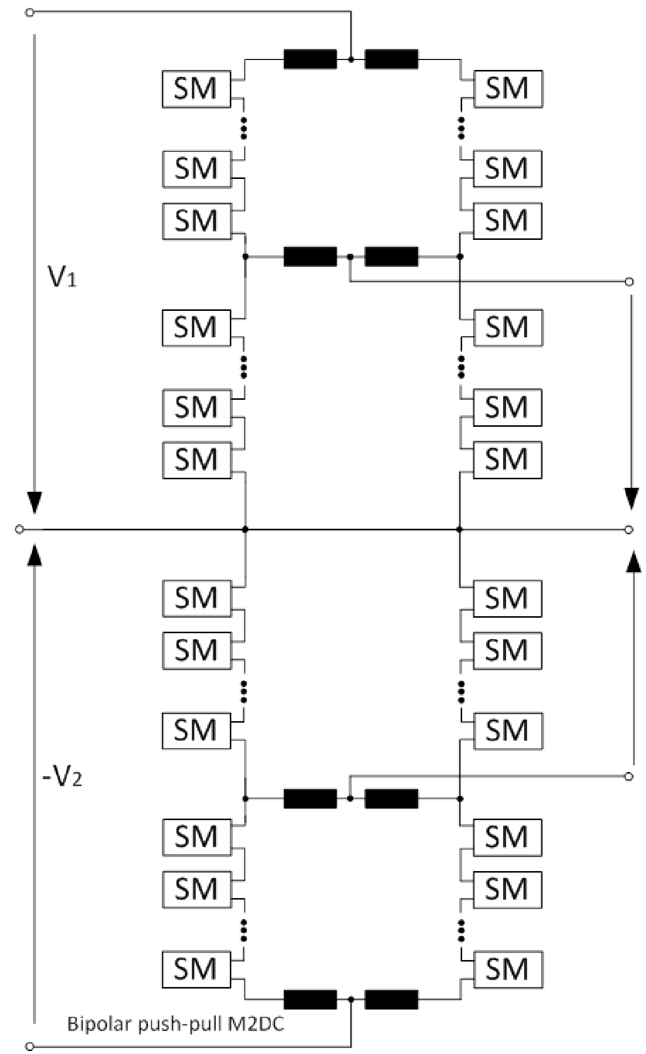
Disadvantages:

- - Control complexity
- - Major issues in cell balancing currents
- - The non isolated versions suffer from an energy drift and require an internal AC rebalancing current to be circulated
- - Poor power capacity factor which gets worse as the ratio between the DC voltages increases
- - They are not suited for interfacing smal amounts of power to a large HVDC
- - No galvanic separation
- - Suitable for smal voltage gain <2
- - Requires large number of semiconductors, 50% more devices than a conventional buck-boost converter
- - Compared to DAB, the investment cost is at least by a factor of three higher.
- which results in a poor efficiency of less than 95.5%

Hard switching-Non isolated

11. M2DC Push Pull Uni and Bipolar





Hard switching-Non isolated

11. M2DC Push Pull Uni and Bipolar

Advantages:

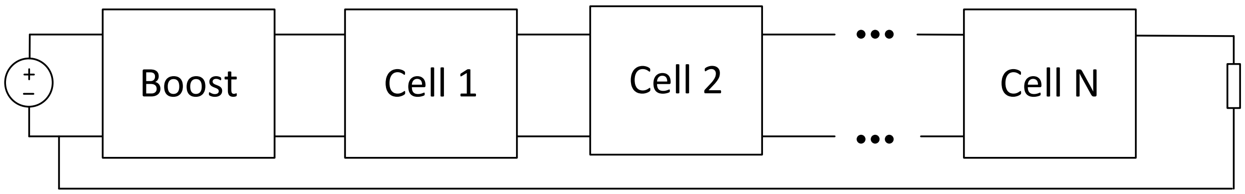
- Secondary power loop introduced that exchanges power with the primary power loops at the input and the output
- Power is exchanged between the primary and the secondary loops by using the principle of orthogonality of power flow at different frequencies

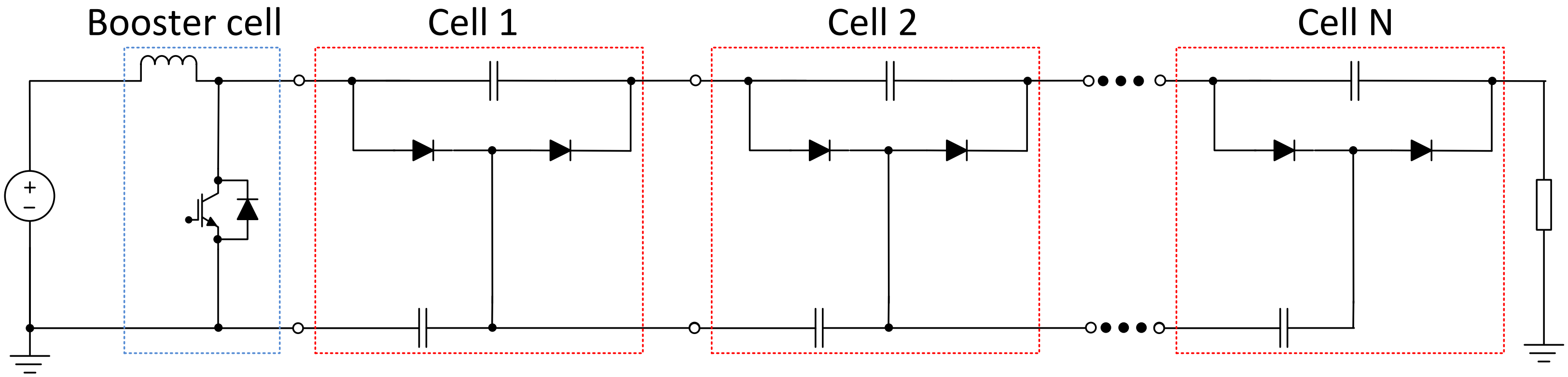
Disadvantages:

- Control complexity
- Not suitable for high voltage ratios, because in this case the circulating current in the converter becomes high

Hard switching-Non isolated

12. Cockcroft Walton





Hard switching-Non isolated

12. Cockcroft Walton

Advantages:

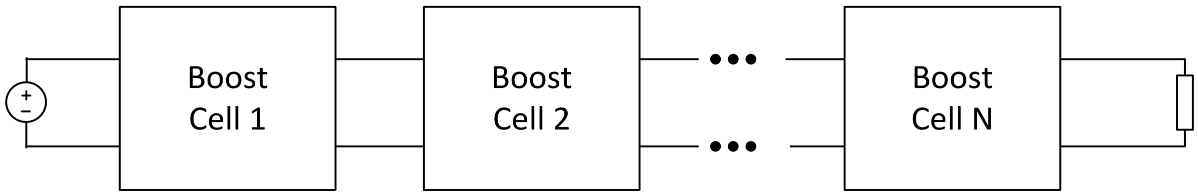
- - Possible to reach high voltage gain
- - Low weight and volume
- - Simple control
- - Simple structure
- - Switches can be diodes
- - Soft switching capability
- - Ripple cancellation with symmetrical and double ladder

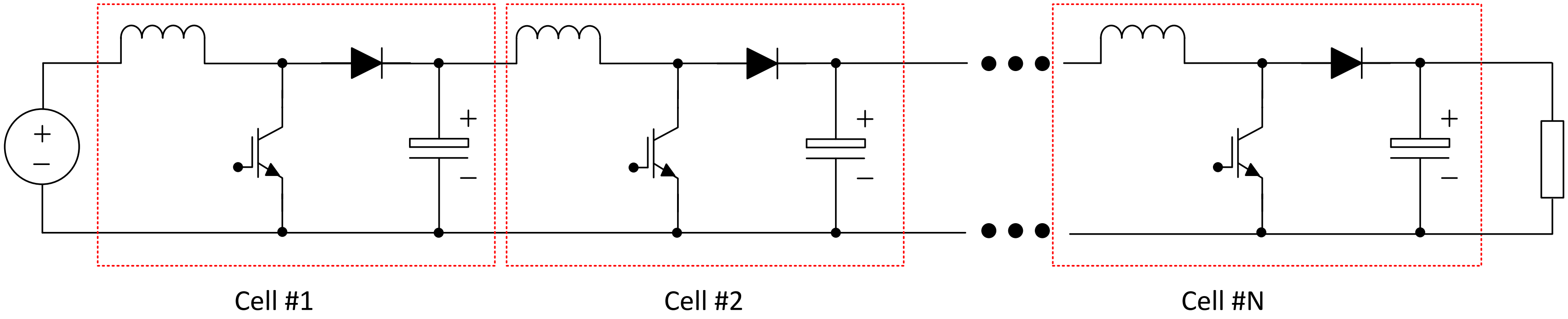
Disadvantages:

- - Suitable for high voltage, low current applications
- - No ripple cancellation with classic ladder
- - Poor voltage regulation
- - No galvanic separation
- - Large ESR capacitors (or series resistances) are prefferable for low current ripple, hence high
- output impedance and additional losses
- - Pulsed output current
- - Insulation to ground
- - Voltage sag at higher stages

Hard switching-Non isolated

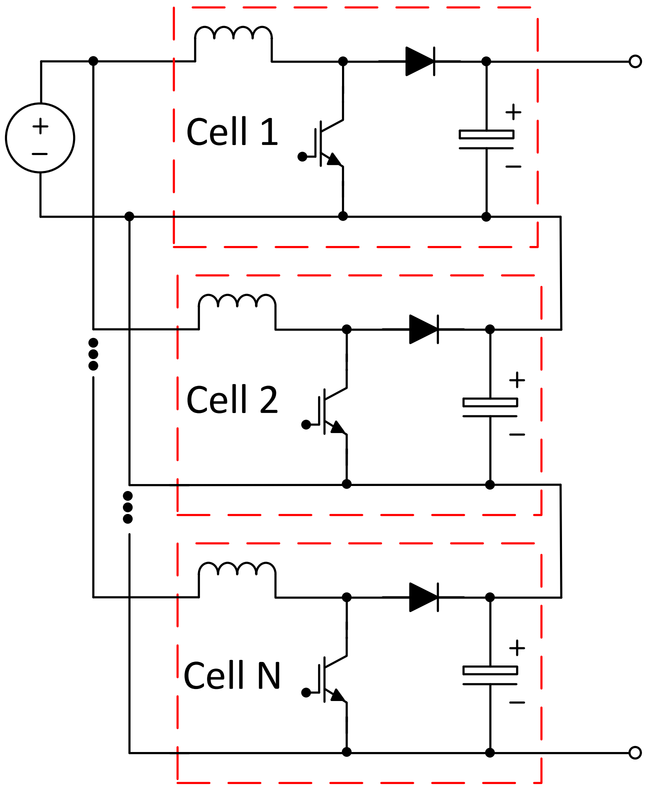
13. Cascaded Boost

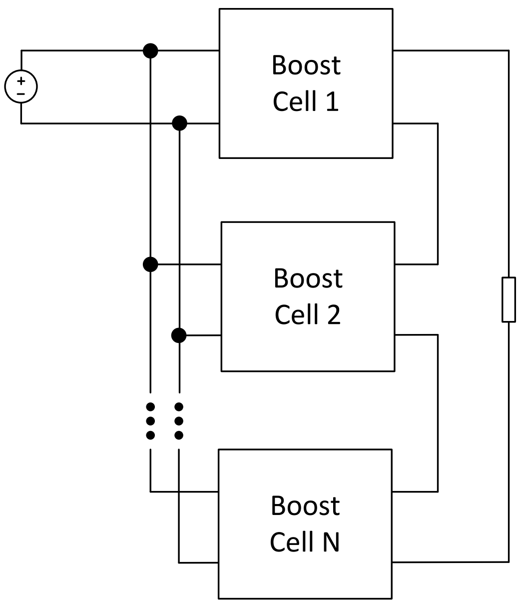




Hard switching-Non Isolated

14. Series Boost





Series boost connection

Hard switching-Non Isolated

Cascaded and Series Boost

Advantages:

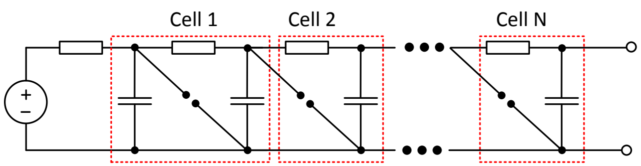
- - Reduced switch and diode voltage stress on lower stages
- - High flexibility
- - Suitable for high power applications through interleaving connections
- - Interleaved operation for low current ripple
- - softswitching operation possible through the use of a resonant inductor L

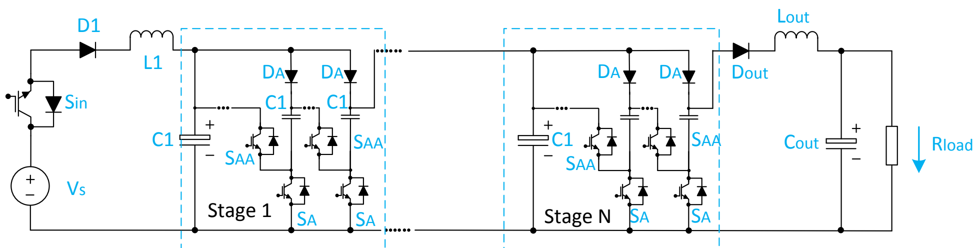
Disadvantages:

- - Total power processed N times (according to N stages)
- - High switch and diode voltage stress on higher stages
- - Maximum and minimum duty-cycle limitation to guarantee soft commutation
- - High switch RMS current
- - Voltage stress reduction related to the number of cells
- - Regarding multiple module boost converter, because the duty ratio of the main switch is large to achieve high-voltage gain, the switching frequency is relatively low to reduce the losses and also allows sufficient turn-off time for the switches. Therefore, increasing the size of passive elements, such as boost inductors and filter capacitors is inevitable due to low switching frequency.
- - Diode reverse recovery causes loss, even at low frequency and increases the turn-on stress of the power switch.

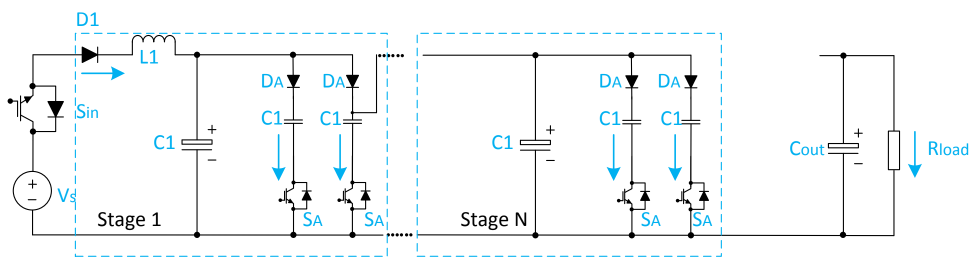
Hard switching-Non isolated

15. Marx converter

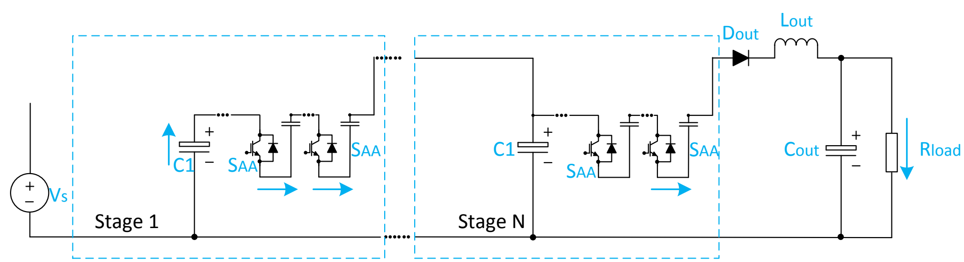




Generalized configuration for the Marx dc-dc converter with N stages with M capacitors per stage



Charging of capacitors in parallel



Discharging of capacitors in series

Hard switching-Non isolated

15. Marx converter

Advantages:

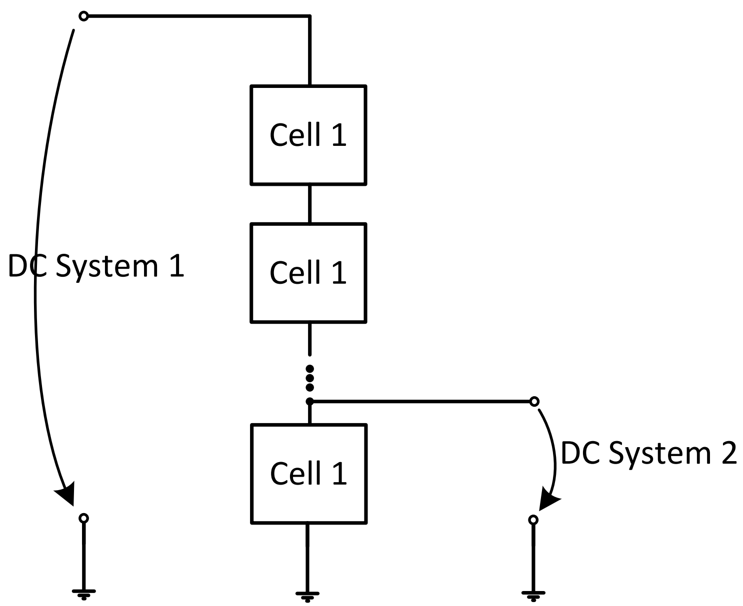
- Compared to boost converter, the Marx dc-dc converter is shown to be competitive and even advantageous for higher dc gain. At dc gain of 8, the Marx dc-dc converter has lower VA ratings on the inductor, capacitor and IGBT. Efficiency is increasing as the gain increases. At dc gain of 8, the efficiency of the Marx converter is evaluated at 98.3% compared to 96.8% for the boost converter (insert reference).
- Possibility of soft switching

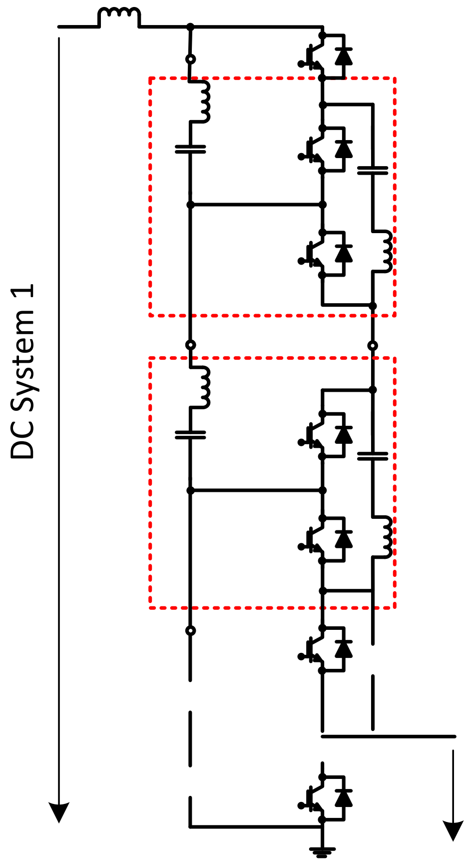
Disadvantages:

- - Doesn’t have voltage regulator property. It only amplifies its input voltage by the designed gain. As a result, it is neccesary to add an additional stage at the input that will provide the control variable to regulate the output voltage.

Soft switching-Non Isolated

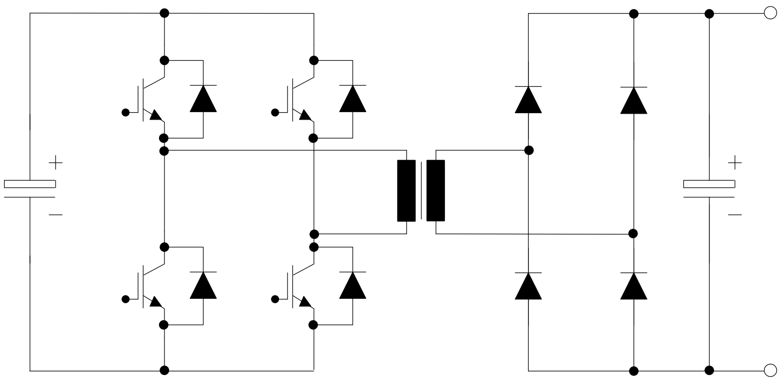
16. Resonant Cockcroft Walton

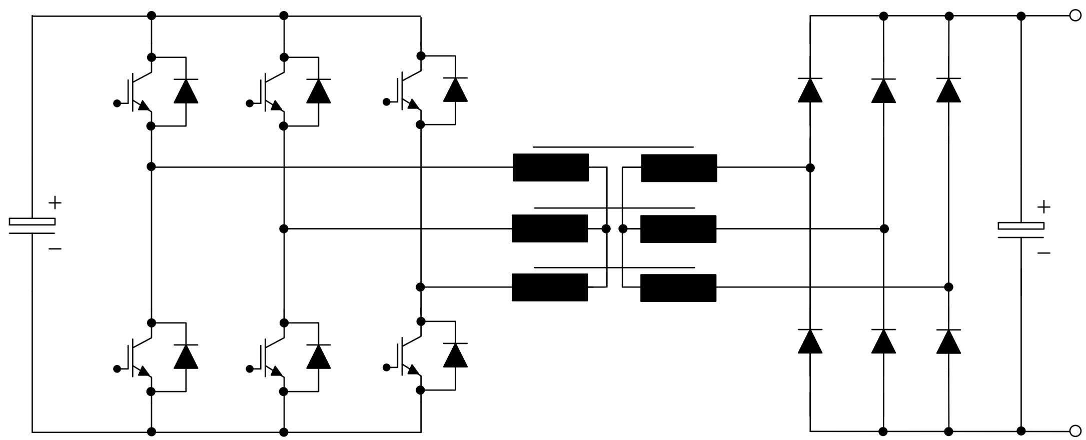




Soft switching-Isolated

17. Phase shift-Single Active Bridge





Soft switching-Isolated

17. Phase shift-Single Active Bridge

Advantages:

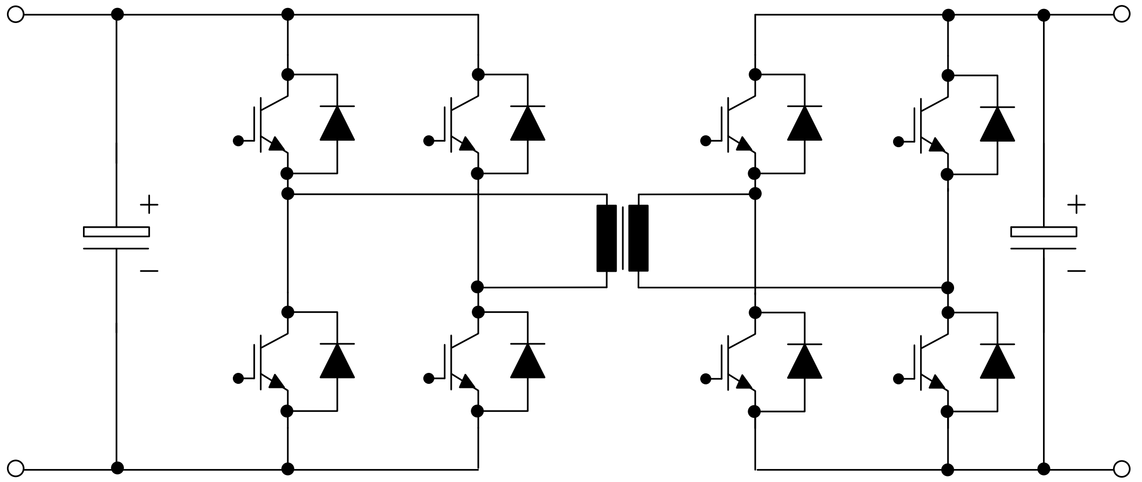
- The converter is easy to control and current control can be used
- Constant frequency operation
- Can be used in high power applications and dc-dc converters
- Compact and low-weight design
- Can be used in high voltage applications
- The leakage inductance can be integrated in the circuit
- Low number of passives

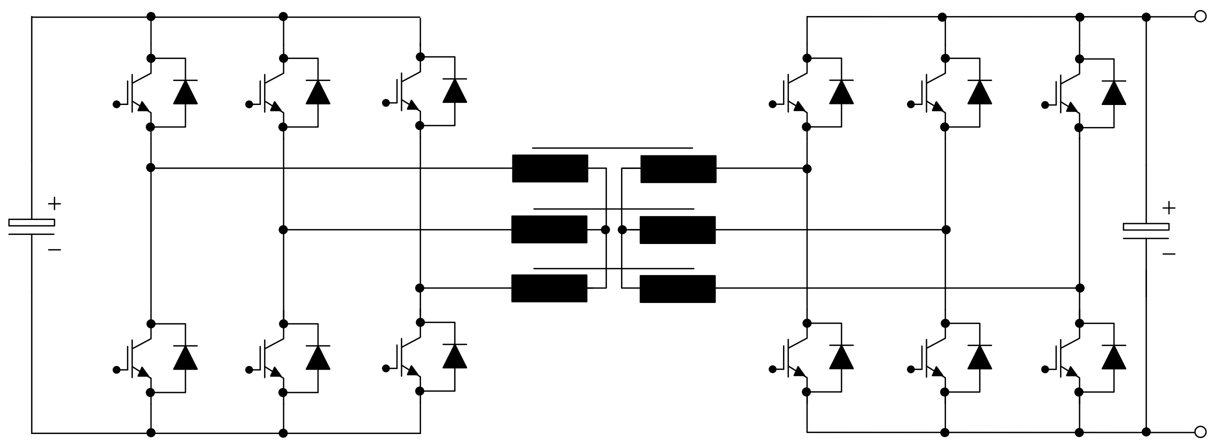
Disadvantages:

- output diodes are hard switched
- Interactions of the leakage inductance with the output rectifier
- The use of a half bridge as an input bridge is not possible

Soft switching-Isolated

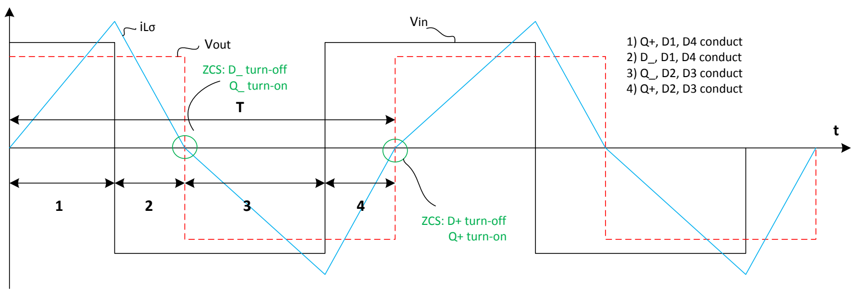
18. Phase shift-Dual Active Bridge

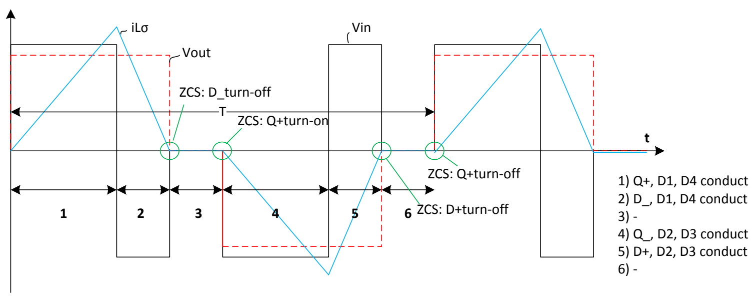


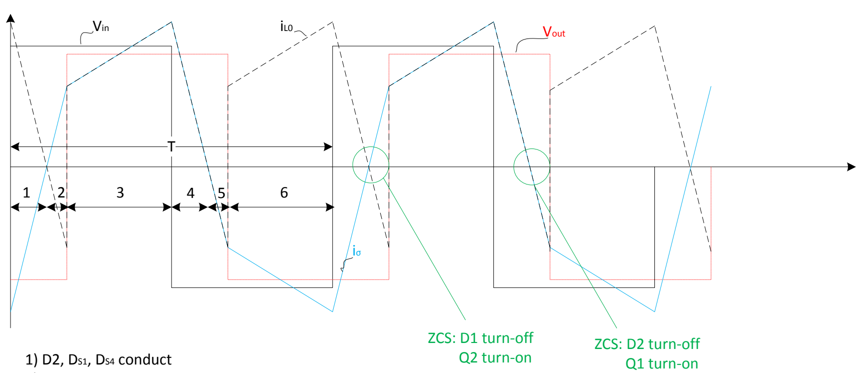


Soft switching-Isolated

18. Phase shift-Dual Active Bridge



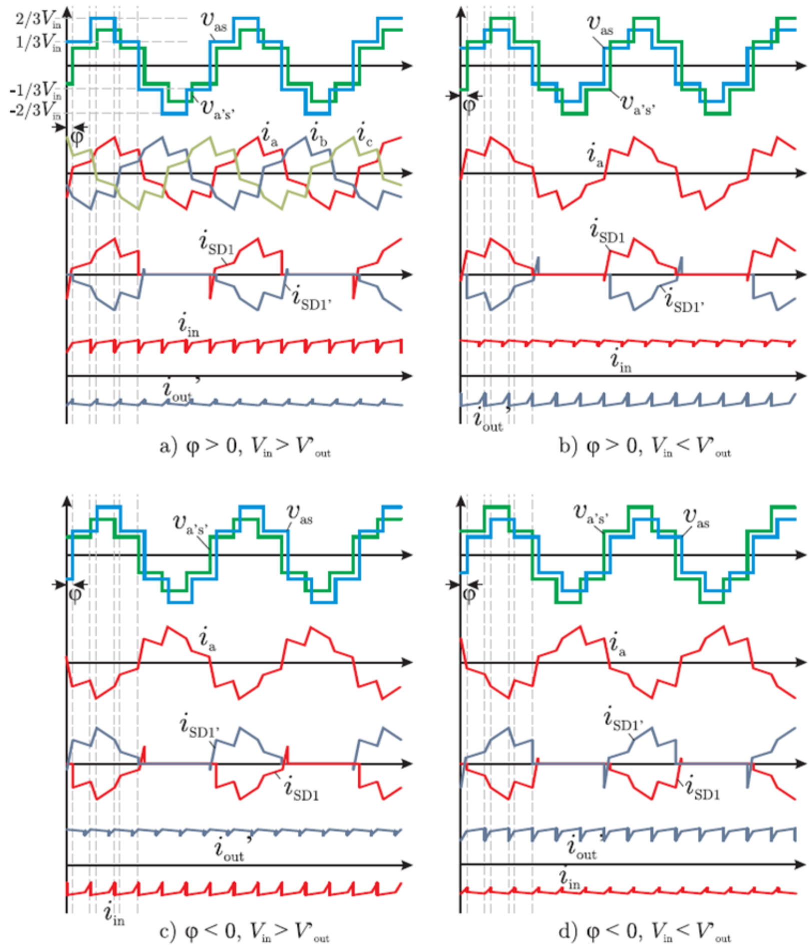




1) D2, D_{s1}, D_{s4} conduct
2) Q1, Q_{s1}, Q_{s4} conduct
3) Q1, D_{s2}, D_{s3} conduct
4) D1, D_{s2}, D_{s3} conduct
5) Q2, Q_{s2}, Q_{s3} conduct
6) Q2, D_{s1}, D_{s4} conduct

Soft switching-Isolated

18. Phase shift-Dual Active Bridge



Soft switching-Isolated

18. Phase shift-Dual Active Bridge

Advantages:

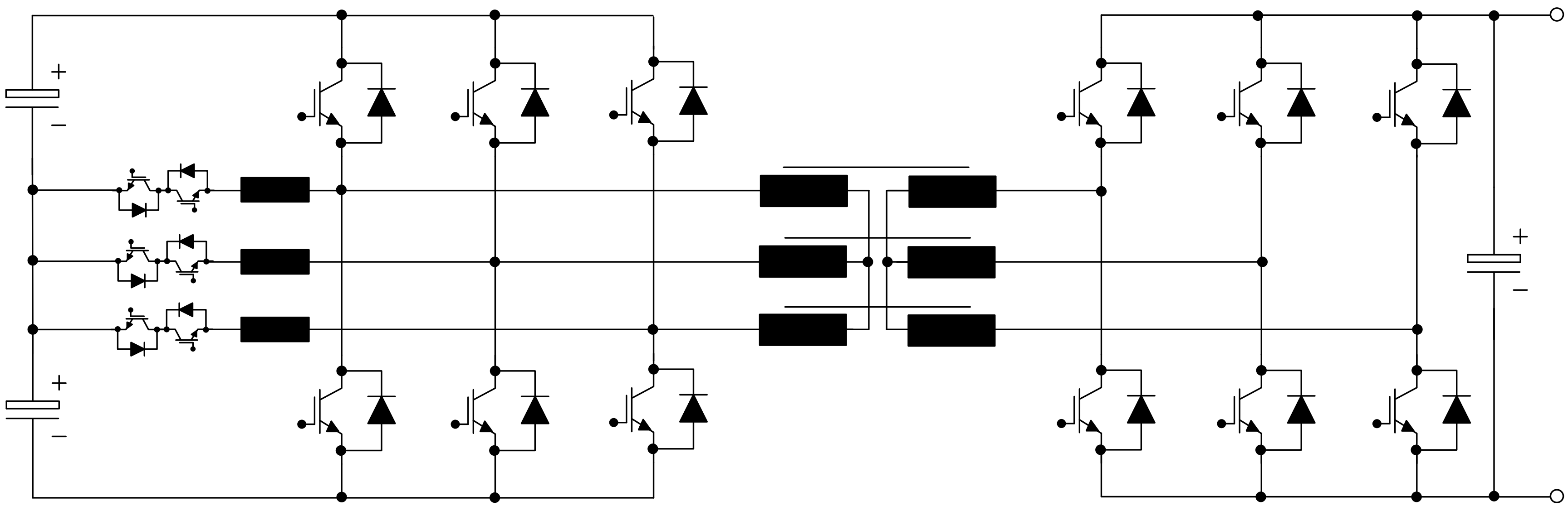
- Step up and step down operation
- Control simplicity
- Constant frequency
- Minimum number of passive components
- Ideally no switching losses without increased conduction losses
- By controlling the secondary active switching devices, soft-switching can be achieved

Disadvantages:

- High ripple current through the output capacitor
- Comparably high KVA rating of the transformer
- At light loads additional energy is needed in order to achieve ZVS.

Soft switching-Isolated

19. Phase shift-DAB with ARCP



Three phase dual active bridge
with ARCP

Soft switching-Isolated

19. Phase shift-DAB with ARCP

Advantages:

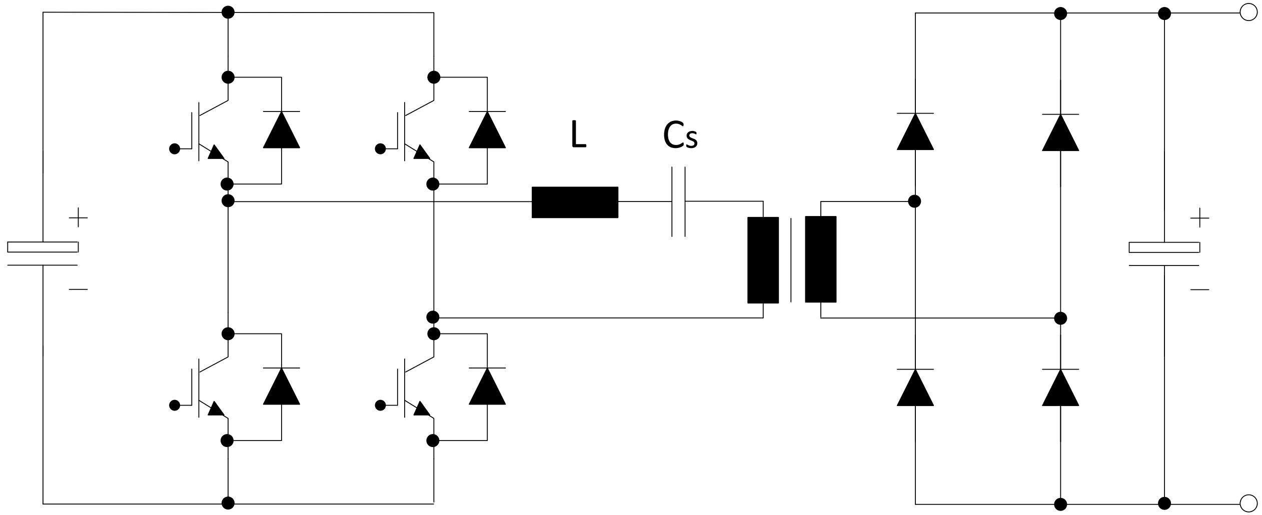
- Has the lowest (as HS-PWM topology) transformer KVA rating
- Due to soft switching it can run at higher frequencies and as a result has the smallest transformer compared with other soft-switched topologies
- Lower main device stresses than any other soft-switched topology
- Current mode and voltage mode PWM control can be used
- Simple control

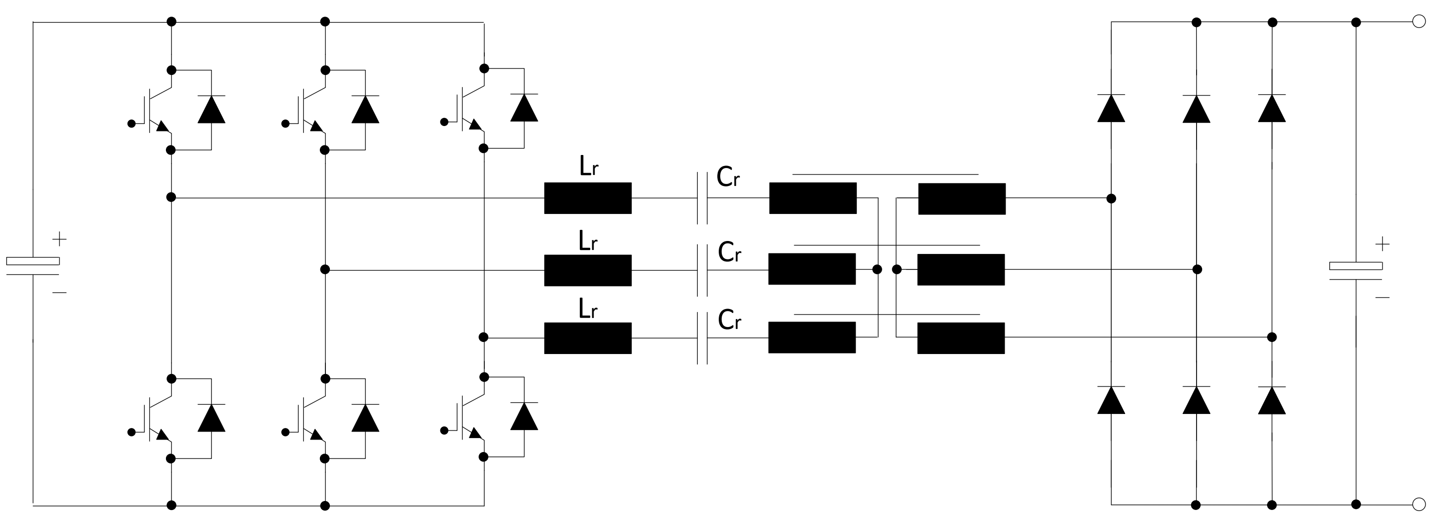
Disadvantages:

- Large number of passive components
- Large number of active components
- Output diodes are hard switched
- Hald bridge operation is not possible.

Soft switching-Isolated

20. Resonant load - SRC

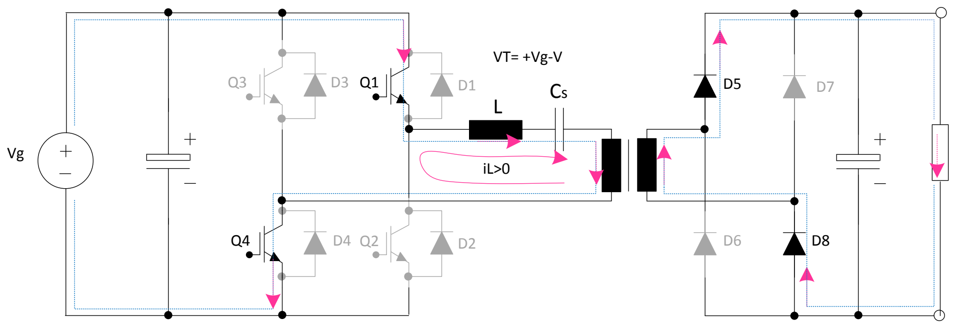


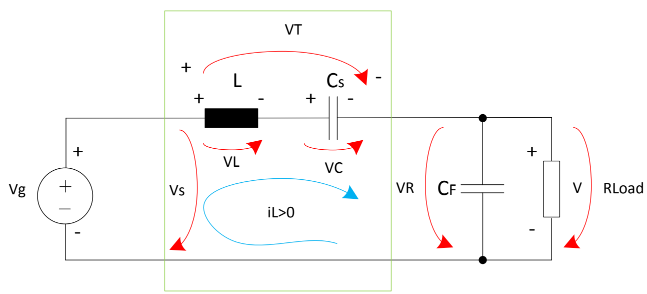


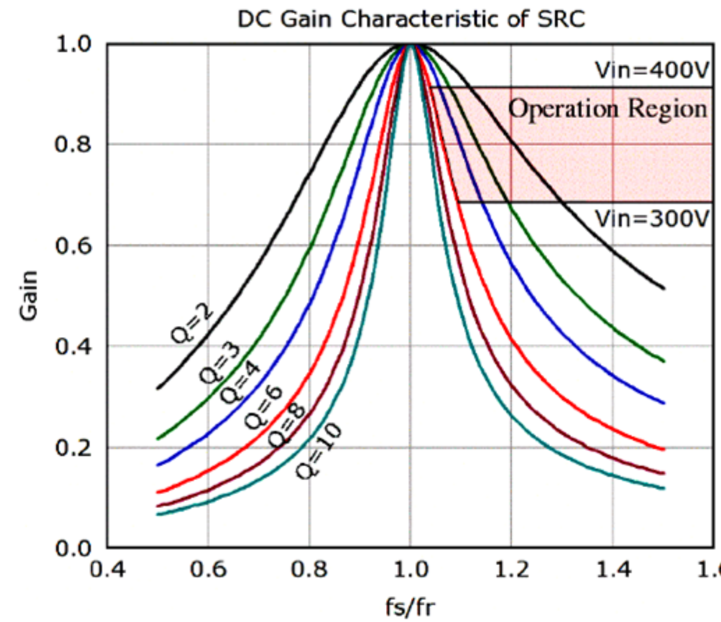
Soft switching-Isolated

20. Resonant load - SRC

1) Q_1, Q_4, D_5, D_8 conduct ($i_L > 0$) => V_C ↗







VT(t)= Vs(t)- VR(t)

Vs= +Vg

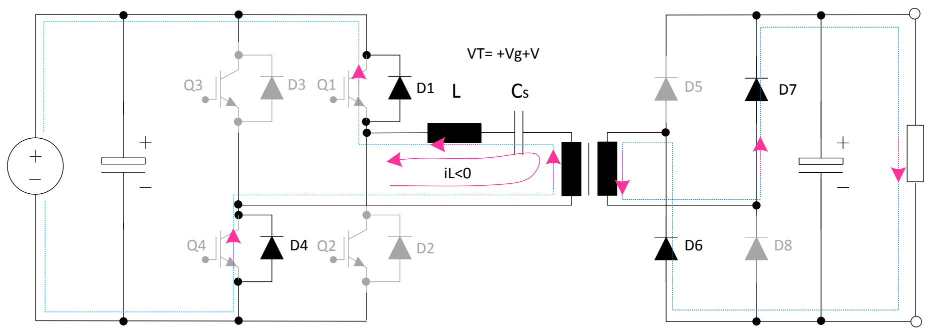
VR= +V

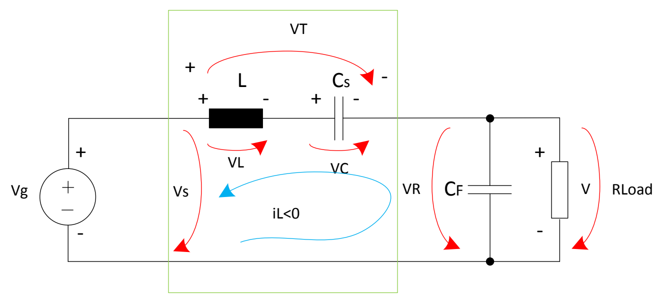
VT= +Vg-V

Soft switching-Isolated

20. Resonant load - SRC

2) D_1, D_4, D_7, D_6 conduct ($i_L < 0$) => V_c ↘





$V_T(t) = V_s(t) - V_R(t)$

$V_s = +V_g$

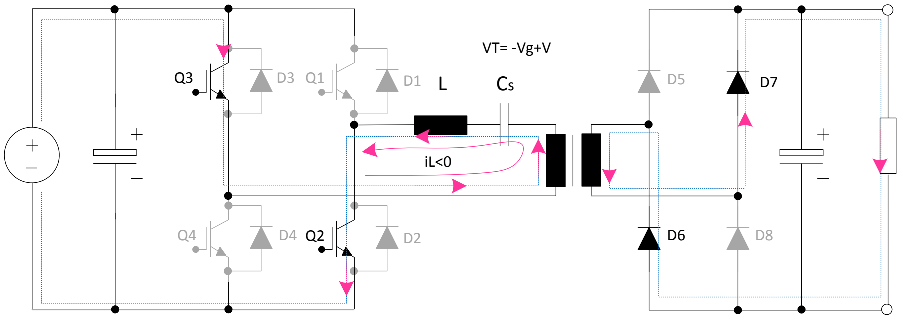
$V_R = -V$

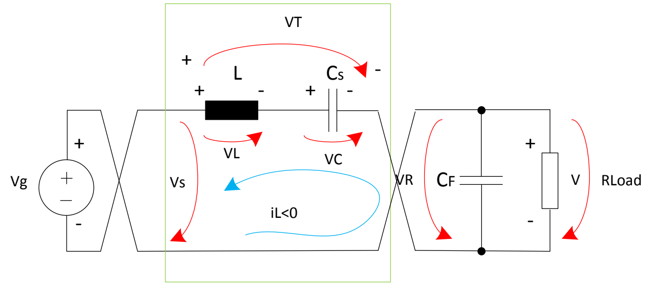
$V_T = +V_g + V$

Soft switching-Isolated

20. Resonant load - SRC

3) Q_2, Q_3, D_7, D_6 conduct ($i_L < 0$) => V_c ↘





$V_T(t) = V_s(t) - V_R(t)$

$V_s = -V_g$

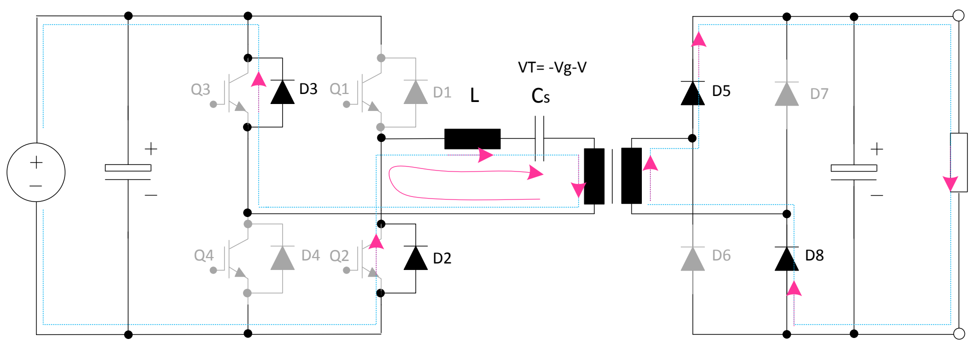
$V_R = -V$

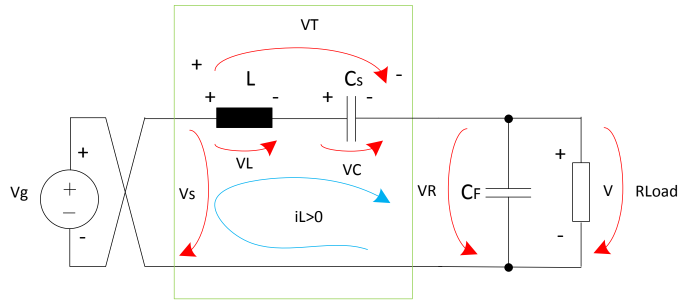
$V_T = -V_g + V$

Soft switching-Isolated

20. Resonant load - SRC

4) D2, D3, D8, D5 conduct ($i_L > 0$) => V_c ↗

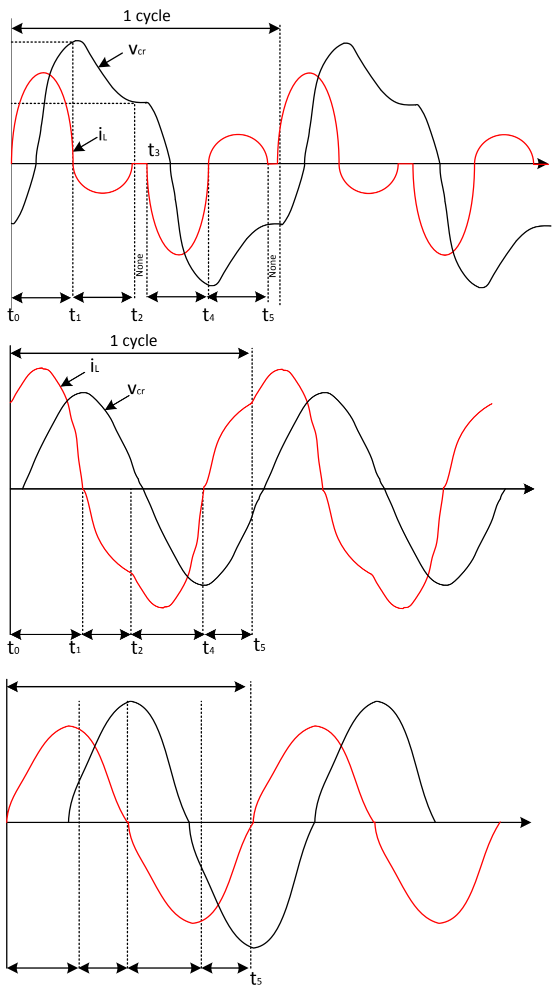


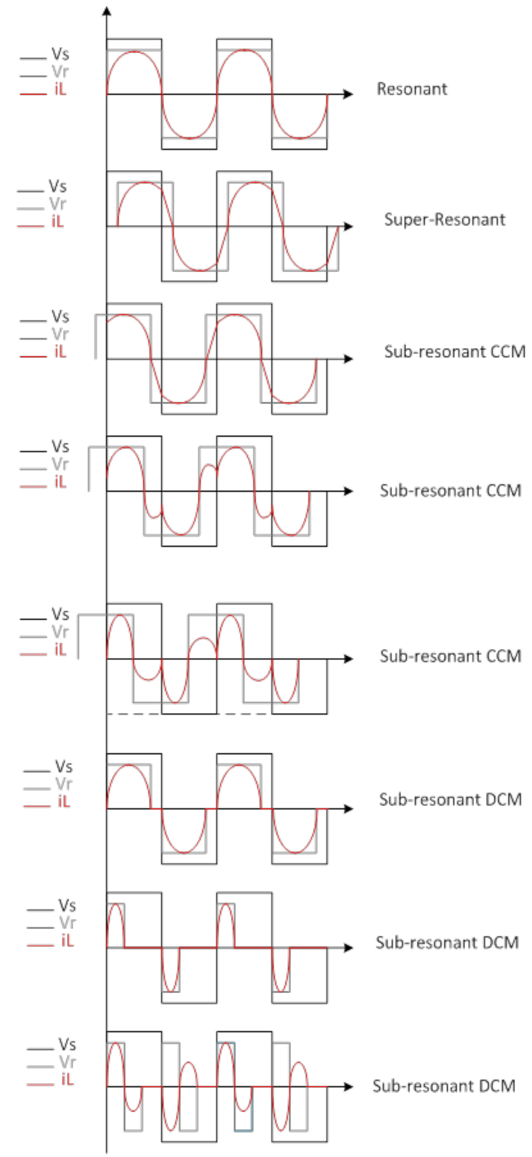


VT(t)= Vs(t)- VR(t)
Vs= -Vg
VR= +V
VT= -Vg-V

Soft switching-Isolated

20. Resonant load - SRC

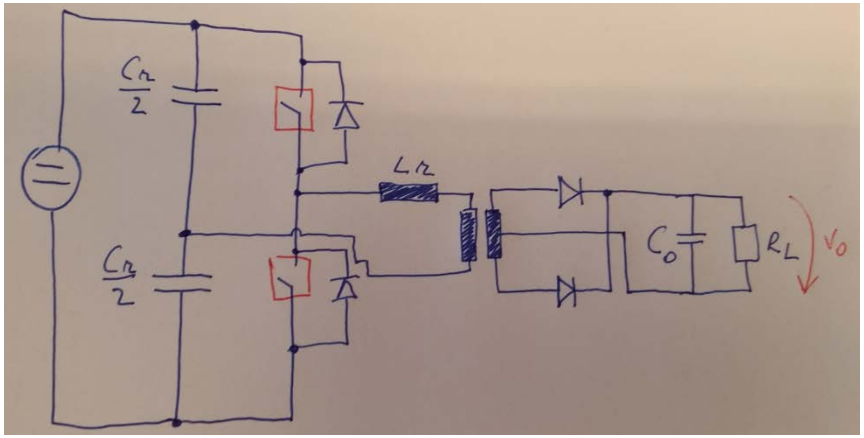




Circuit waveforms under different operating conditions: sub-resonant DCM, sub-resonant CCM, super-resonant CCM

Soft switching-Isolated

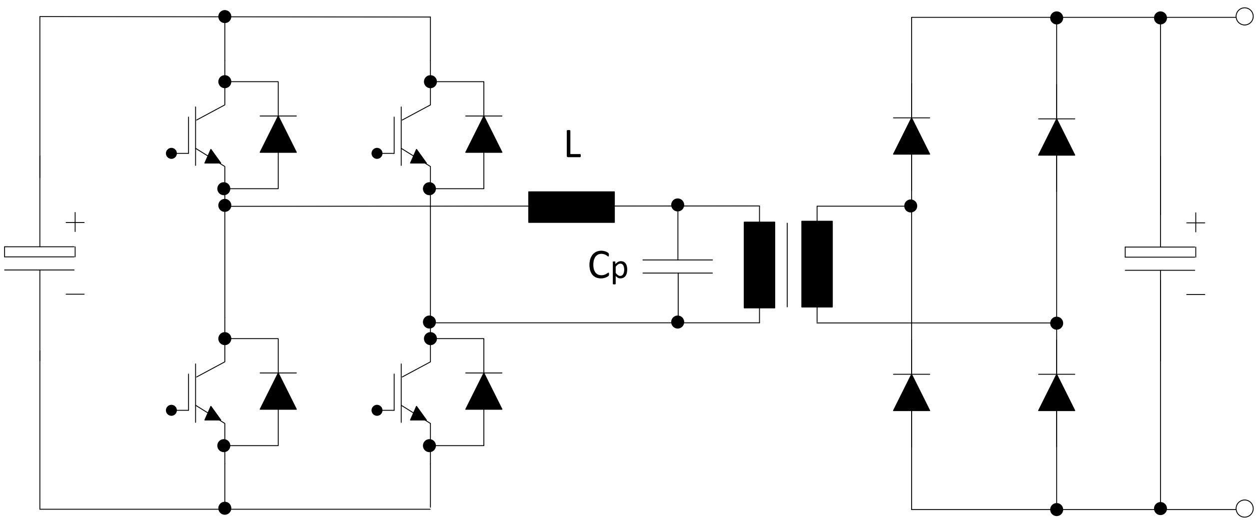
21. Resonant load-SRC



Alternate implementation of SRC

Soft switching-Isolated

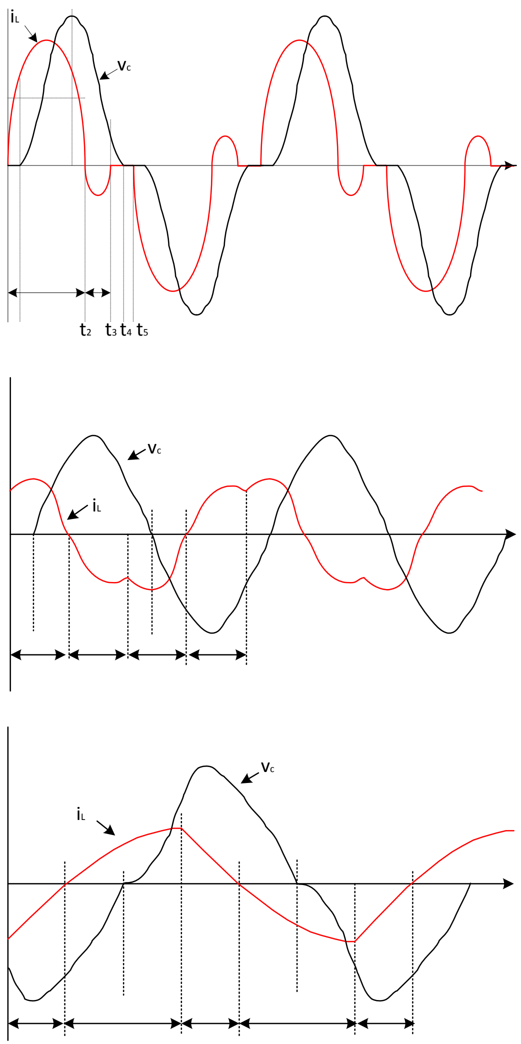
22. Resonant load- PRC

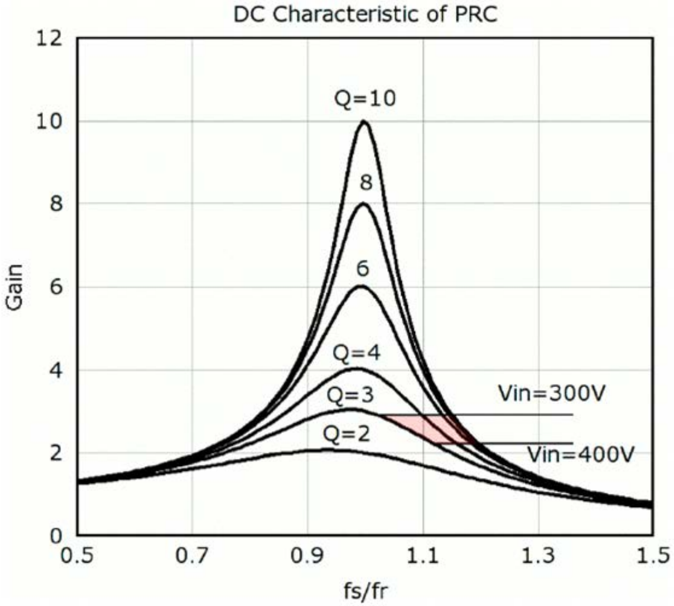


Parallel Resonant Converter

Soft switching-Isolated

22. Resonant load- PRC

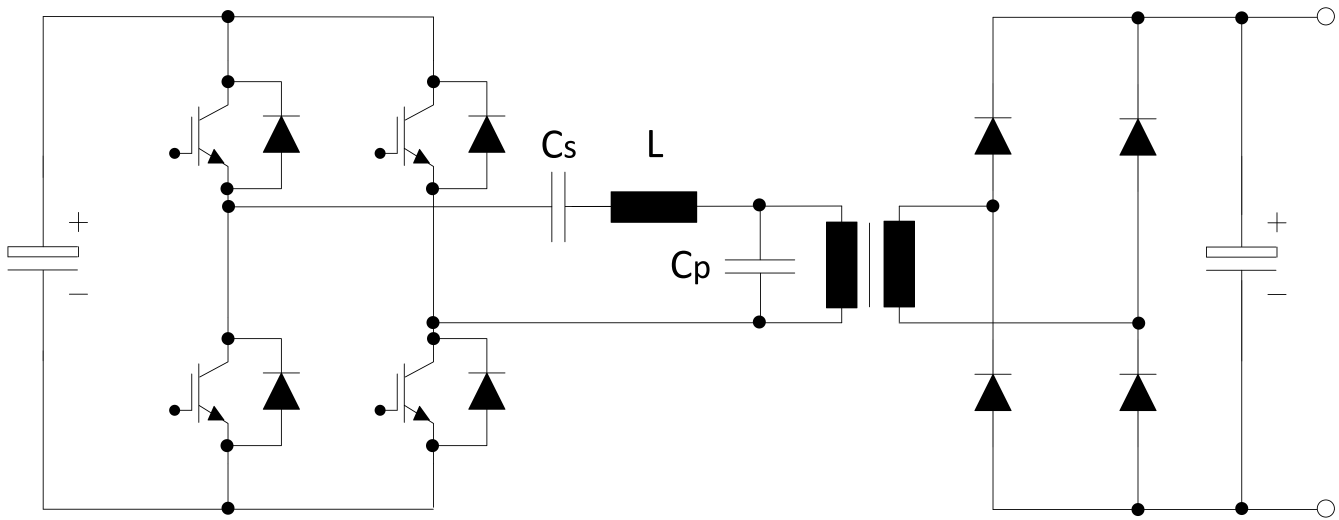




Circuit waveforms under different operating conditions: sub-resonant DCM, sub-resonant CCM, super-resonant CCM

Soft switching-Isolated

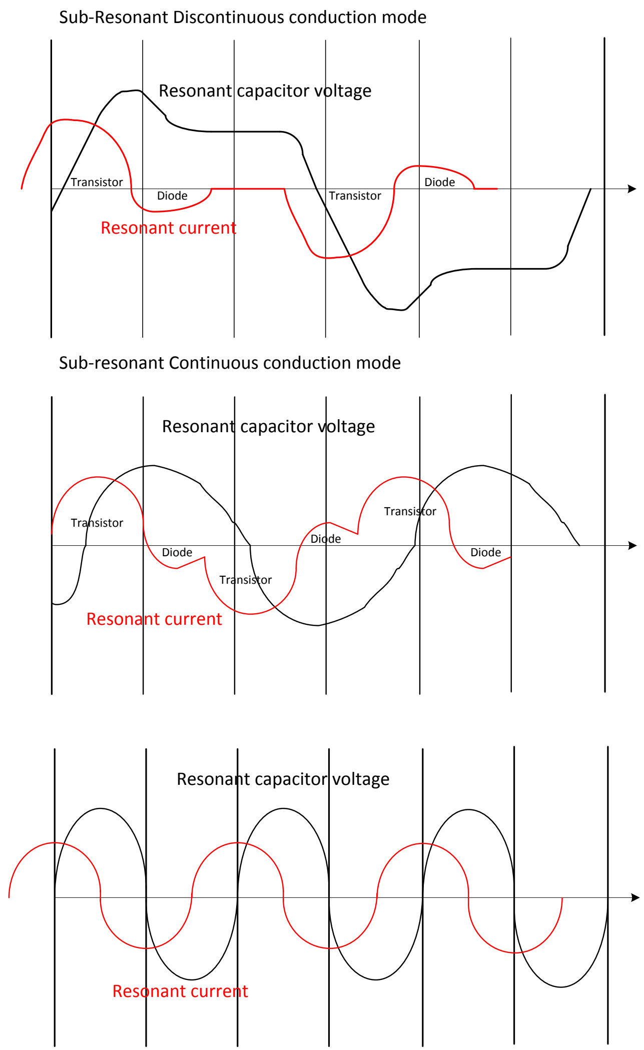
23. Resonant load-LCC

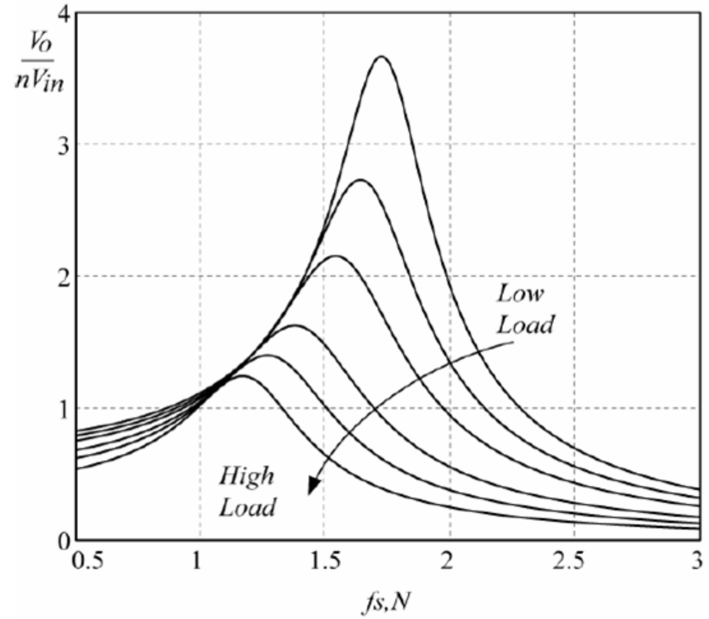


LCC Converter

Soft switching-Isolated

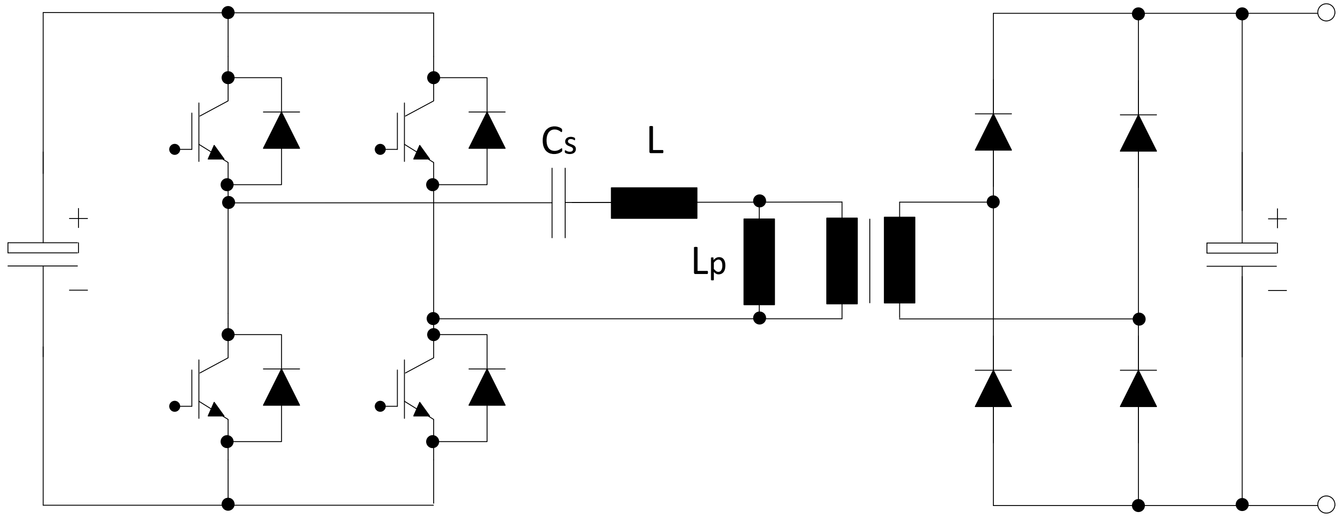
23. Resonant load-LCC





Soft switching-Isolated

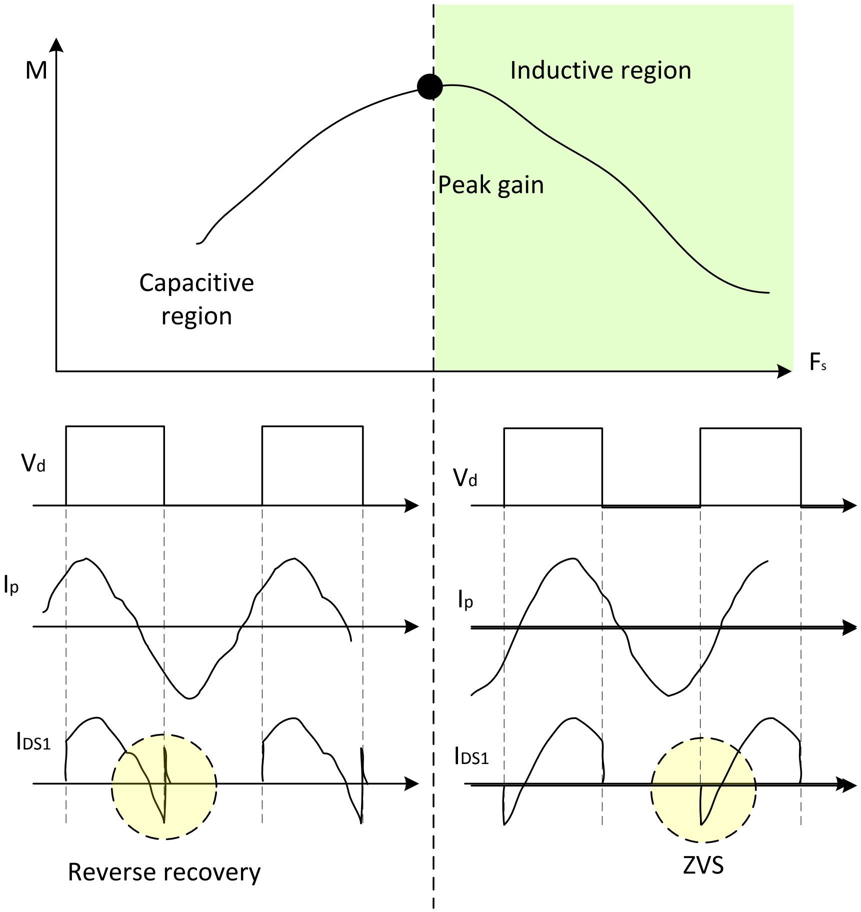
24. Resonant load-LLC



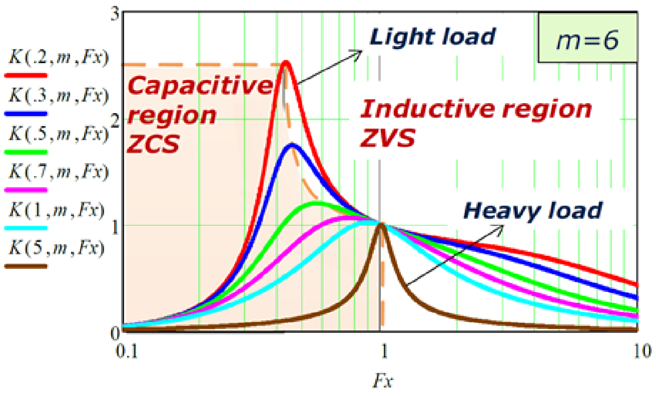
LLC Converter

Soft switching-Isolated

24. Resonant load-LLC



Operation Waveforms for Capacitive and Inductive regions



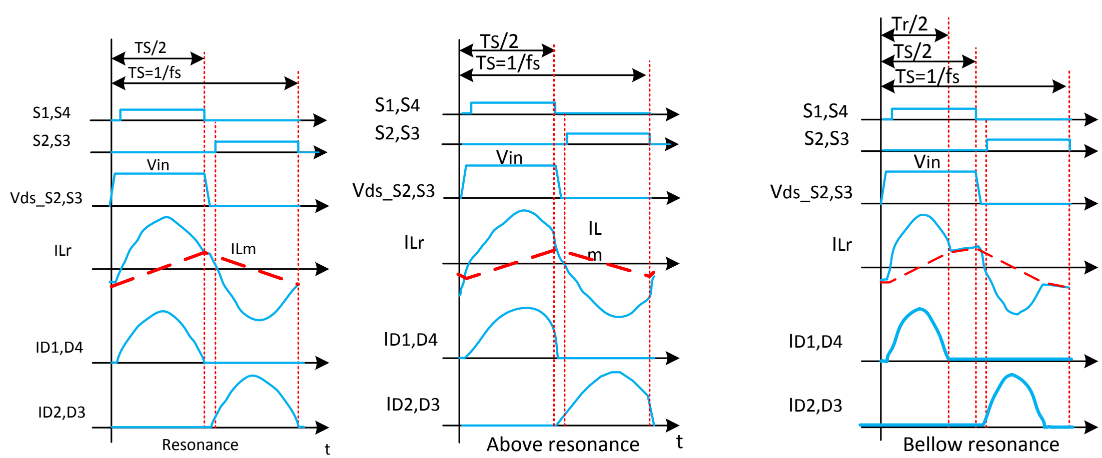
Soft switching-Isolated

24. Resonant load-LLC

At Resonant frequency operation fs=fr.
Each hald of the switching cycle contains a complete power delivery operation, where the resonant half cycle is completed during the switching hald cycle.
Be end of the switching hald cycle, the resonant inductor current ILR reached the magnetizing current ILM, and the rectifier current reaches zero.
The resonant tank has unity gain and best optimized operation and efficiency, therefore, transformer ratio is designed such that the converter operates at this point at nominal input and output voltages.

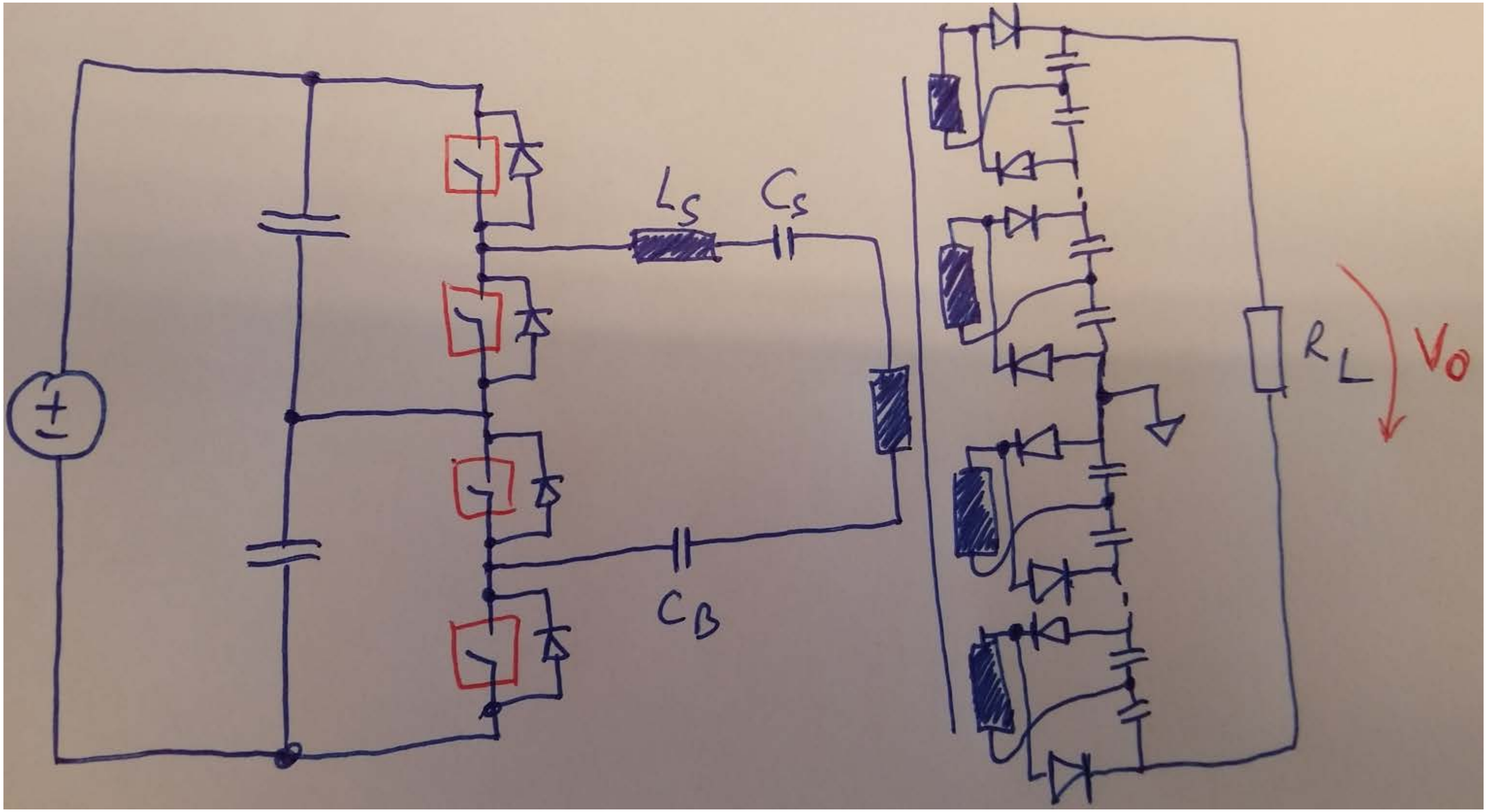
Above resonant frequency operation fs>fr.
Each half of the switching cycle contains a partial power delivery operation, similar to the resonant frequency operation, but it differs in that the resonant hald cycle is not completed and interrupted by the start of the other hald of the switching cycle, hence primary side MOSFETs have increased turn off losses and secondary rectifier diodes have hard commutation.
The converter operates in this mode at higher input voltage, where a step down gain or buck operation is required.

Below resonant frequency operation fs<fr
Each half of the switching cycle contains a power delivery operation, at the time when resonant half cycle is completed and resonant inductor current ILR reaches the magnetizing current, the freewheeling operation starts and carries on to the end of the switching hald cycle, hence primary side have increased conduction losses due to the circulating energy. The converter operates in this mode at lower input voltage, where a step up gain or boost operation is required.



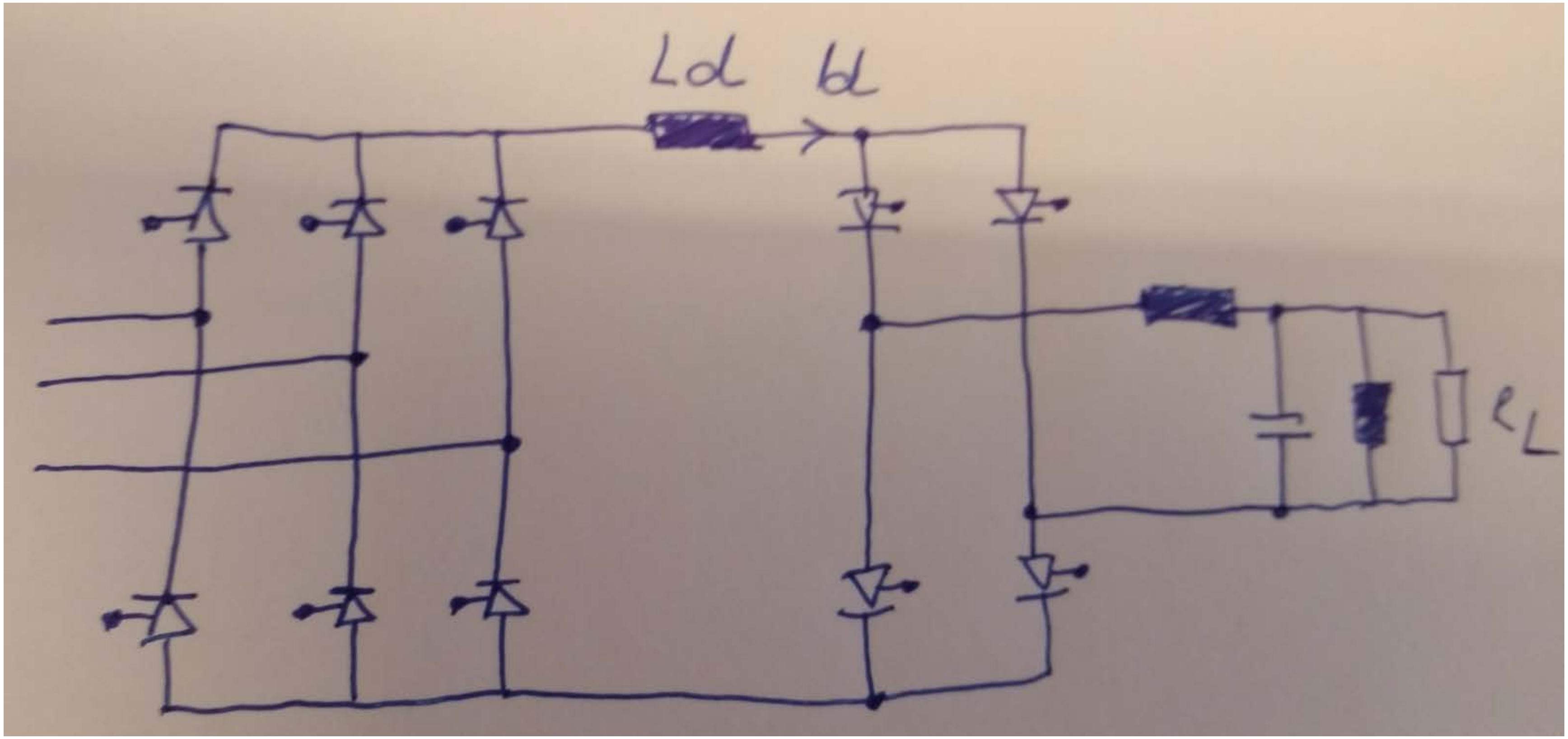
Soft switching-Isolated

25.Resonant load-SRC multilevel



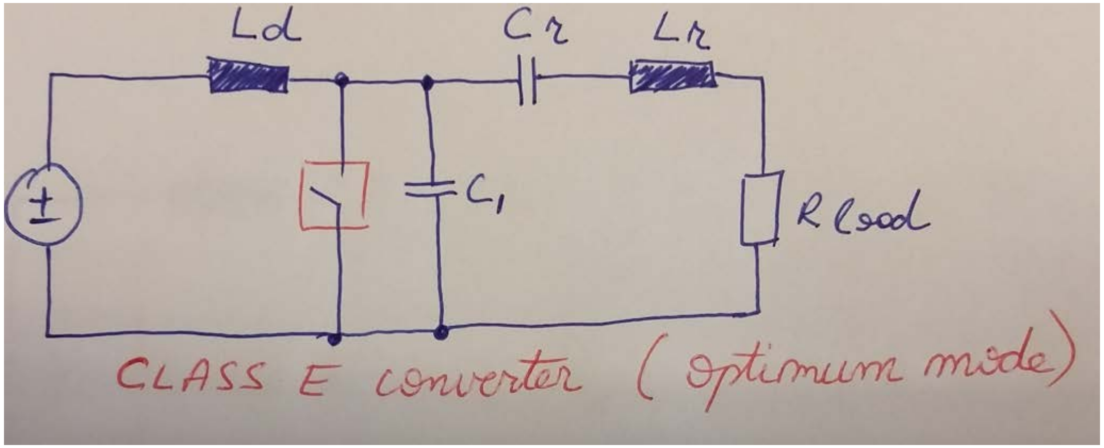
Soft switching-Isolated

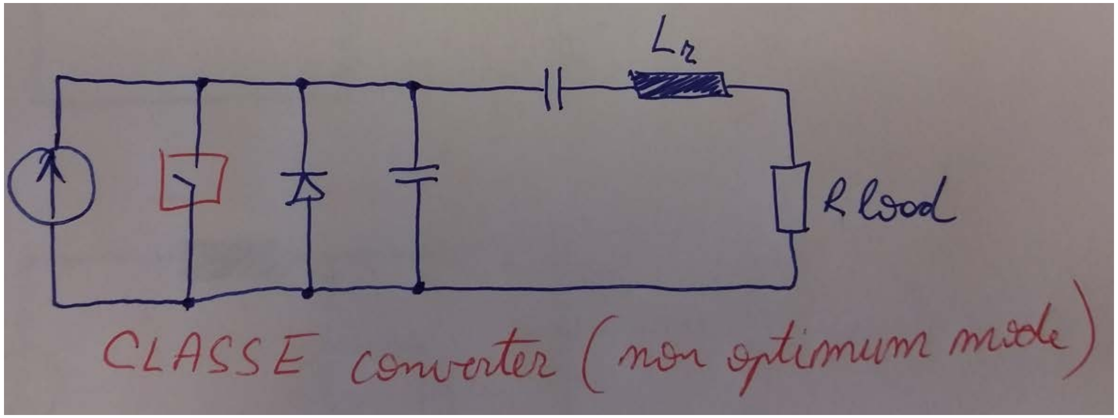
26.Resonant load-Current source parallel resonant inverter



Soft switching-Isolated

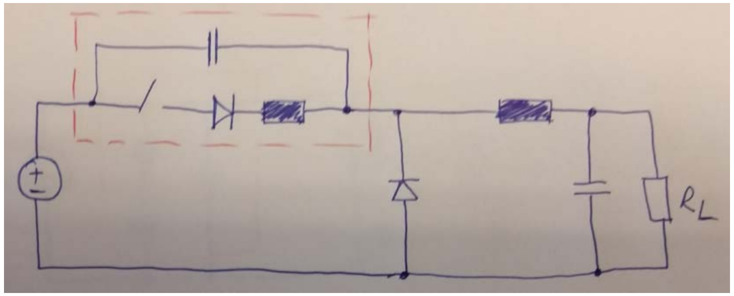
27.Resonant load Class E converter

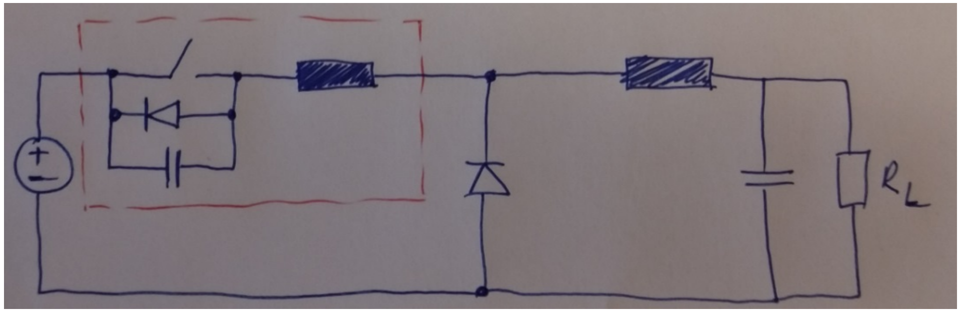


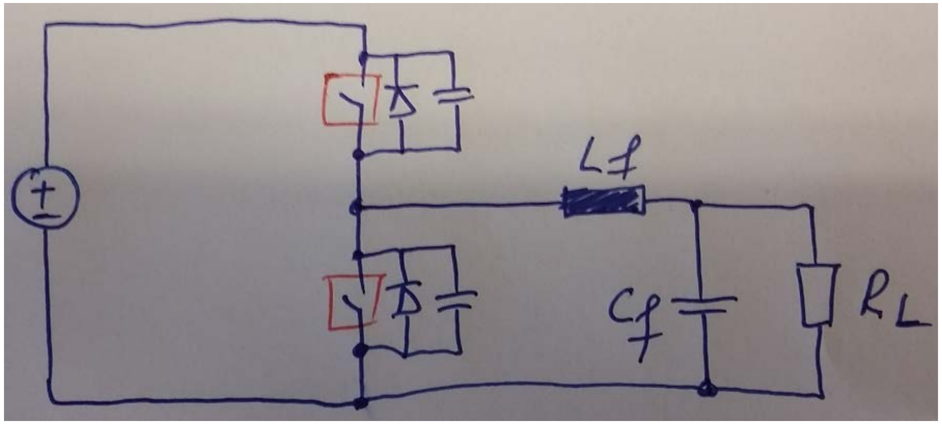


Soft switching

28.Resonant Switch

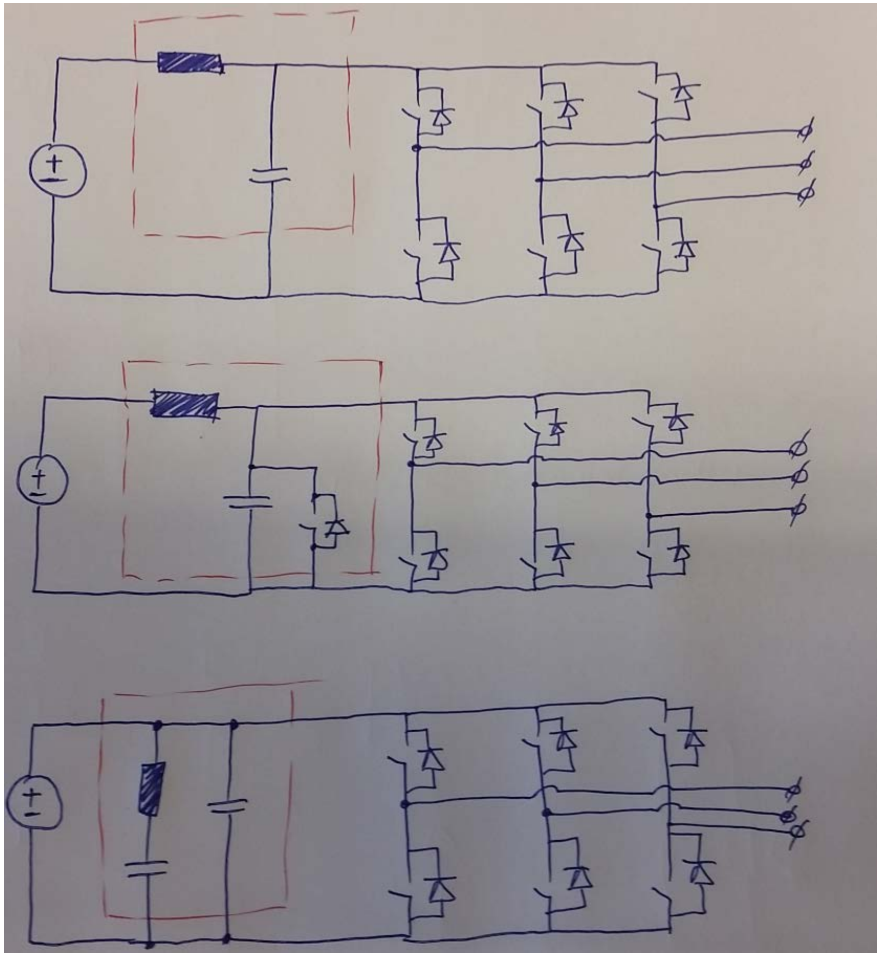






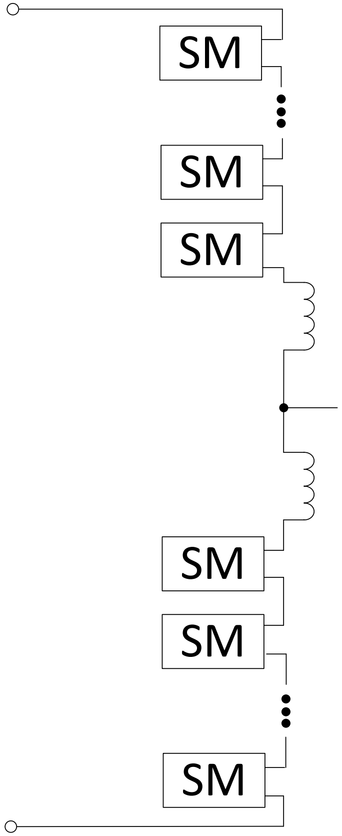
Soft switching

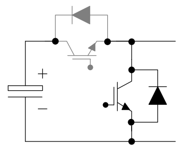
29.Resonant DC link



Soft switching-Isolated

30. Q2L MMC



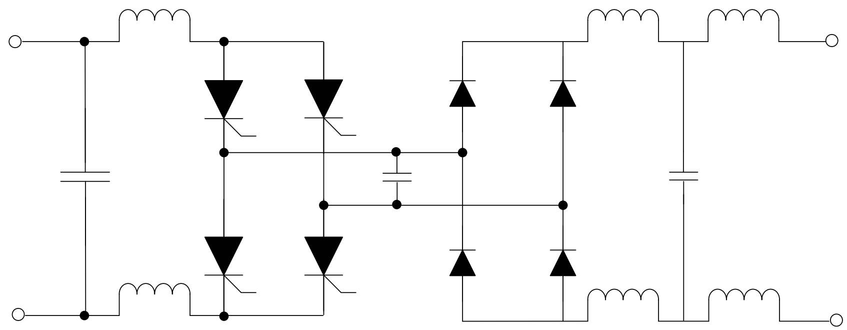


Advantages:
- two level operation with controllable values of voltage derivative, dv/dt
- low cell capacitance requirements results in a considerable reduction in converter footprints
- lower losses due to higher fundamental output voltage and the absence of a dc common mode component in converter arm currents, soft switching occurs owing to the dc
-transformer topology;
- beside flexibility of manufacturing and installation, the modular design results in additional output control capabilities; voltage magnitude control and selective harmonic elimination

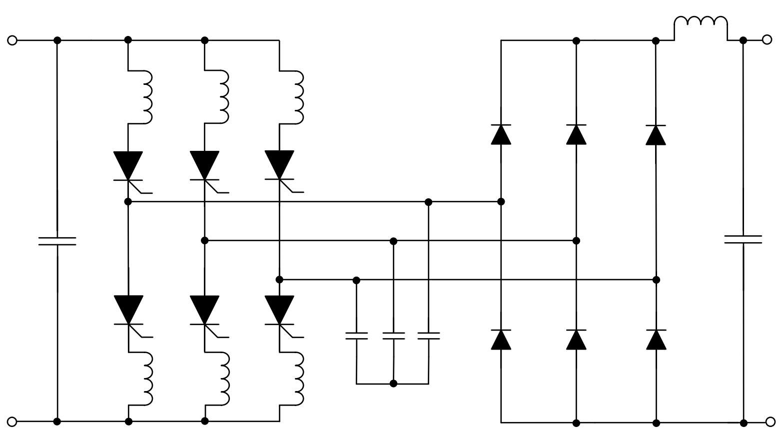
Disadvantages:
- Control complexity
- No galvanic separation
- Suitable for smal voltage gain <2
- Unable to filter out dc current ripple

Soft switching-Non Isolated

31. Parallel Resonant



Jovcic 1phase step up resonant converter



Jovcic 3phase step up resonant converter

Soft switching-Non Isolated

31. Parallel Resonant

Advantages:

- Simple converter topology
- Soft switching
- Use of thyristors

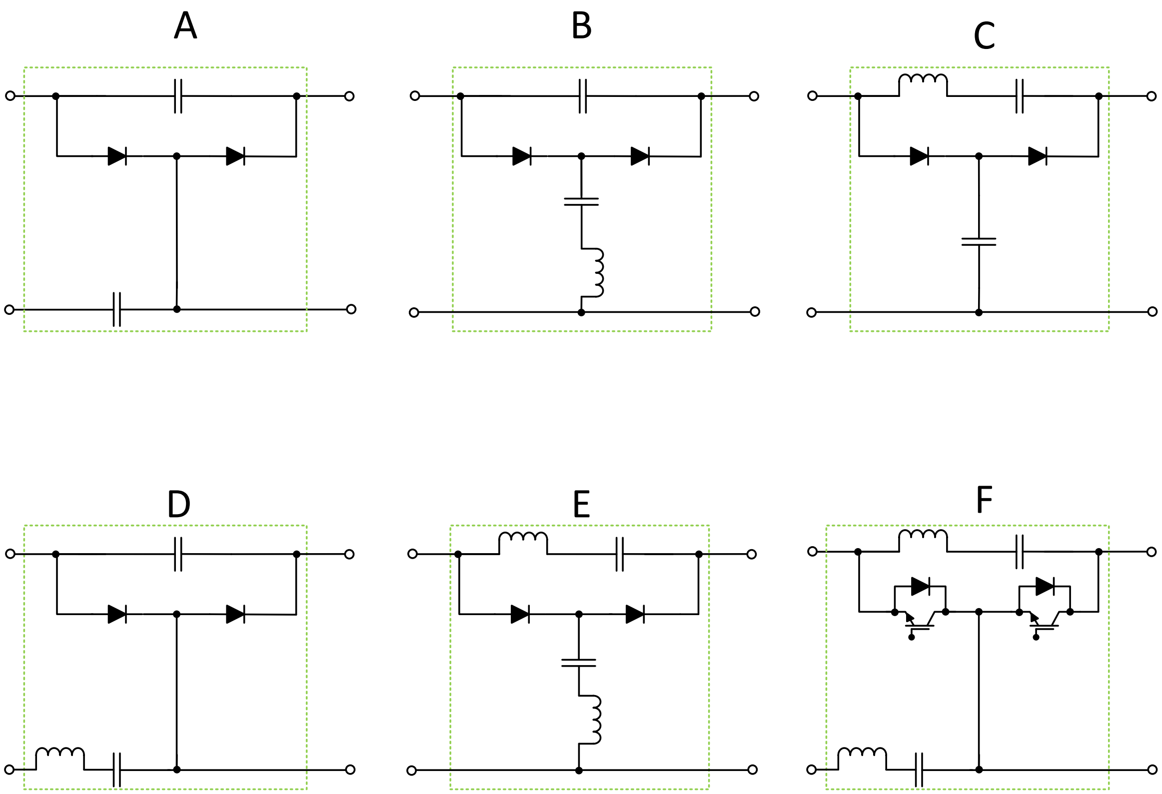
Disadvantages:

- No galvanic separation
- High component stress on resonant tank and switches

Soft switching-Non Isolated

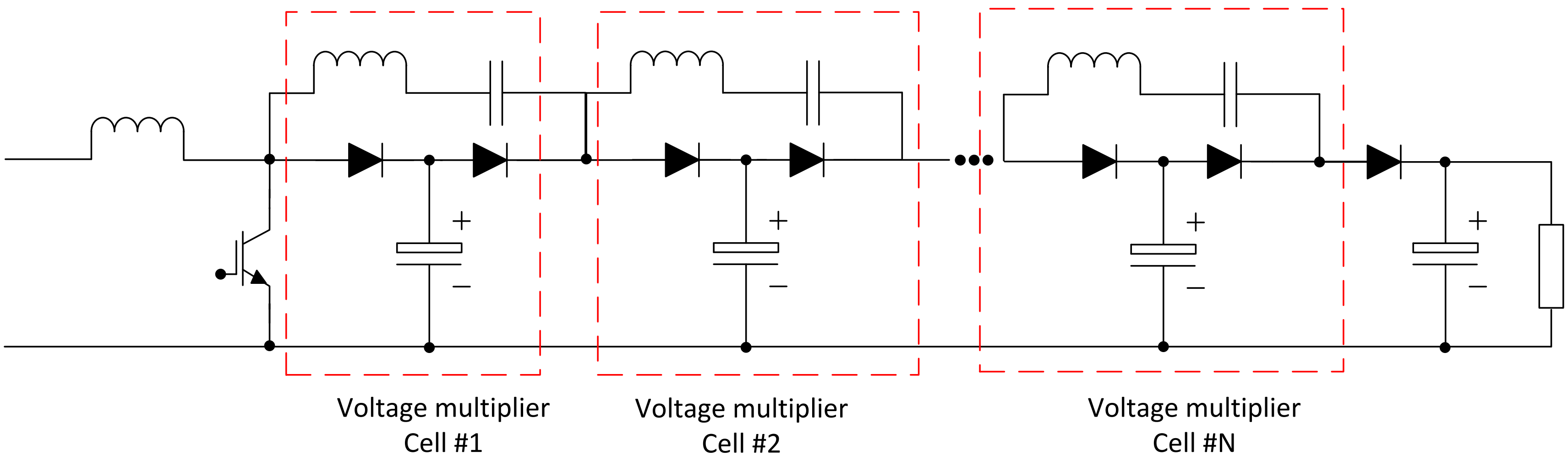
32. Switched Capacitor Cells

Voltage multiplier cells



Soft switching-Non Isolated

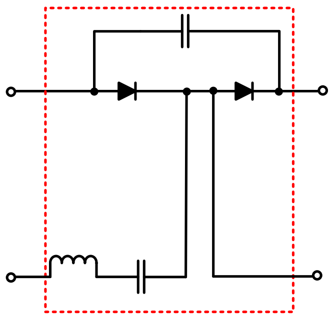
33. Boost with Voltage Multiplier

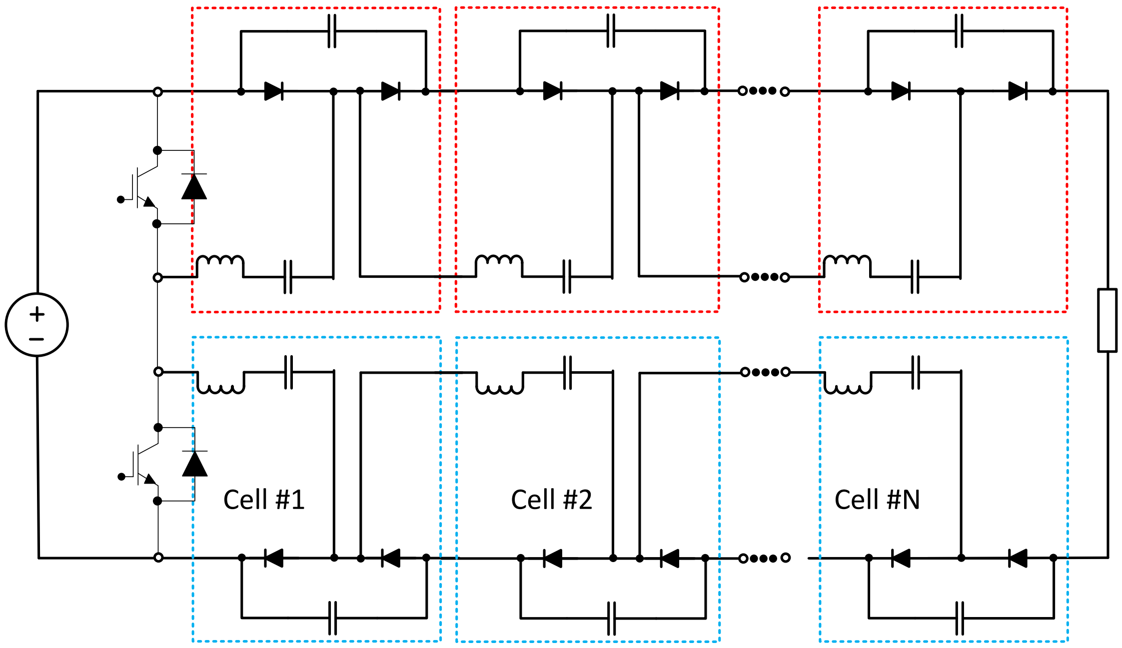


Boost with voltage multiplier

Soft switching-Non Isolated

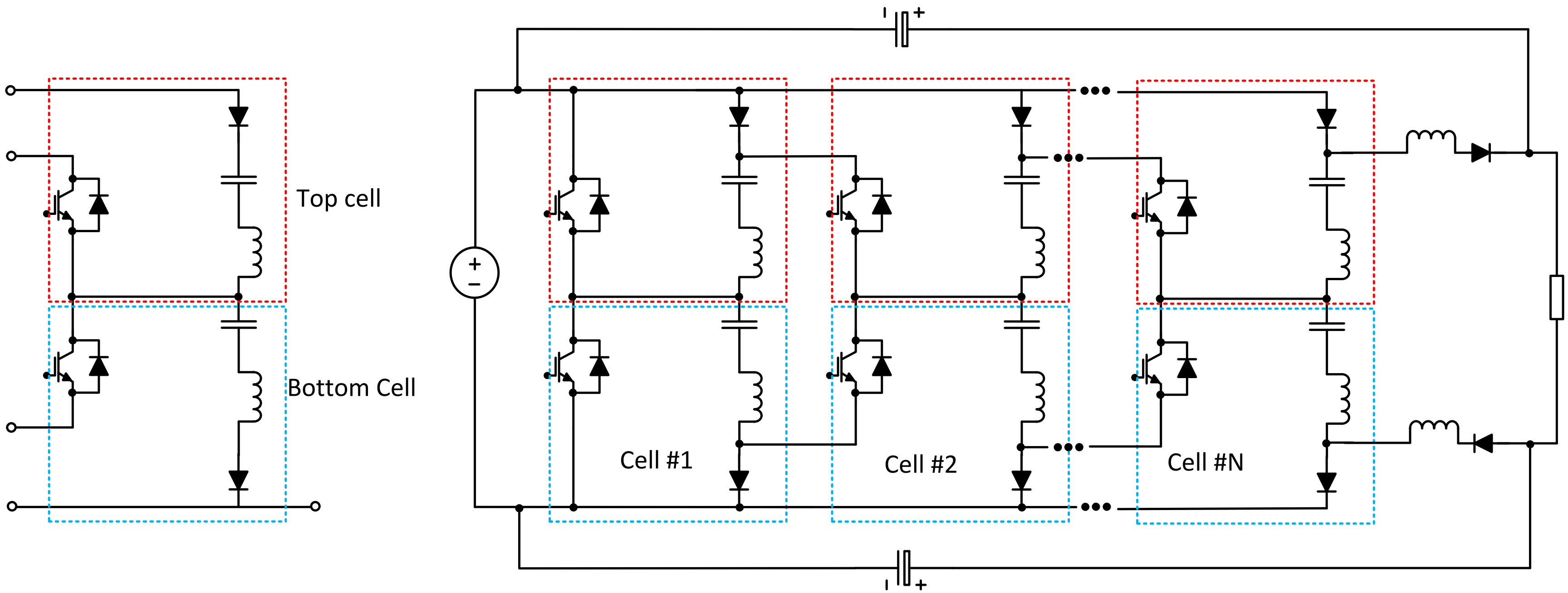
34. ZCS RSC (Zero Current Switching Resonant Switched Capacitor)





Soft switching-Non Isolated

35. High gain RSC



Soft switching-Non Isolated

35. High gain RSC

Advantages:
- Interleaved operation for low current ripple
- Soft switching operation available at resonance
- Improved voltage regulation (due to cascaded boost converter)
- (A.Huang) Modular structure
- (A.Huang) Low-voltage stress of the switches and reduced switching loss

Disadvantages:
- Insulation to ground
- No galvanic separation (unless provided in the cascaded converter)
- Large ESR capacitors are preferable for low ripple
- Suited mainly for low current applications
- Voltage sag at higher stages (especially if many stages are used)
- (A.Huang) Large number of capacitors, high passive component losses and large physical size are limiting the use in high-voltage gain offshore wind energy systems
- The switched capacitor converters are modular, where each module increases outpu voltage only by the value of the input voltage. To achieve stepping ratio of say 10, nine capacitor modules are needed and over 18 switched, which implies significant losses and complexity.
- Limited voltage capability for ZVS-RSC