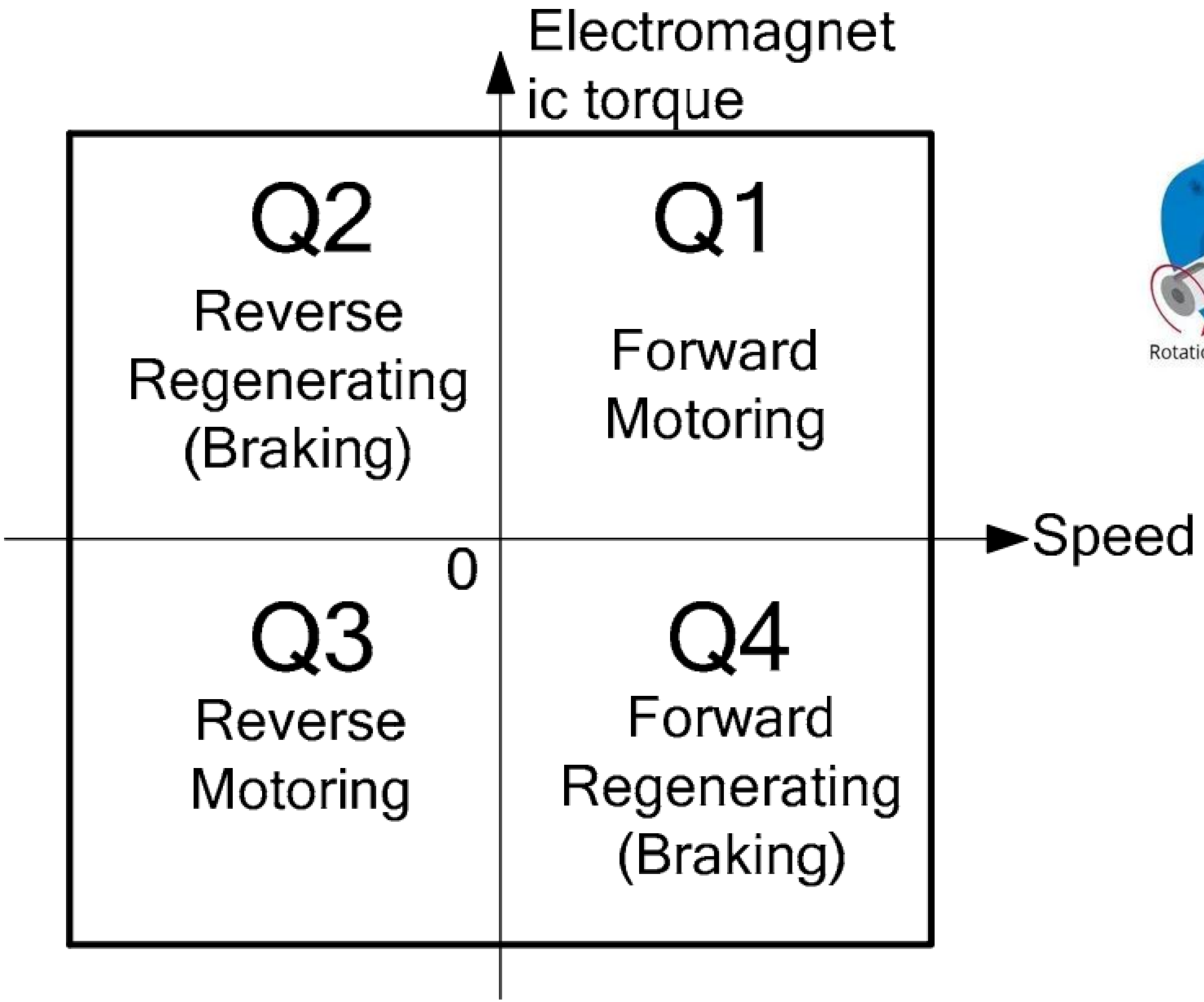
ITMO

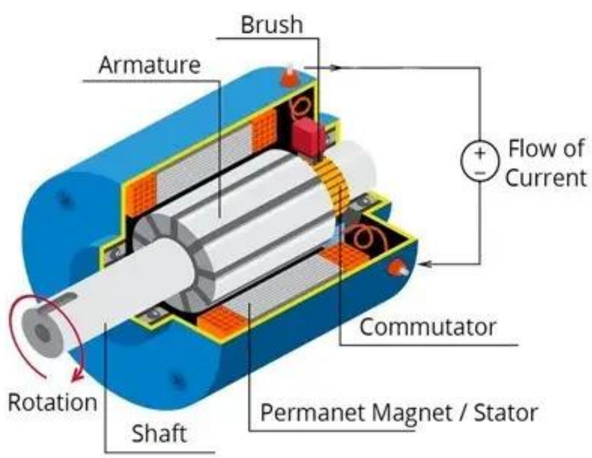
Actuators

Lection 8

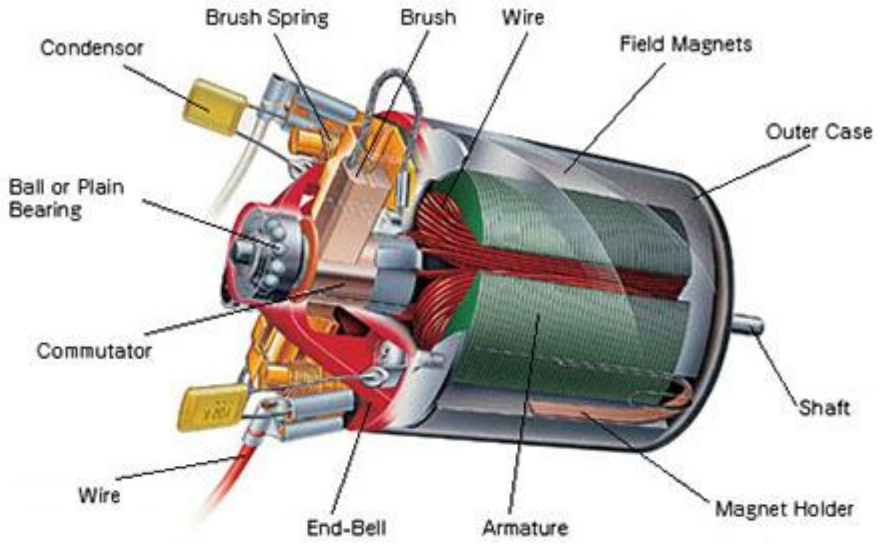
DC drive power converters with pulse-width modulation (PWM)

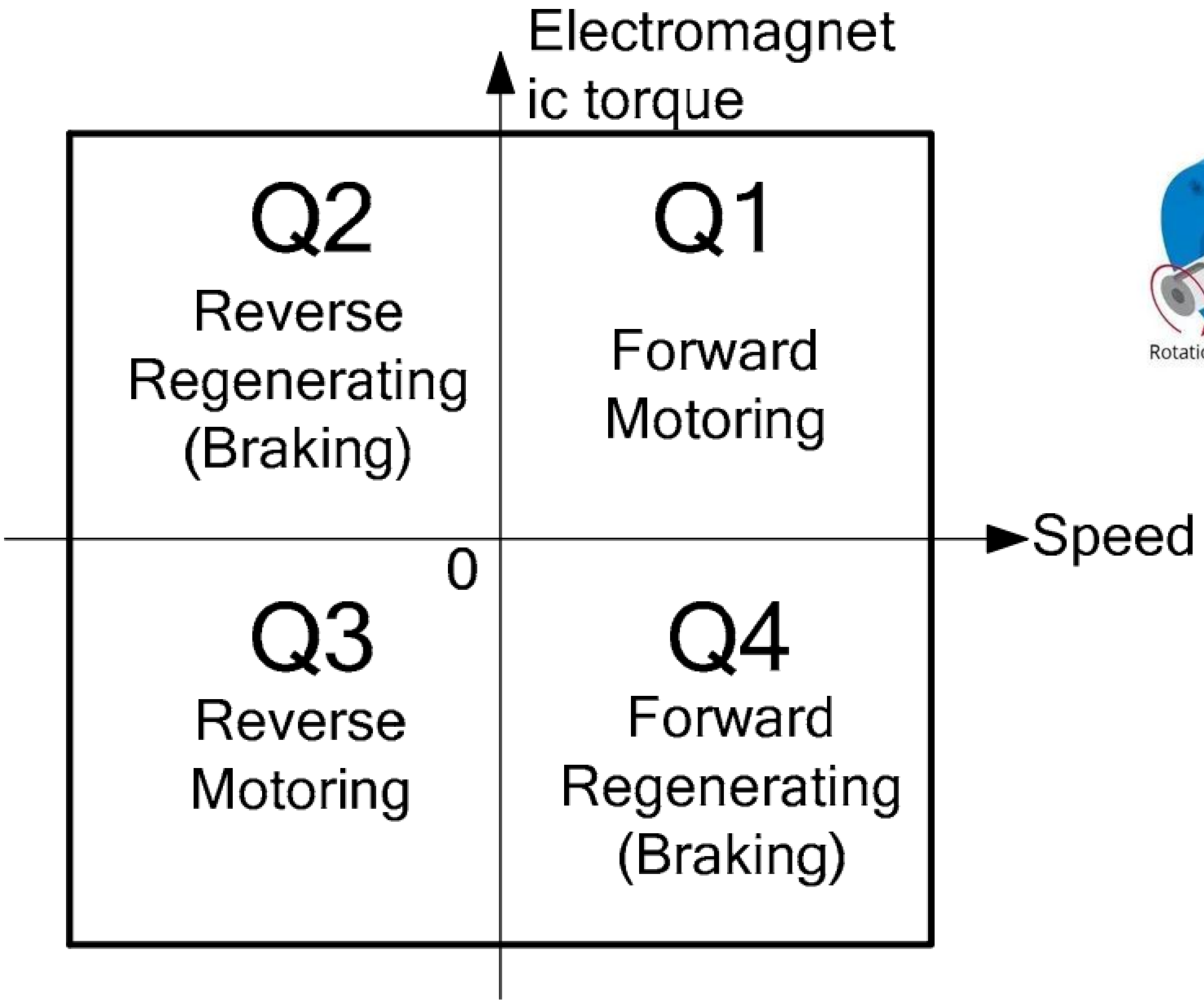
Asc. Prof. Nikolai Poliakov
Asc. Prof. Sergei Lovlin
Asc. Prof. Dmitry Lukichev


Electromagnetic torque
Q2
Reverse Regenerating (Braking)
Q1
Forward Motoring
Speed
0
Q3
Reverse Motoring
Q4
Forward Regenerating (Braking)


Brush
Armature
Flow of Current
Commutator
Rotation
Shaft
Permanet Magnet / Stator


The RC Valleys
TRACKSTAR
BRUSHED MOTOR
540/80T


Brush Spring
Brush
Wire
Condensor
Field Magnets
Outer Case
Ball or Plain Bearing
Commutator
Shaft
Wire
End-Bell
Armature
Magnet Holder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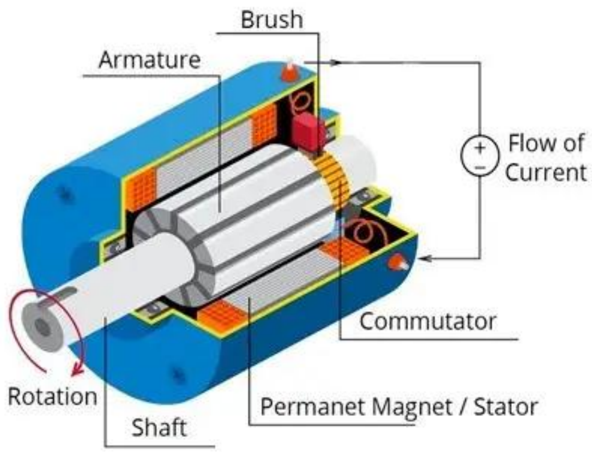
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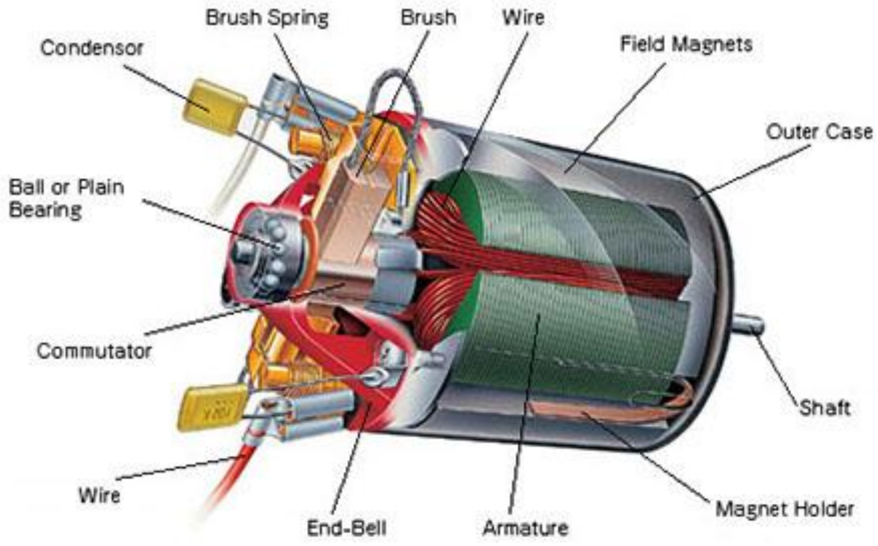
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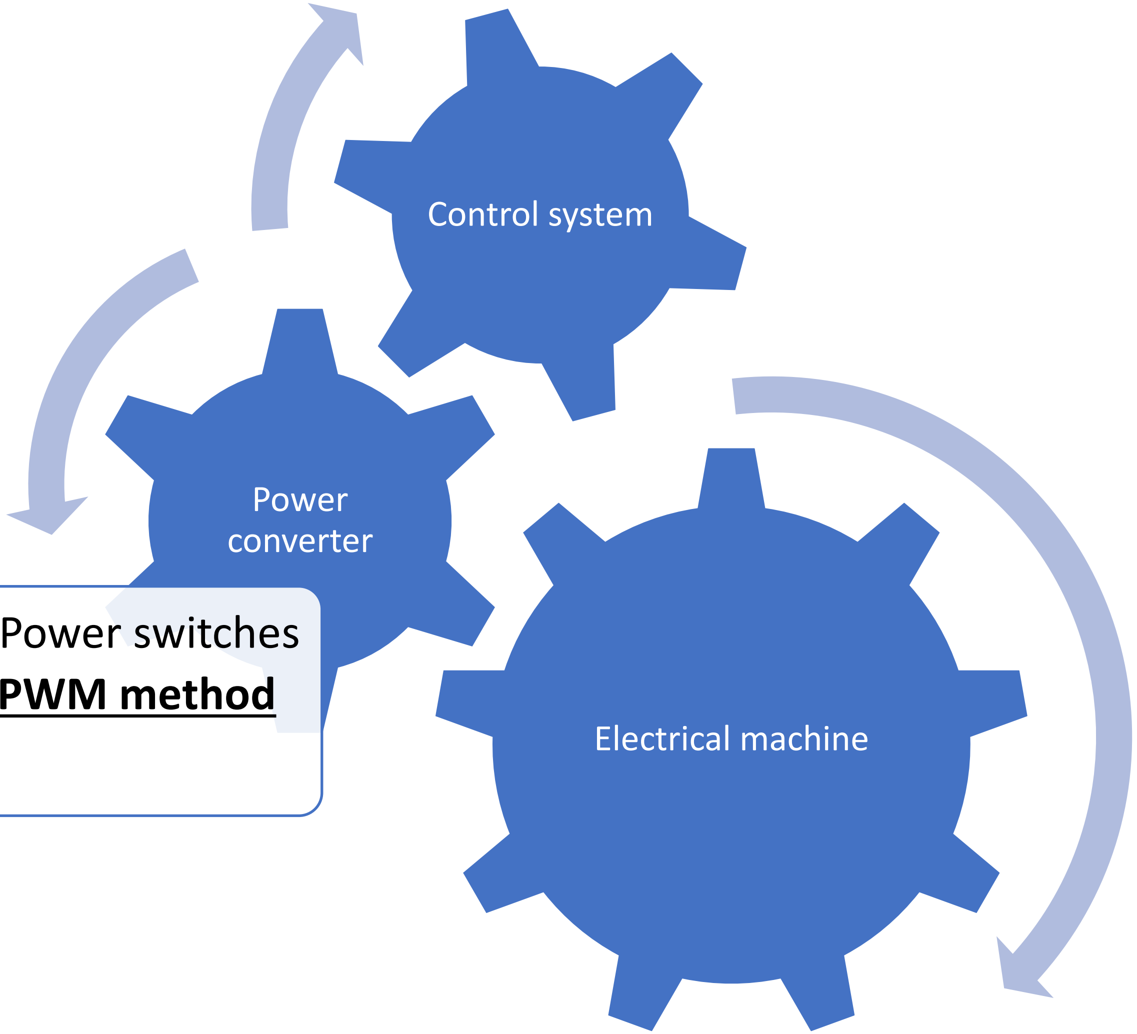
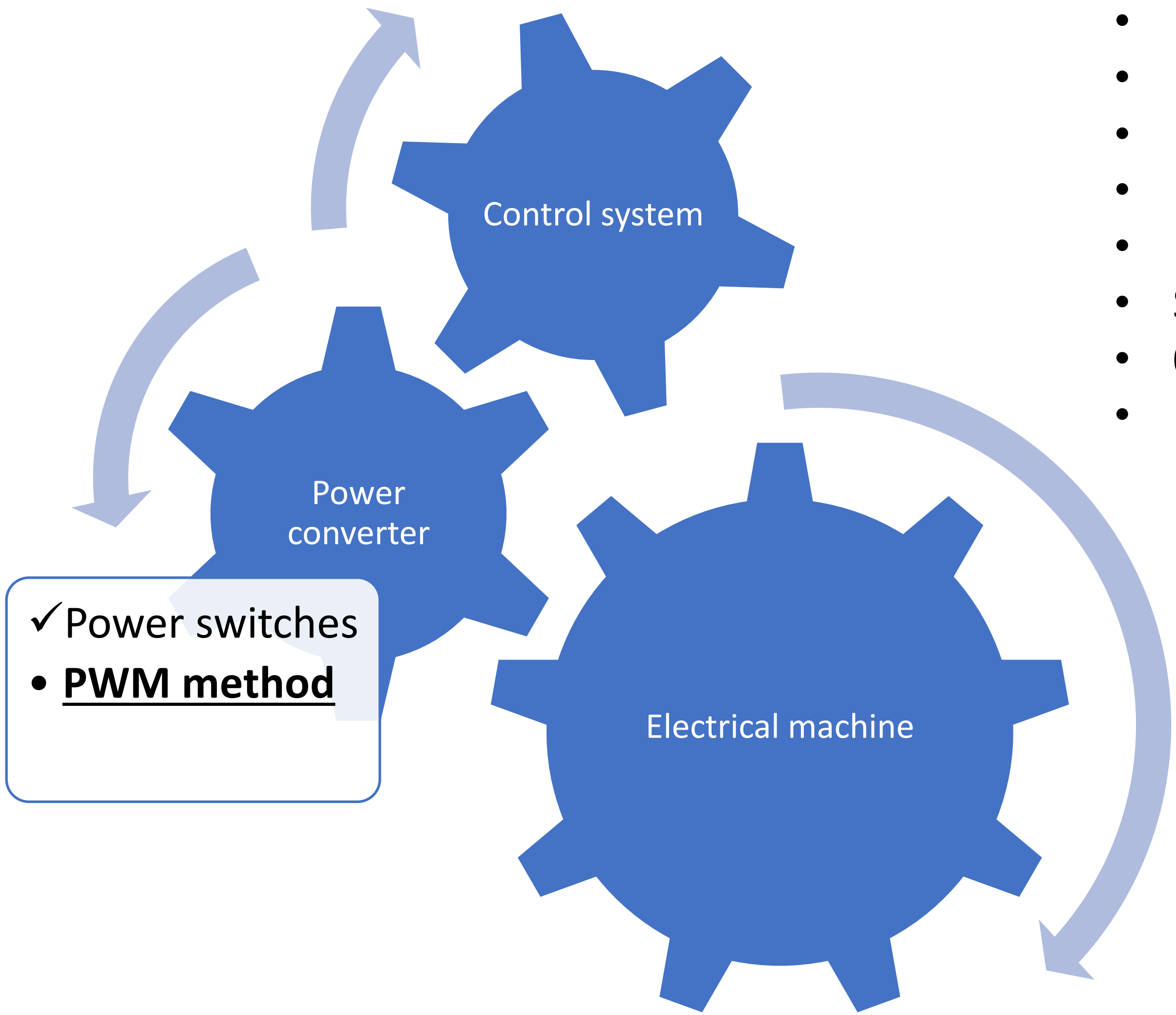
PWM method



- ✓Power switches
- **PWM method**

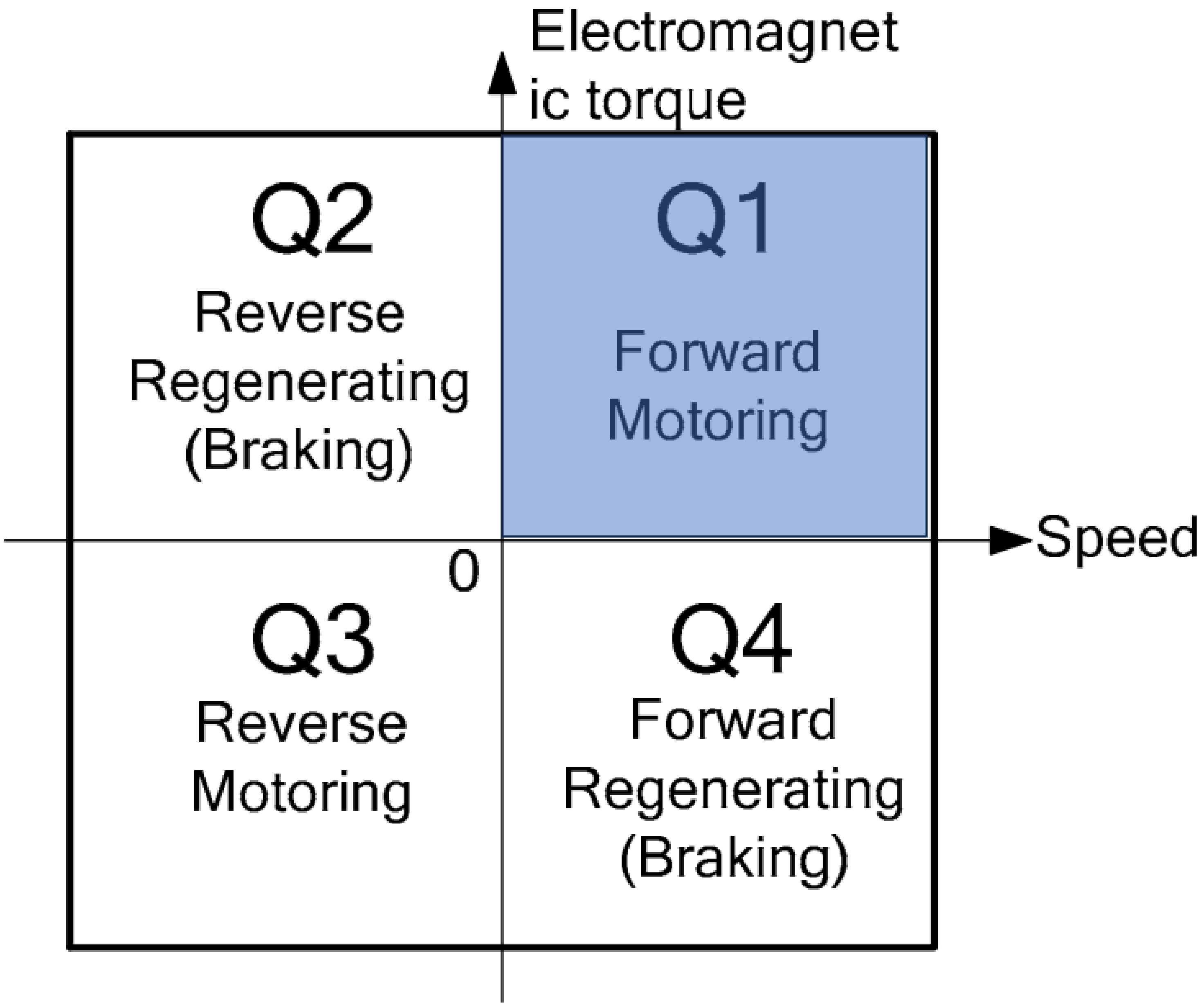
- **DC machine**
- AC Induction machine
- AC synchronous machine
  - permanent magnet synchronous machine

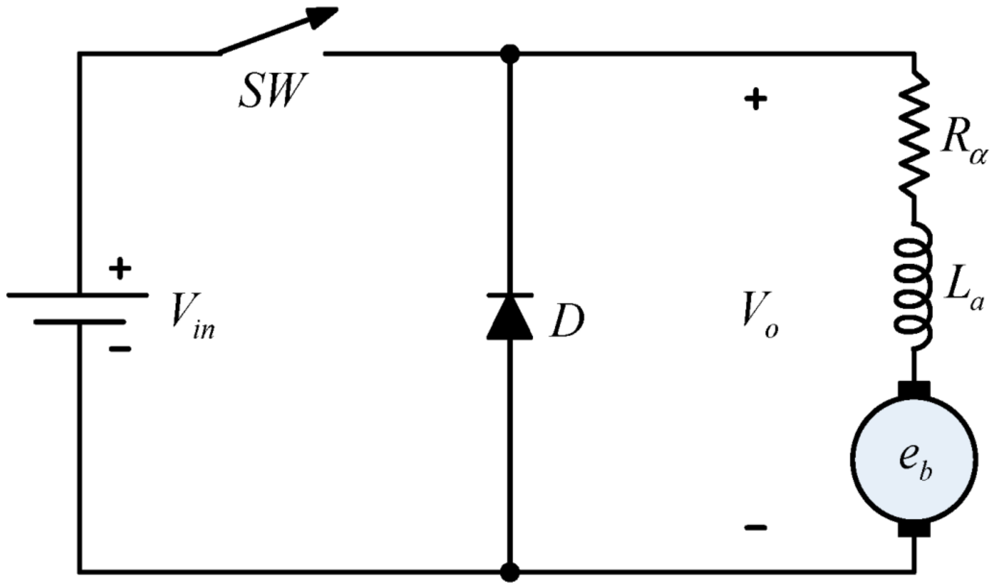
PWM power converter general features



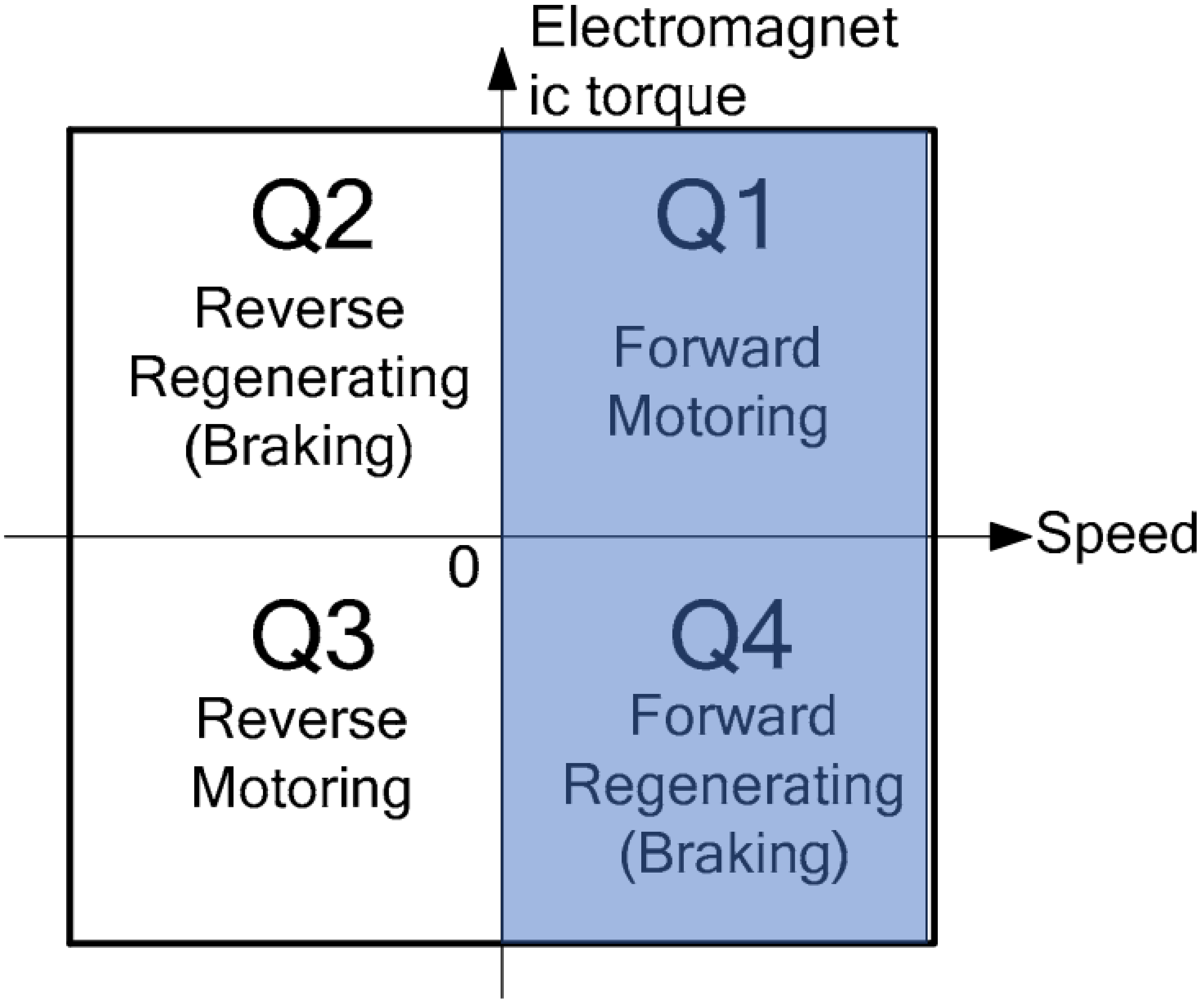
- Reduced ripple current
- Regeneration operation
- High frequency operation (∝ kHz
- High response speed
- High order harmonics
- Suffer from excessive voltage and
- 0.5 kW to hundred kW
- High Efficiency

- **DC machine**
- AC Induction machine
- AC synchronous machine
  - permanent magnet synchronous machine





- rapid transit systems
- mine haulers
- trolley cars
- forklift trucks
- marine hoist.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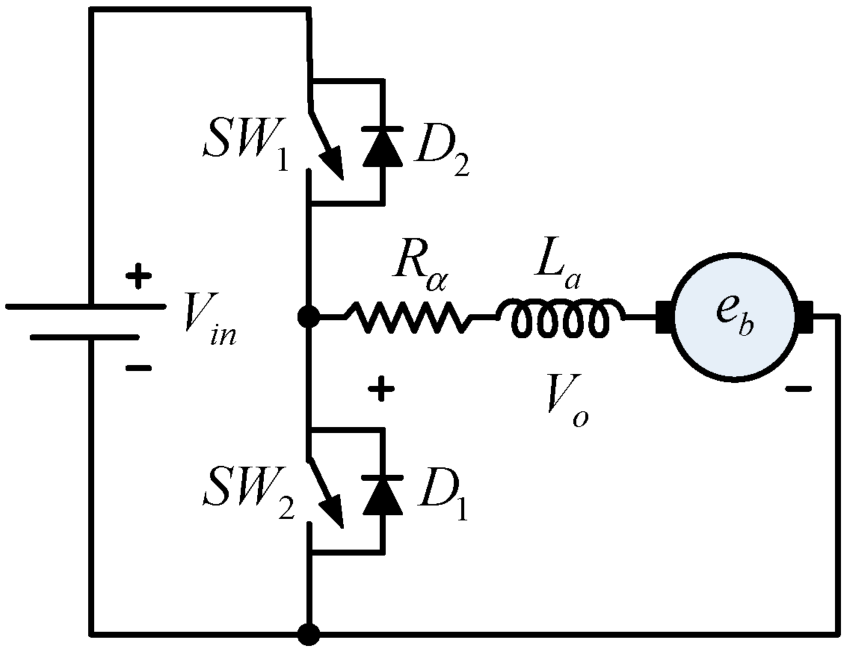
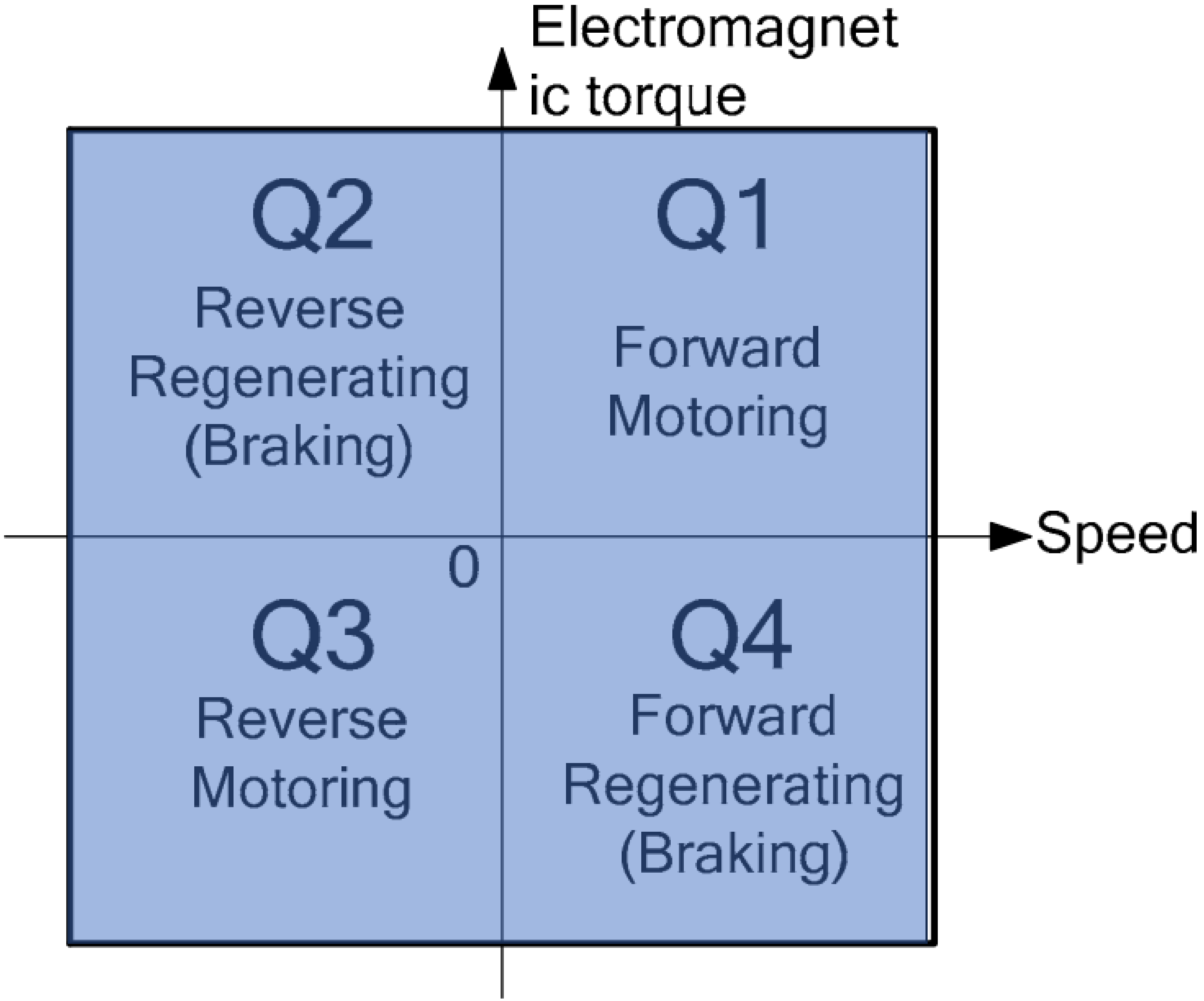

SW1
D2
Vin
+
-
Rα
La
eb
Vo
+
-
SW2
D1

a)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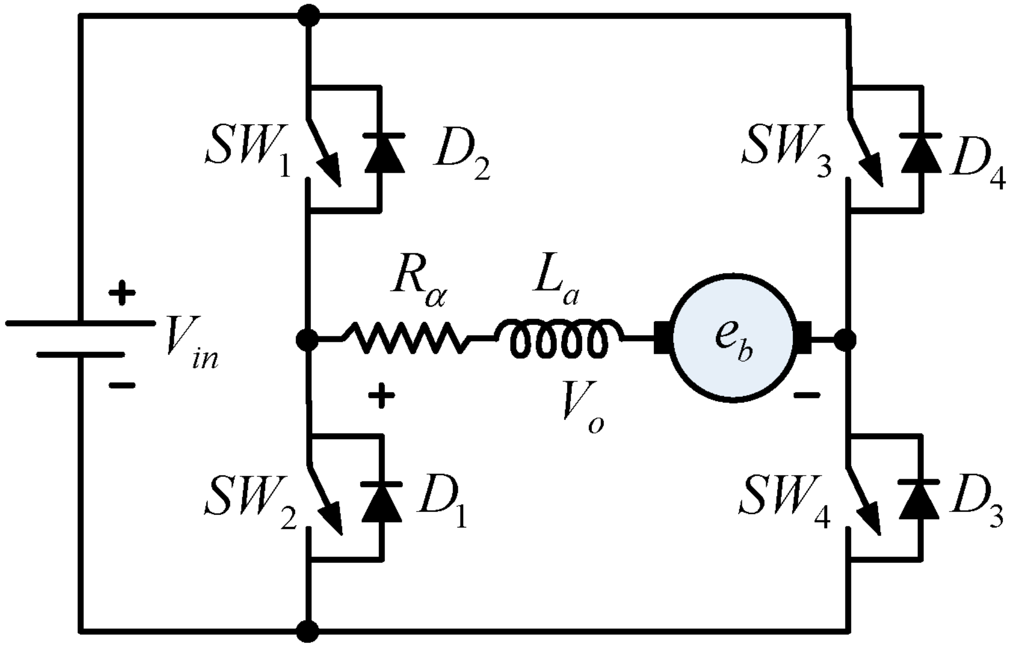

SW_1
D_2
SW_3
D_4
R_α
L_a
V_{in}
e_b
V_o
SW_2
D_1
SW_4
D_3

b)

Hard-Switching Converters

- High switching stress and losses
- Typical switching frequency between 20 kHz and 50 kHz
- Considerable transient effects in the converters

Single-switch Chopper

- 1Q operation
- Simple control circuit

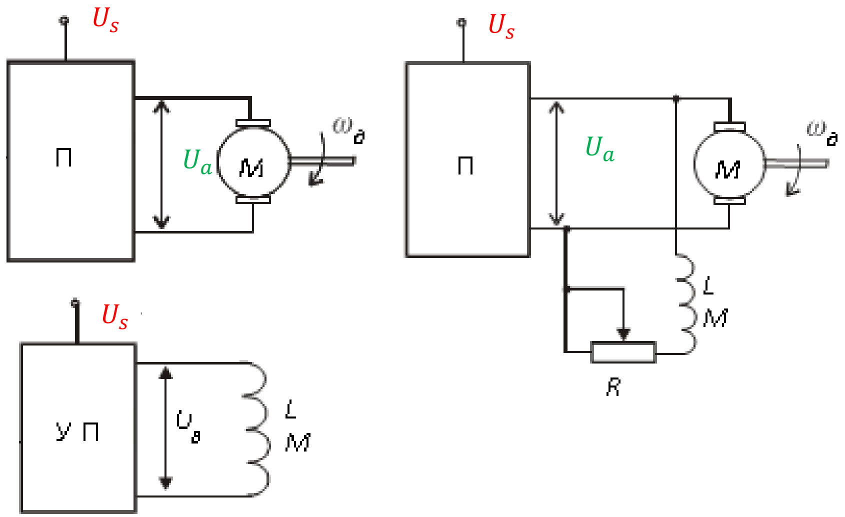
2Q Chopper

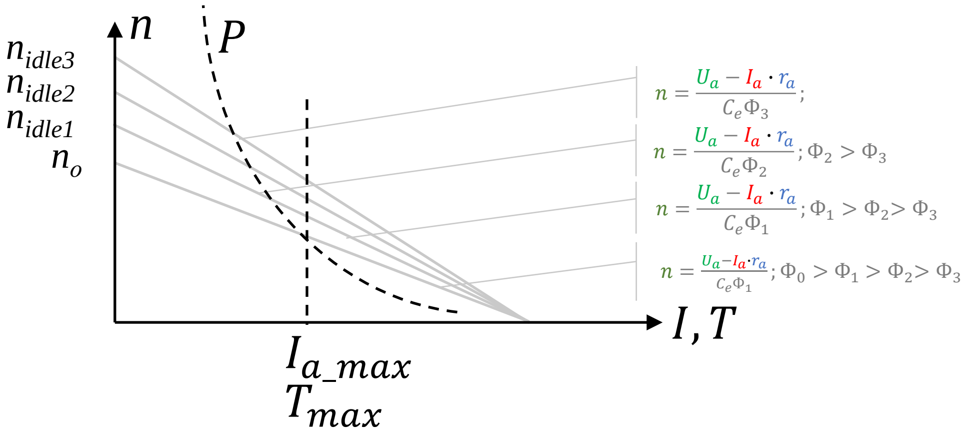
- 2Q operation
- Increased number of switches
- Medium complexity control circuit

H-Bridge or 4Q Chopper

- 4Q Operation
- Increased number of switches
- Medium complexity control circuit
- Current continuity around the zero-current output
- Multilevel output voltage
- Bipolar output voltage => increment to the ripple current value, faster reversal, with minimum crossover distortion

Speed control of DC Drive by changing the magnetic flux



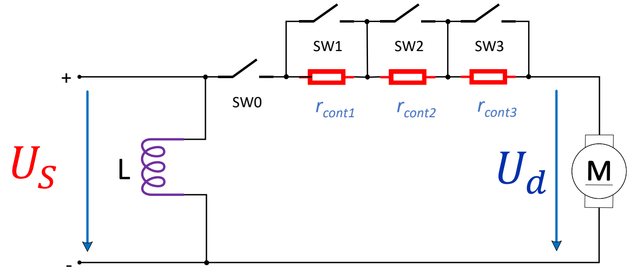


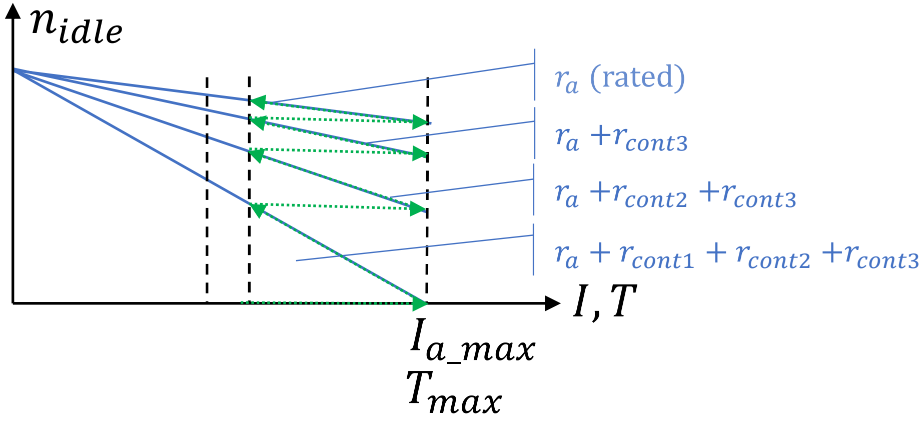
n	— speed	[rpm]
U_a	— armature voltage	[V]
I_a	— armature current	[A]
r_a	— resistance (armature windings)	[Ohm]
r_{cont}	— additional resistance	[Ohm]
T	— torque	$[N \cdot m]$
C_e	— constructive constant	[V/rpm]
Φ	— magnetic flux	[Wb]
f_{sw}	— switching frequency	[Hz]
T_{sw}	— switching period	[s]

$$\boxed{n = \frac{U_a - I_a \cdot r_a}{C_e \cdot \Phi}}$$

1. Changing Φ doesn't make sense for DC drive with permanent magnets
2. Angular velocity control by attenuation of the magnetic flux Φ is carried out at a constant allowable power
3. The range of control by changing the magnetic flux Φ is determined by the ratio of the greatest angular velocity n_{idle3} to the velocity of the n_o corresponding to the natural characteristic.

Speed control of DC Drive by additional resistances into the armature circuit





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Φ	— magnetic flux	[Wb]
f_{sw}	— switching frequency	[Hz]
T_{sw}	— switching period	[s]

$$t_1 + t_2 = T_{sw}$$

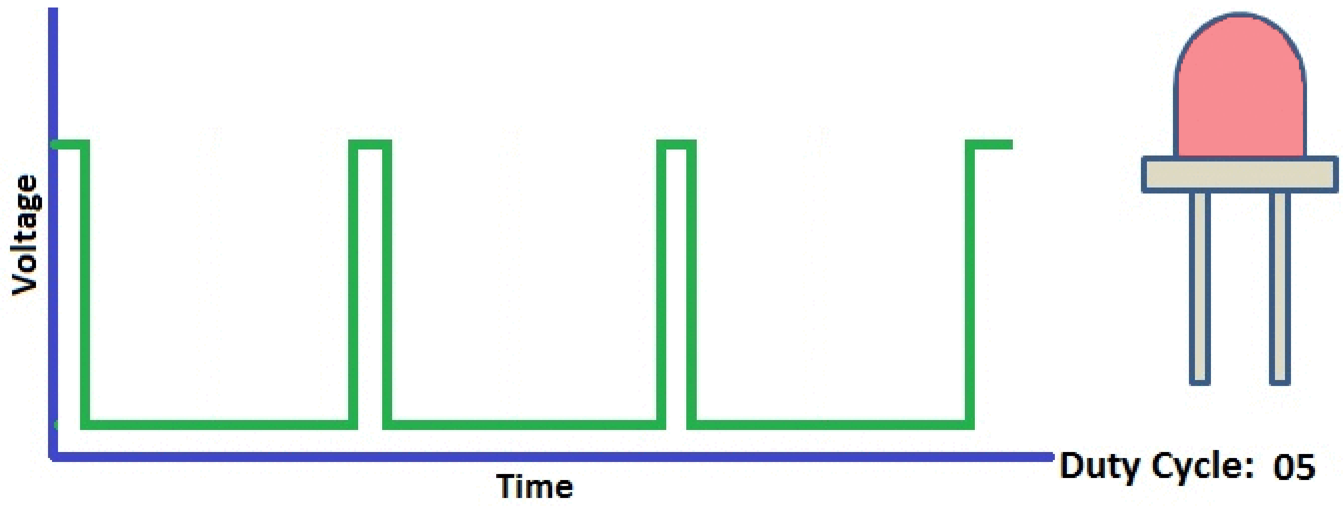
$$f_{sw} = \frac{1}{T_{sw}} = \frac{1}{t_1 + t_2}$$

$$U_a = U_d;$$

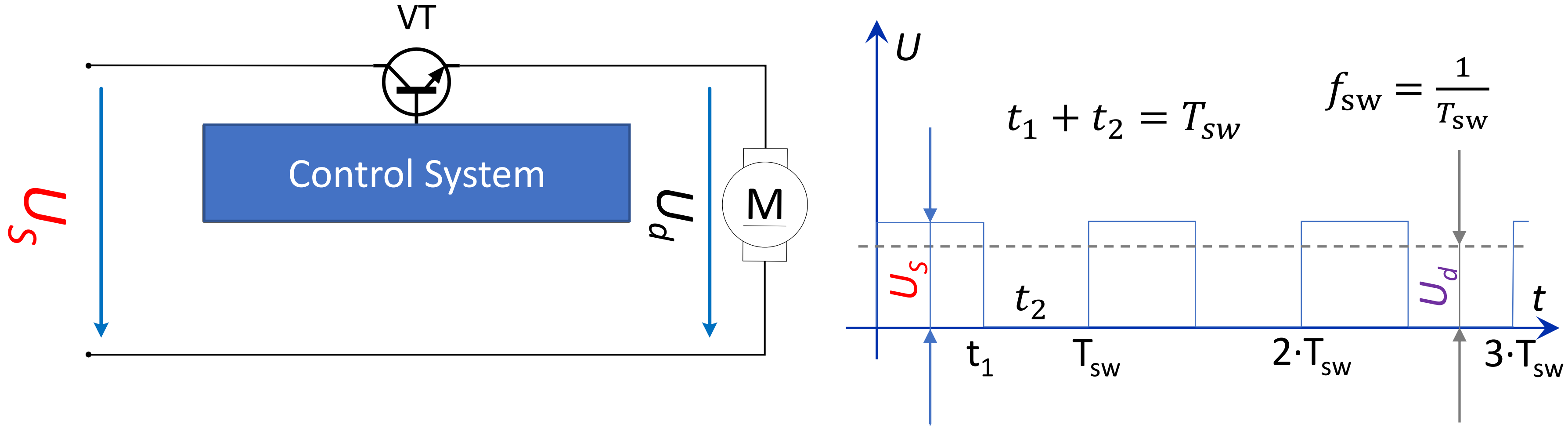
$$\Phi = \Phi_{rated};$$

$$n = \frac{U_a - I_a(r_a + r_{cont})}{C_e \Phi}$$

Changing r_{cont} to control the speed od the drive is extremely ineffective way because of energy losses in r_{cont}



The operations of the pulse width modulation (PWM) converter for electric drive systems are based on the principle of periodic switching of the load circuit with semiconductor switches.



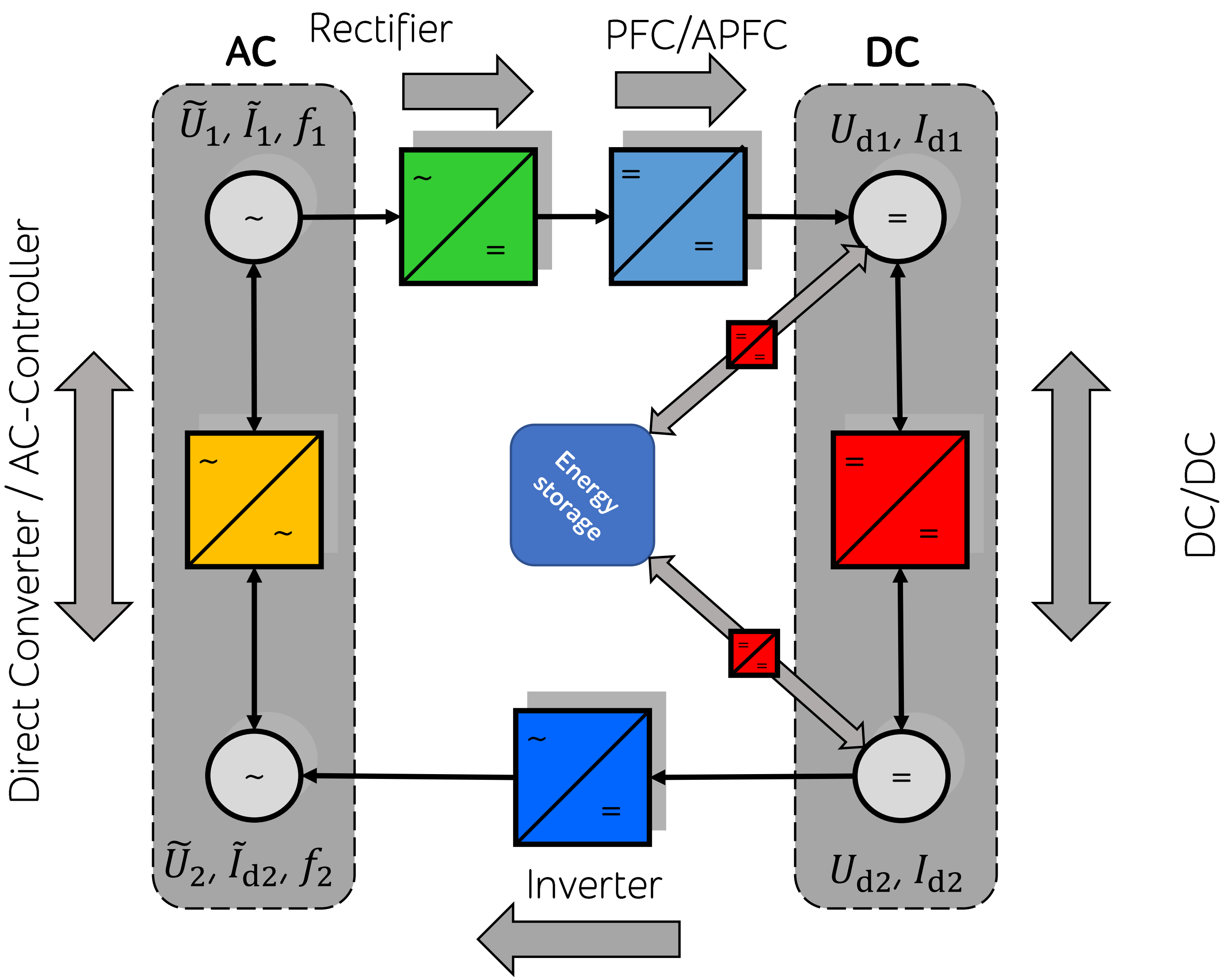
Inverting – converting DC to AC

Types of inverters:

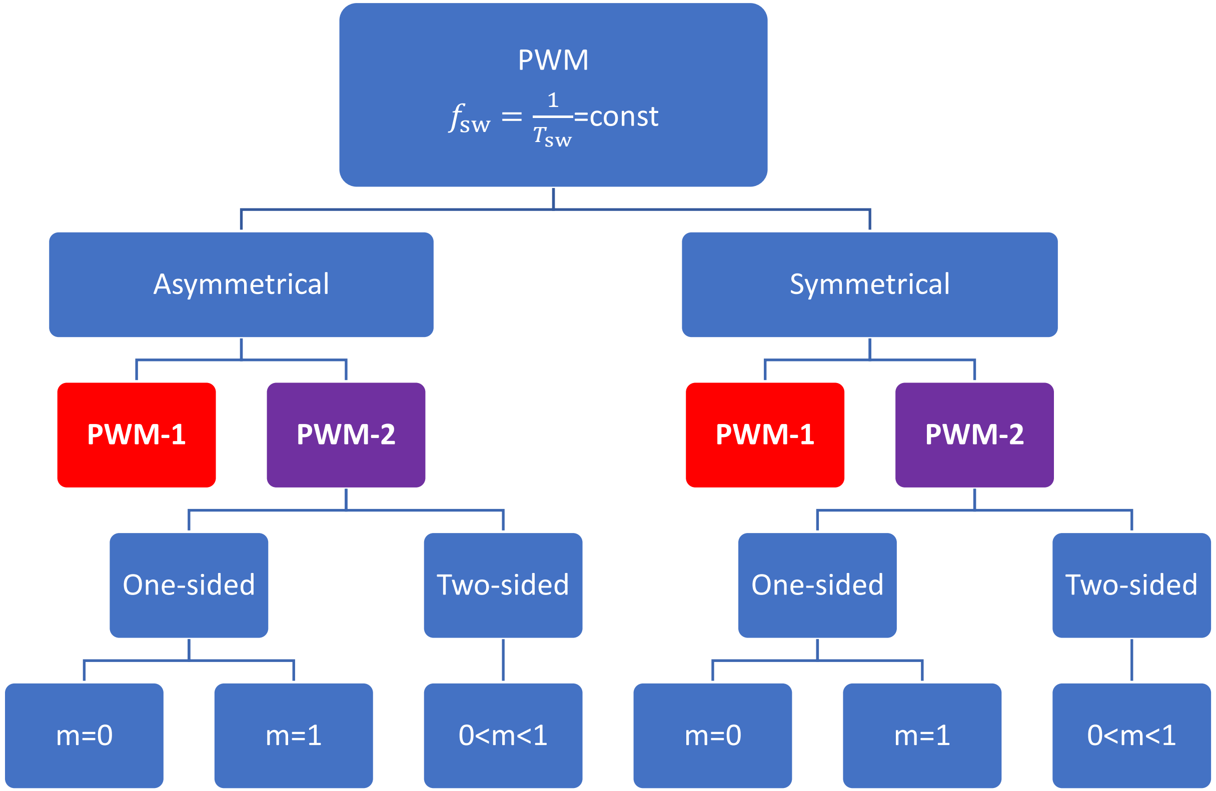
1. Dependent (grid-tie) inverters: convert DC to AC grid with fixed voltage and frequency parameters

2. Standalone inverters
   1. Autonomous voltage inverters (PWM converters, active front-ends).
   2. Autonomous current inverters.
   3. Autonomous resonant inverters (LCC converters, LLC converters, ets).

3. Frequency converters.
   1. Frequency converters with a DC link
   2. Direct frequency converters

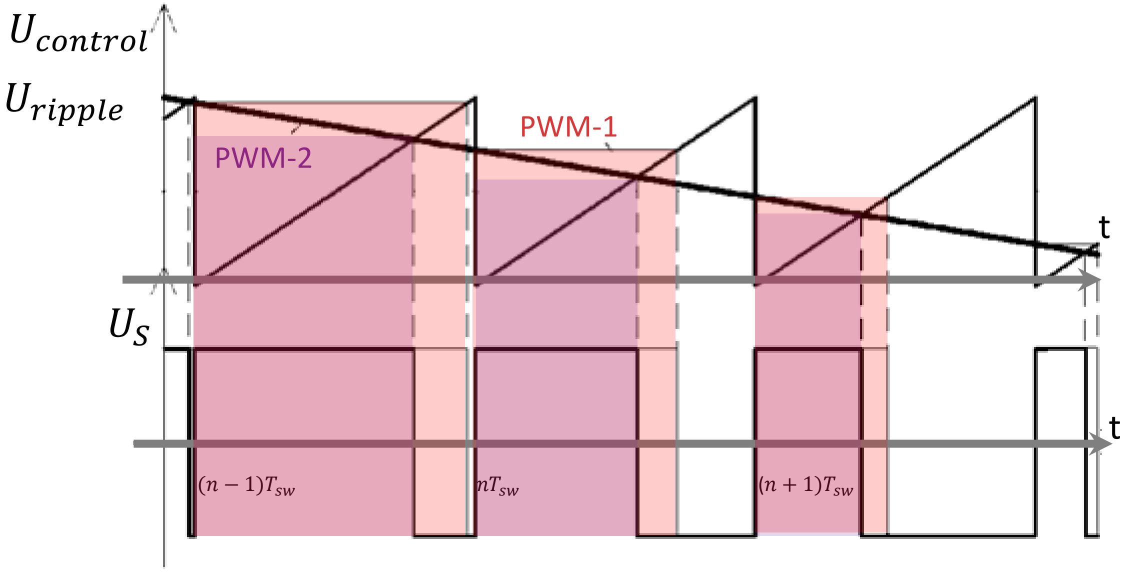


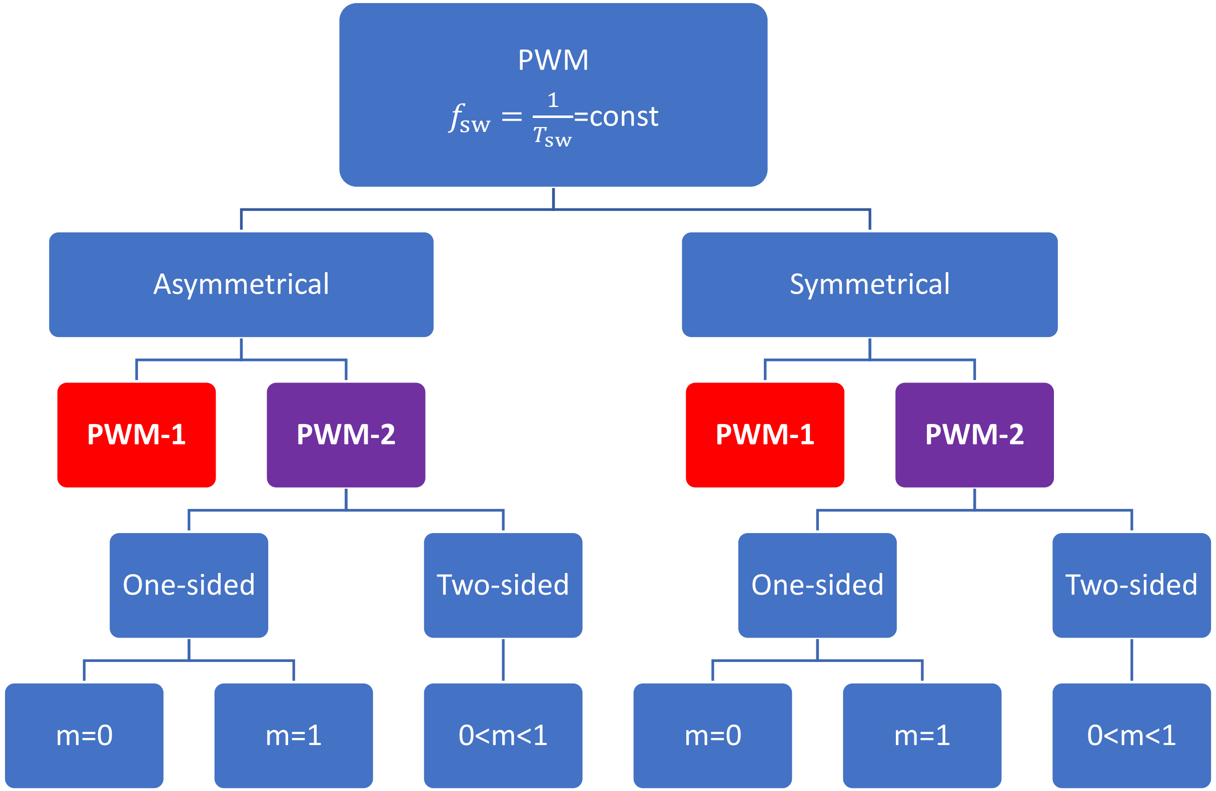
– with a constant switching frequency (symmetrical and asymmetrical)
– with a variable switching frequency.



DC Drive PWM classification

– with a constant switching frequency (symmetrical and asymmetrical)
– with a variable switching frequency.





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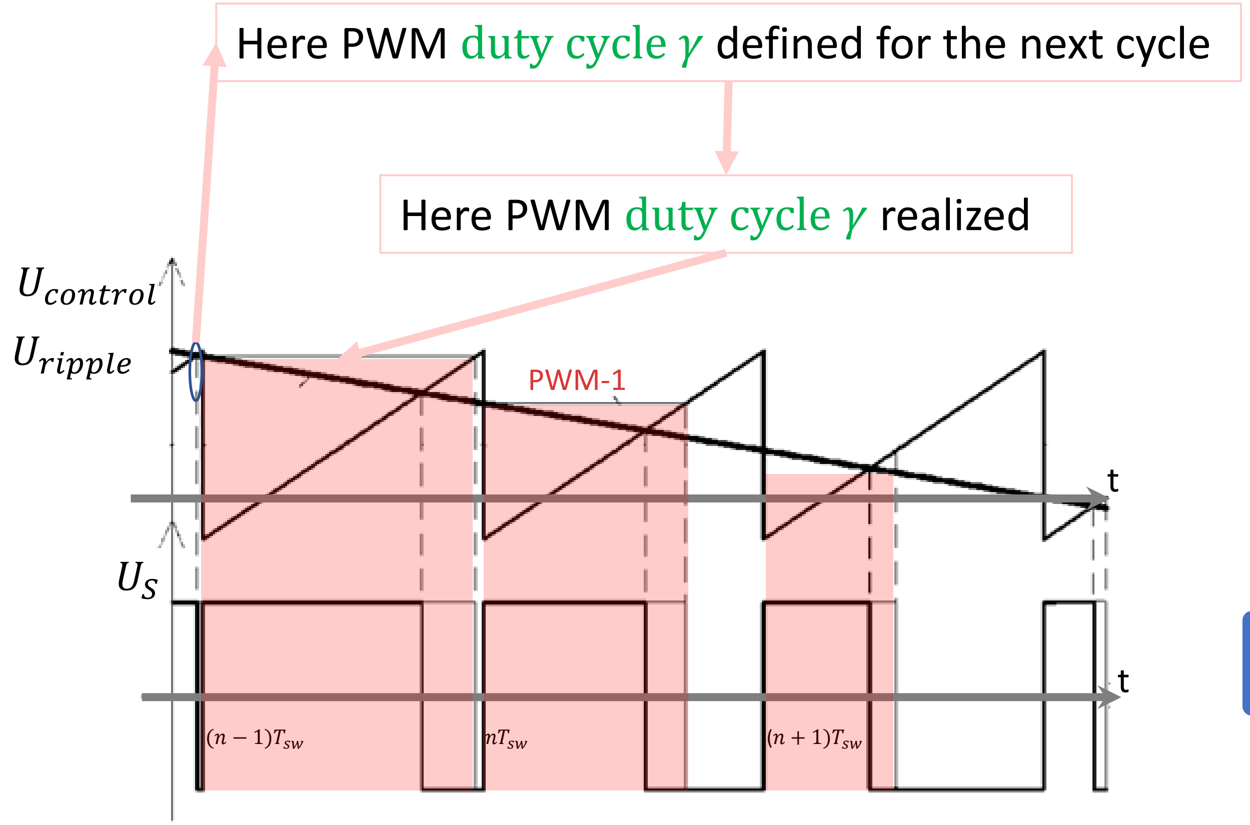

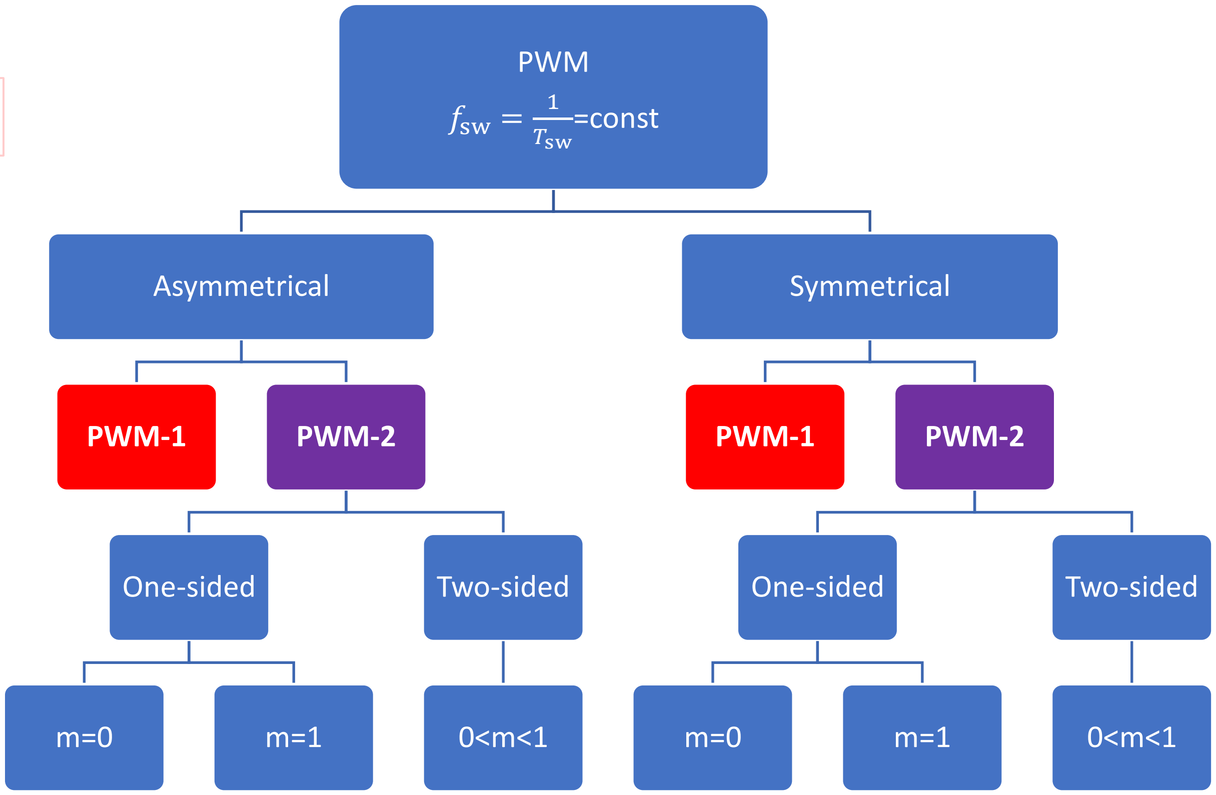

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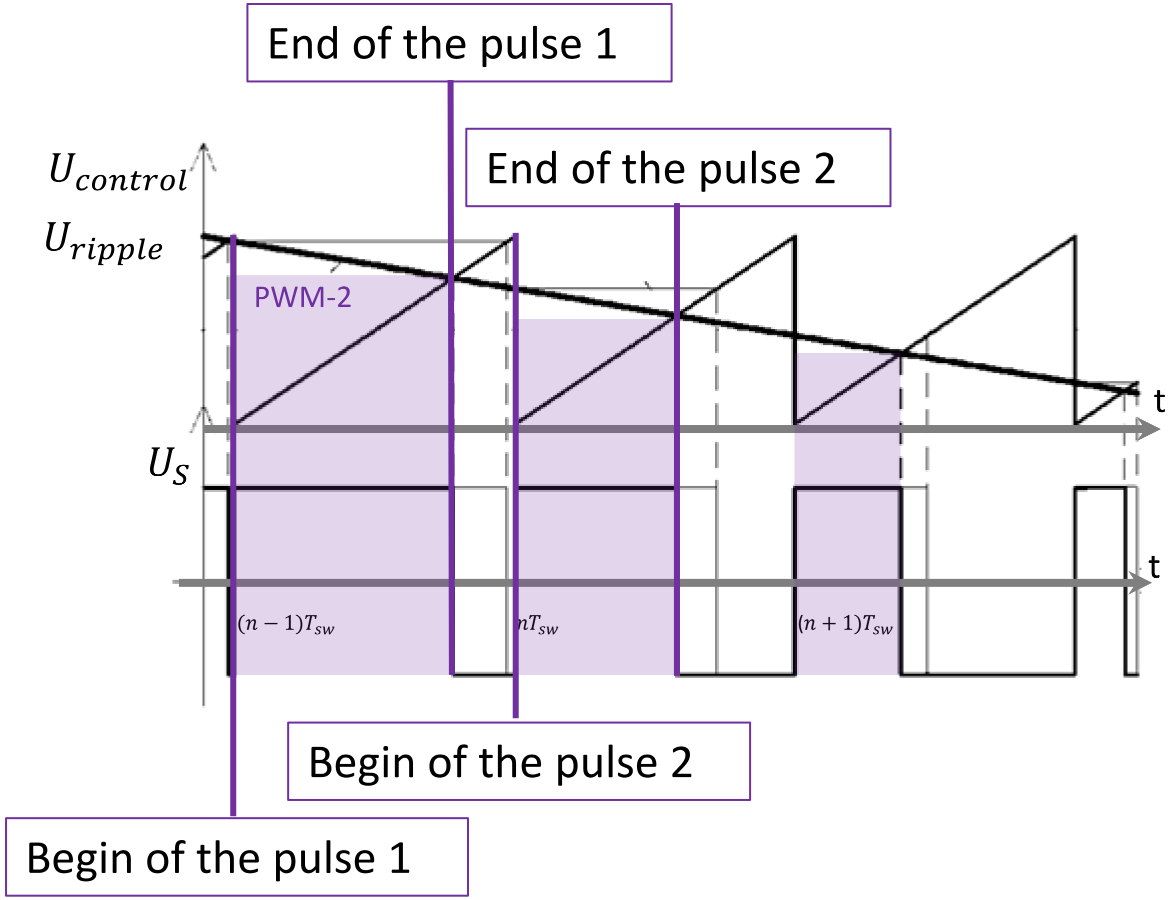
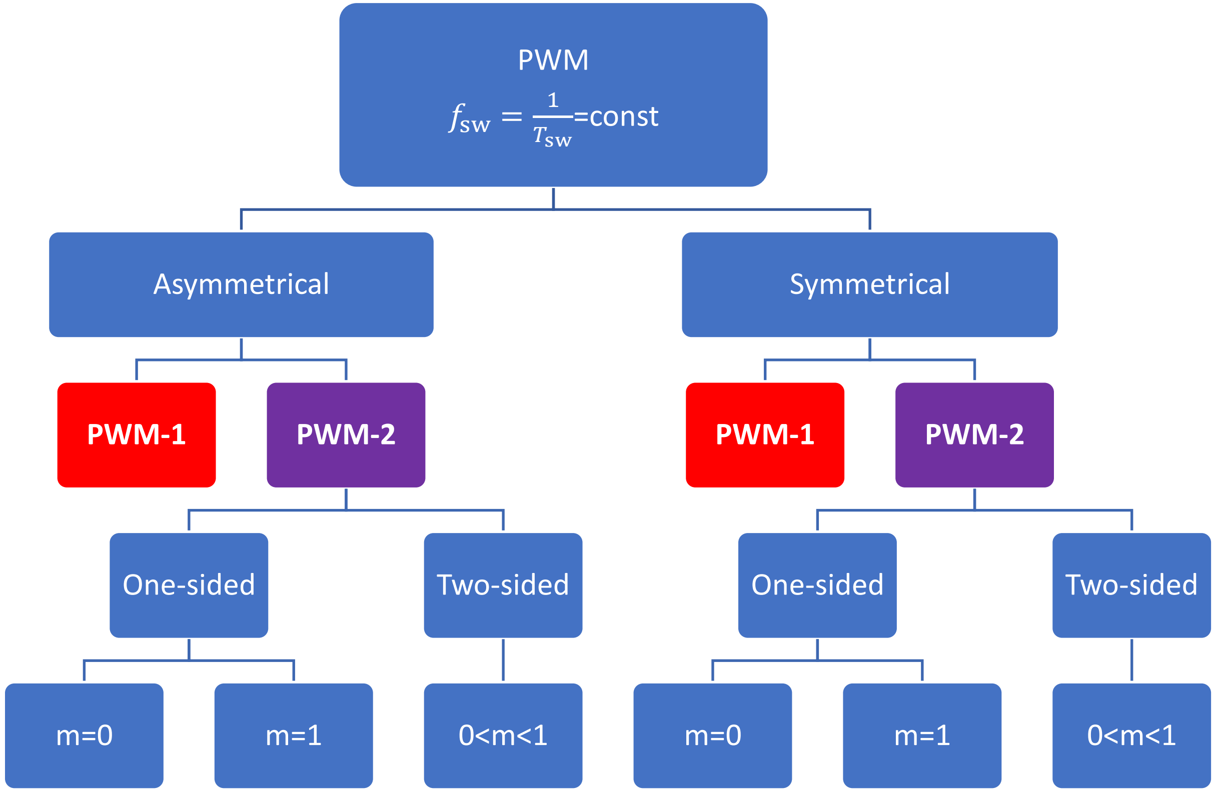




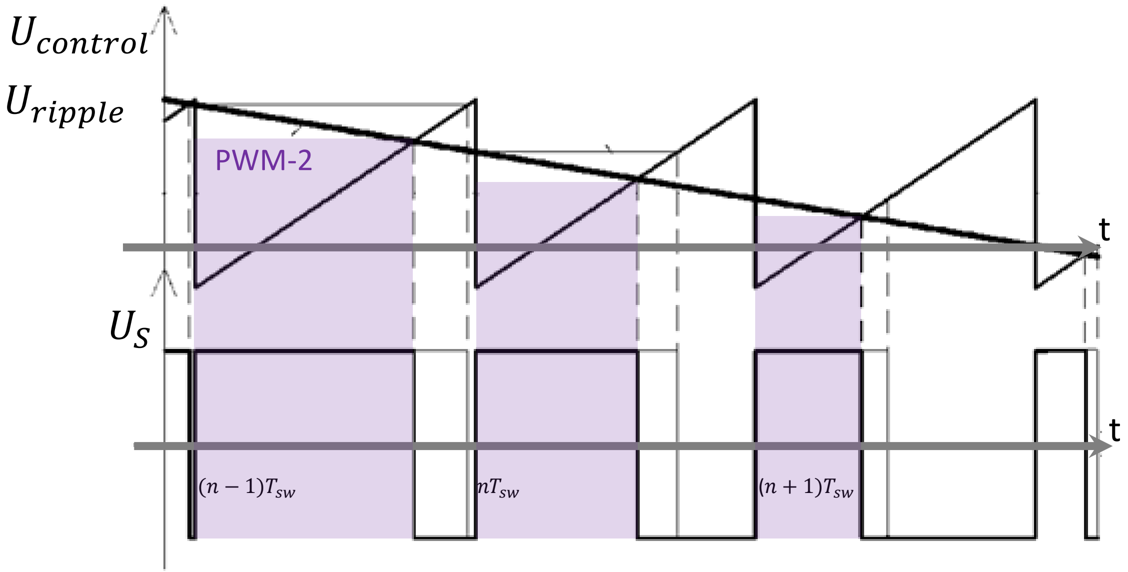
Classification of the PWM by the method of determination of the pulse duration

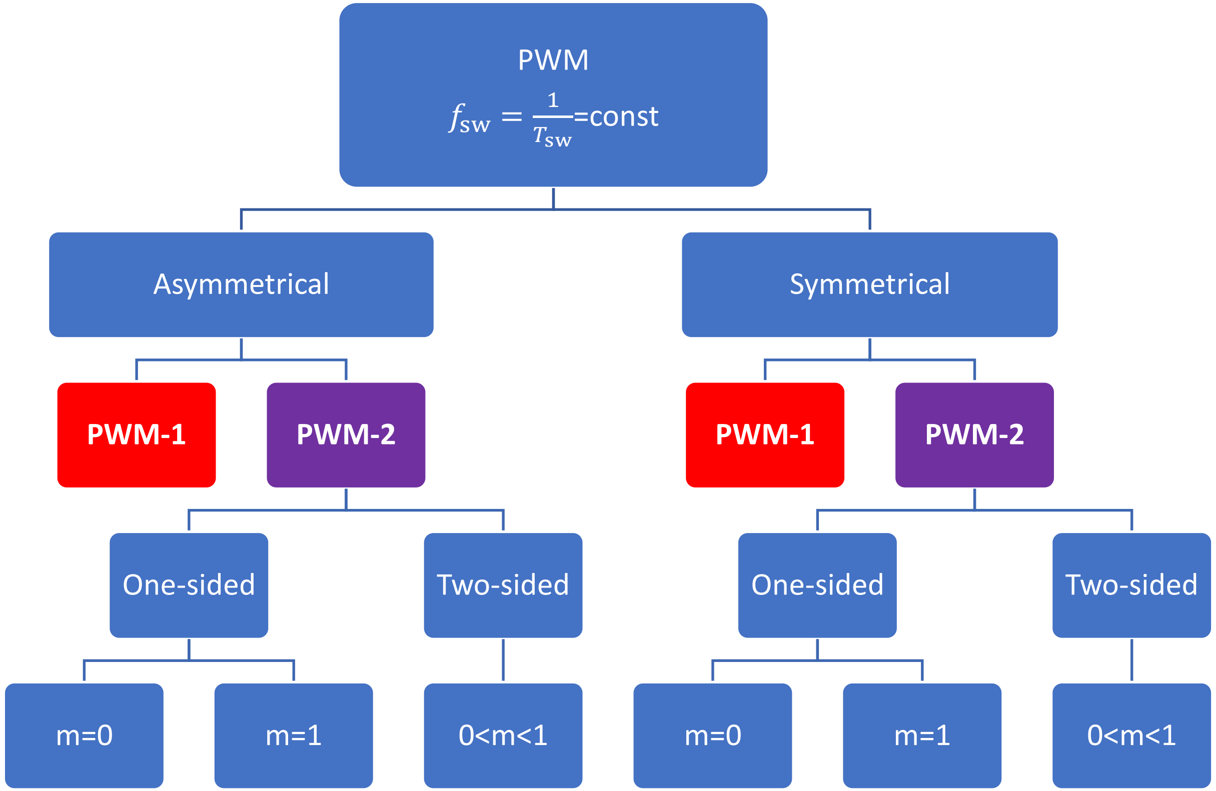
Modulation index m - determines the shape of the modulating signal - saw:

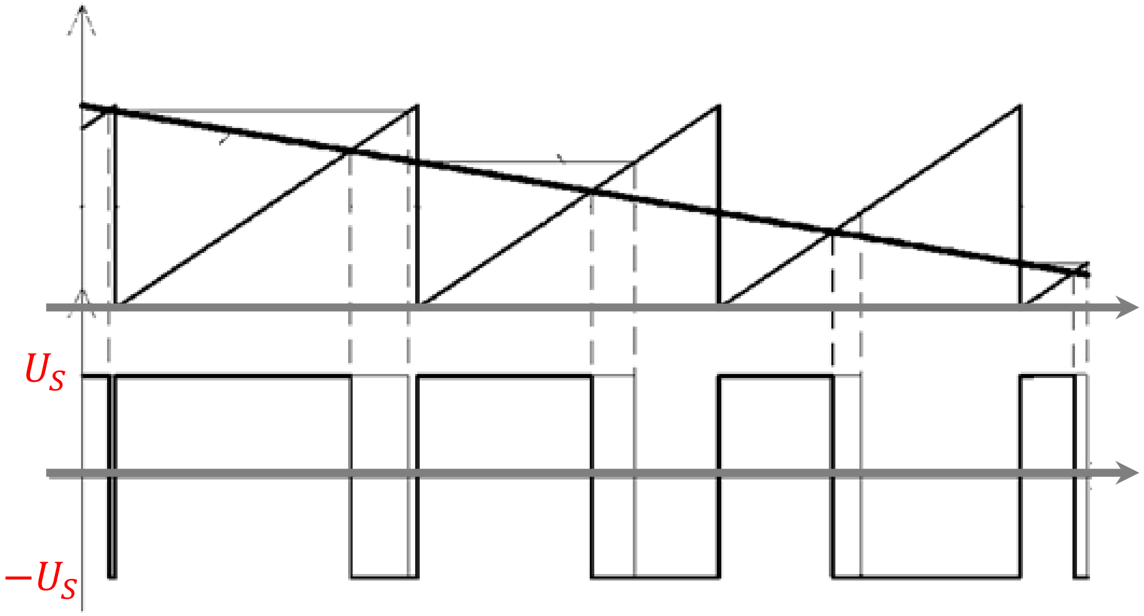
- if m=0 there is a modulation of the anterior front of the pulse (one-sided);

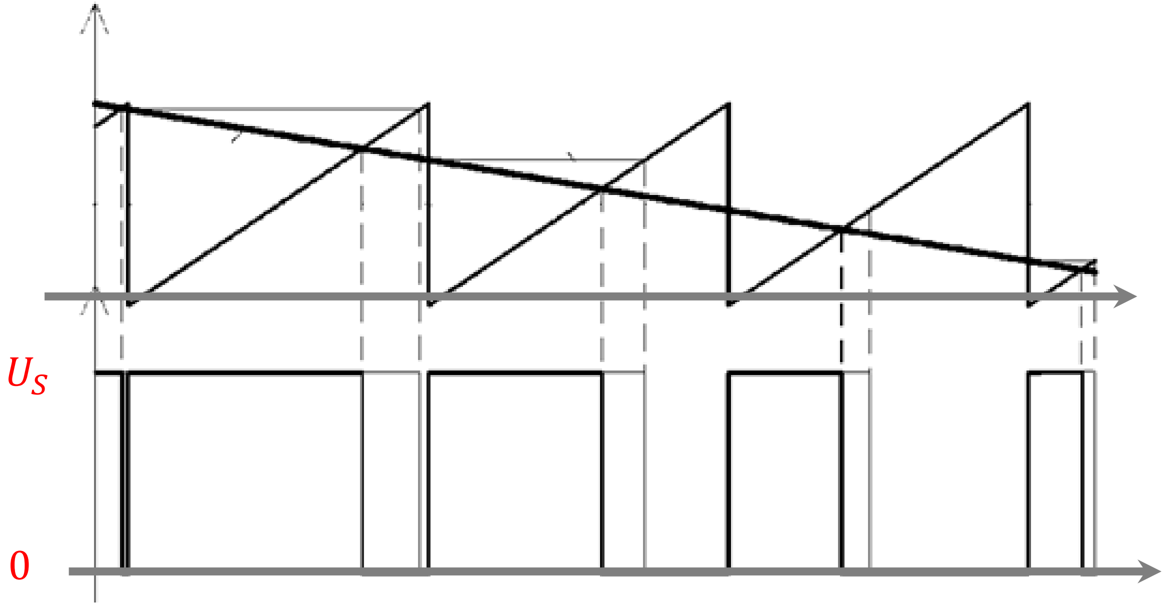
- If m=1- rear pulse front modulation (one-sided);

- if 0<m<1 - modulation of both fronts (two-sided).



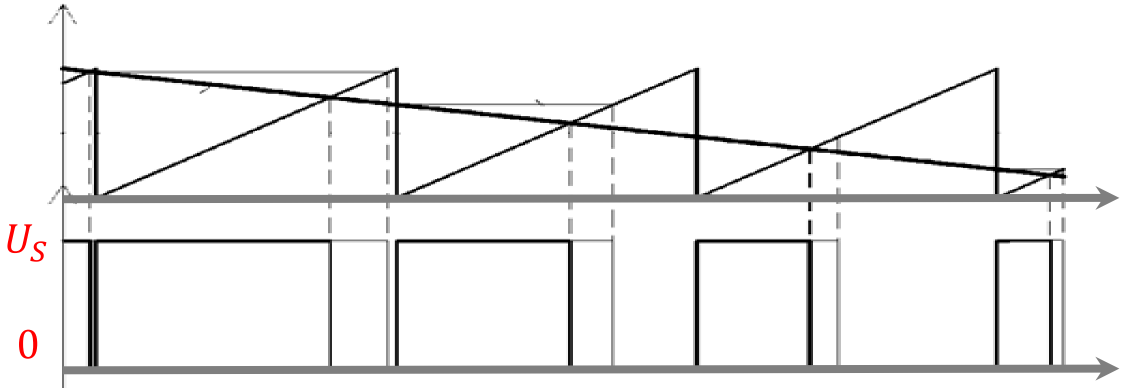


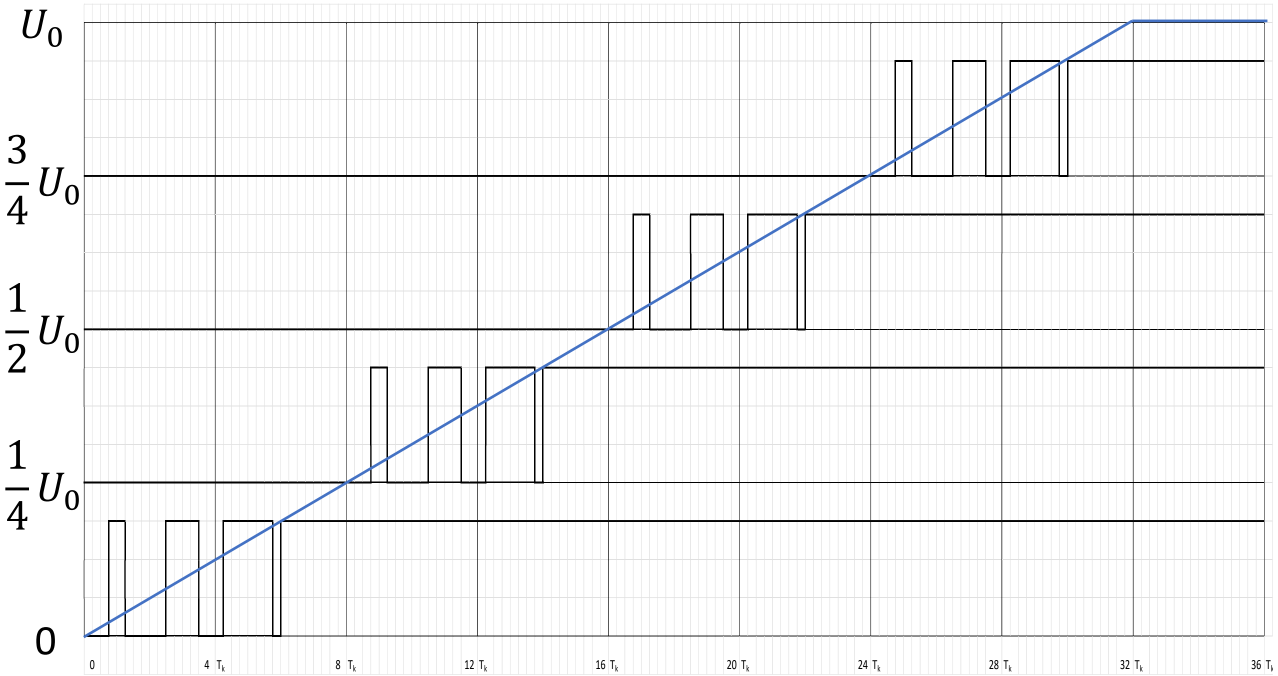




- **bipolar** modulation – the cycle is formed by the combination of pulses of **positive** and **negative** polarity,
- **unipolar** modulation – a clock is formed by a pulse of **one** polarity and a **pause**

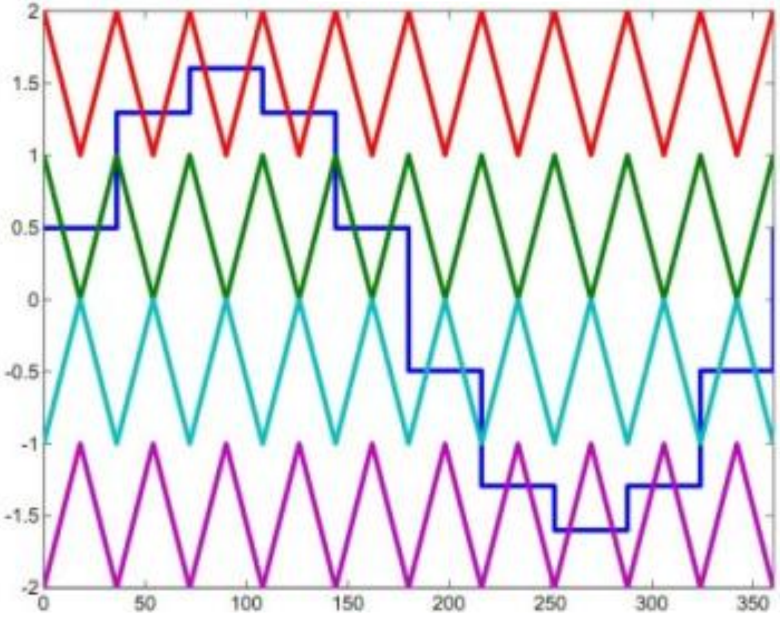
Multi-zone modulation



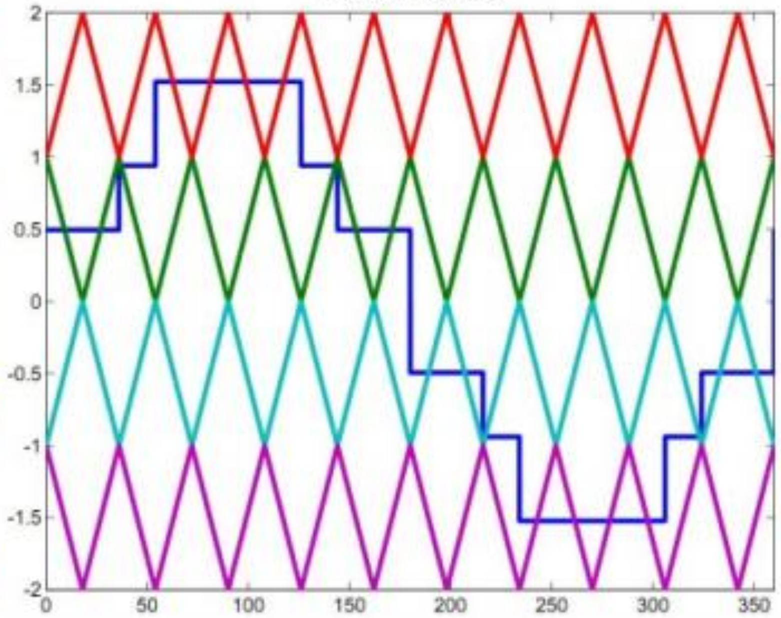


- single-level control algorithms implemented in classical single-phase and three-phase bridge schemes of inverters
- multi-level control algorithms implemented in modified circuits of three-phase inverters.

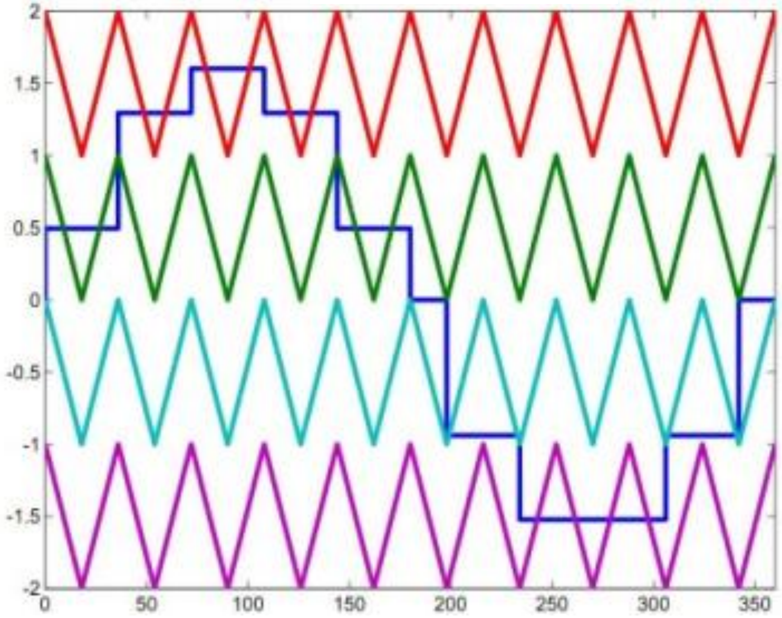
PWM-MST 1



PWM-MST 2



PWM-MST 2



- PWM-MST 1 – common-mode arrangement of all sawtooth signals;
- PWM-MST 2 – 180-degree shift of sawtooth signals;
- PWM-MST 3 – combination of common-mode arrangement of sawtooth stresses;

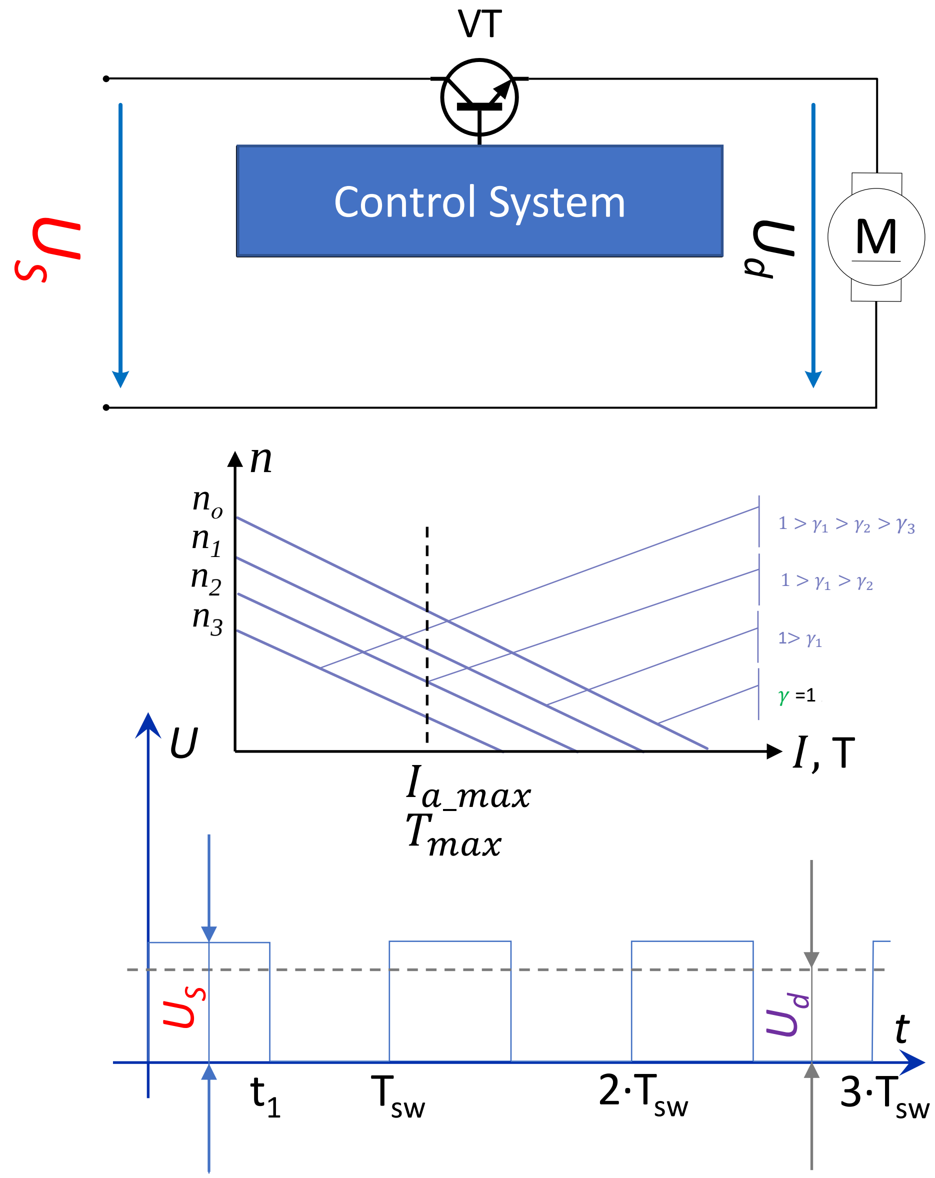
Types of modulation:

1. **Pulse Width Modulation (PWM) with Constant Switching Frequency** $(f_{sw} = const, T_{sw} = const, t_1 = var)$.

2. Pulse-frequency modulation (PFM) $(T_{sw} = var,\ t_1 = const)$

3. Pulse-frequency Width Modulation (PFWM) $(t_1 = var, T_{sw} = var)$

4. Multi-zone pulse modulation (MZPM).



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I_a	— armature current	[A]
r_a	— resistance (armature windings)	[Ohm]
r_{cont}	— additional resistance	[Ohm]
T	— torque	$[\mathrm{N \cdot m}]$
C_e	— constructive constant	[V/rpm]
Φ	— magnetic flux	[Wb]
f_{sw}	— switching frequency	[Hz]
T_{sw}	— switching period	[s]

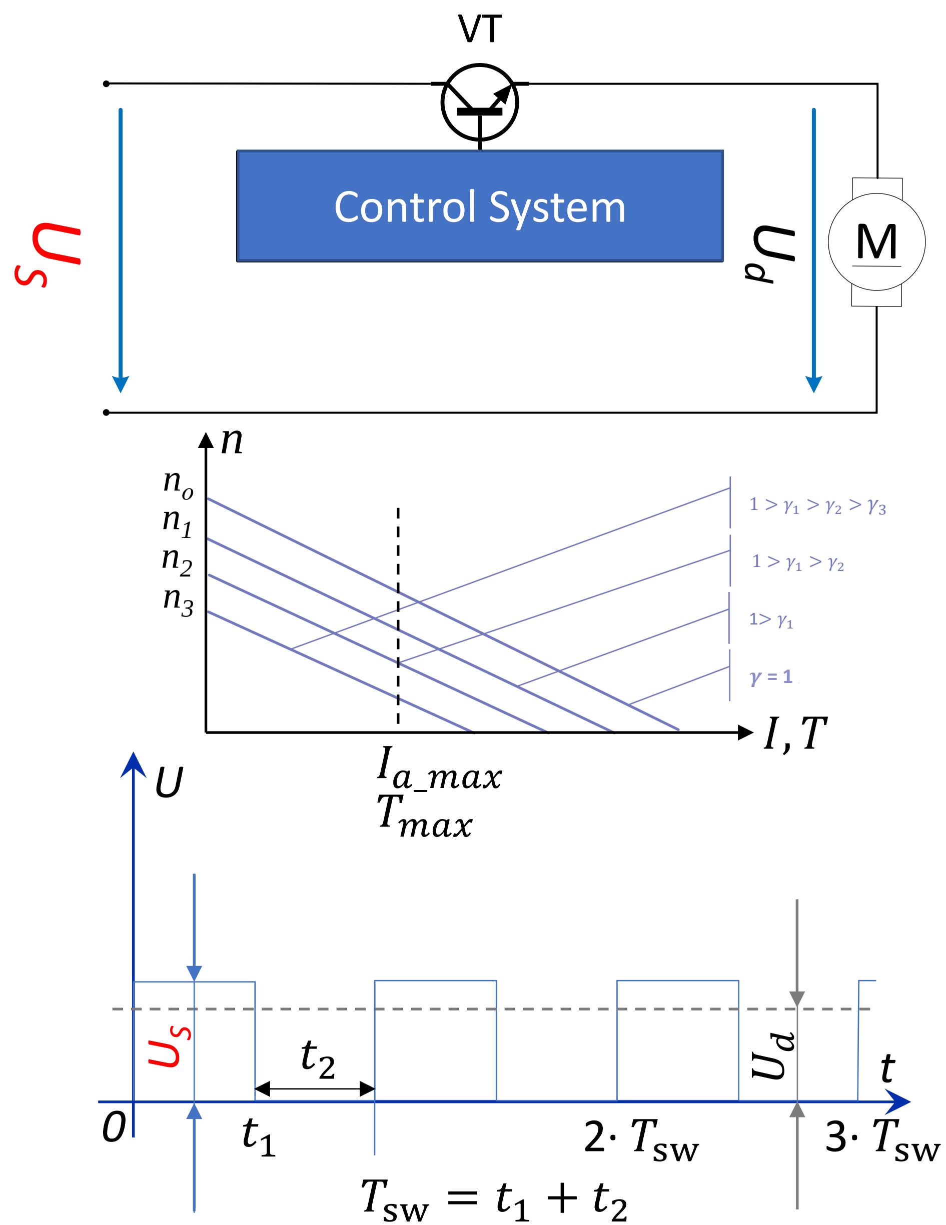
$\gamma = \frac{t_1}{t_1+t_2} = \frac{t_1}{T_{sw}} = t_1 \cdot f_{sw}$ — duty cycle

$$n = \frac{U_a - I_a \cdot r_a}{C_e \cdot \Phi} \quad \rightarrow \quad n = \frac{U_S \cdot \gamma}{C_e \cdot \Phi} - \frac{I_a \cdot r_a}{C_e \cdot \Phi}$$

Types of modulation:

1. **Pulse Width Modulation (PWM) with Constant Switching Frequency** ($f_{sw} = const, T_{sw} = const, t_1 = var$).

Inverters of DC drive systems



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C_e	– constructive constant	[V/rpm]
Φ	– magnetic flux	[Wb]
f_{sw}	– switching frequency	[Hz]
T_{sw}	– switching period	[s]

$$t_1 + t_2 = T_{sw}$$

$$f_{sw} = \frac{1}{T_{sw}}$$

$$U_d = U_a = \frac{1}{T_k}\int_0^{t1} u_S(t)dt$$

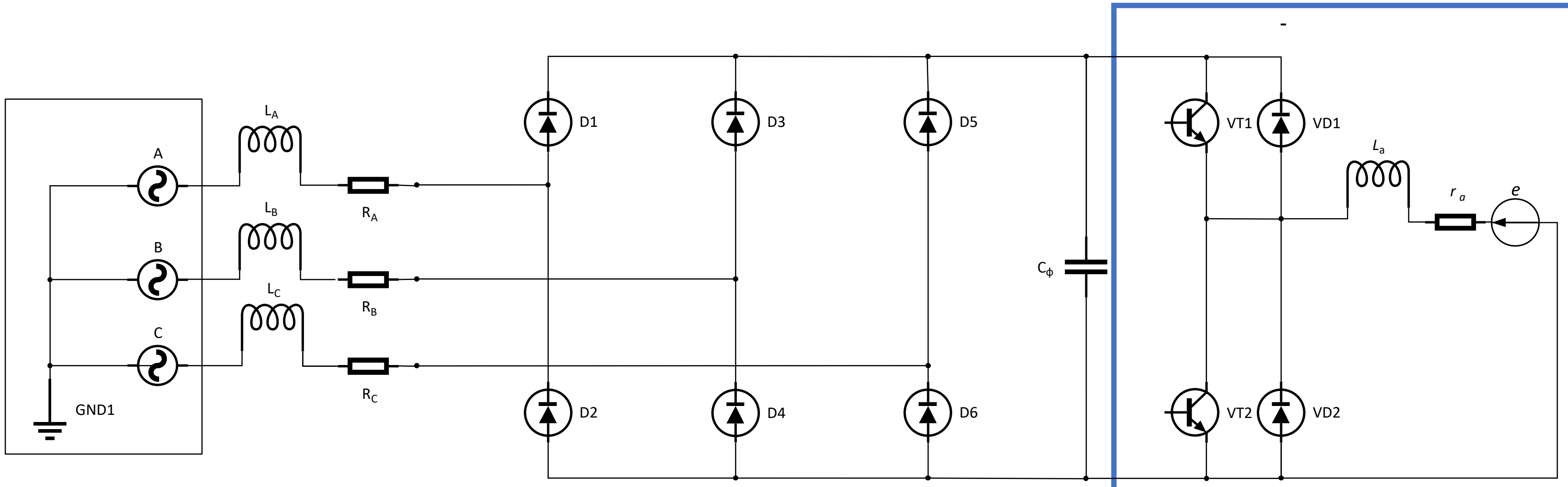
$$U_d = U_a = \frac{U_n \cdot t_1}{T_k} = U_S \cdot f_{sw} \cdot t_1 = \frac{U_S \cdot t_1}{t_1 + t_2} = U_S \gamma$$

$\gamma = \frac{t_1}{t_1+t_2} = \frac{t_1}{T_{sw}} = t_1 \cdot f_{sw}$ – duty cycle,

t_1 - pulse width (pulse active time), t_2 - zero pulse width (pulse inactive time)

$$\boxed{n = \frac{U_a - I_a \cdot r_a}{C_e \cdot \Phi} \quad \rightarrow \quad n = \frac{U_S \cdot \gamma}{C_e \cdot \Phi} - \frac{I_a \cdot r_a}{C_e \cdot \Phi}}$$

The main circuit of transistor PWM converters for electric drive systems



Schemes can be:

- reversible
- **non-reversible**

with

- symmetric switching law.
- **asymmetrical** switching law.

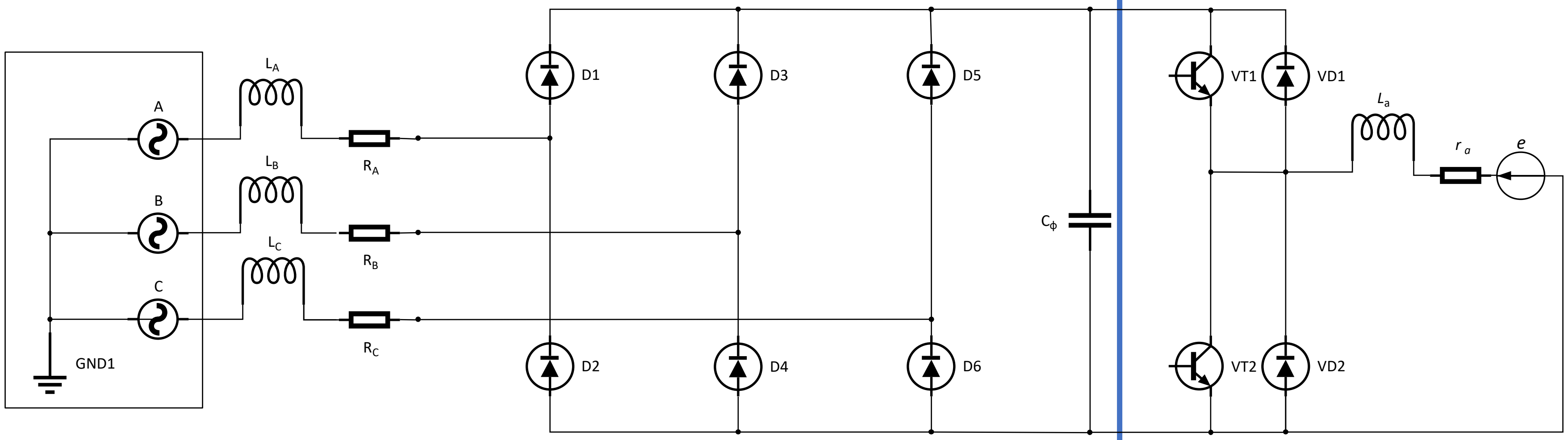
The switching law and method should be chosen to ensure:

1. Equal load on elements of equipment.

2. The armature circuit of the DC machine should not break and should not significantly change its resistance at the time of current flow in the armature circuit.

3. Reversibility of electrical energy flows from the power source to the load and vice versa.

The main circuit of transistor PWM converters for electric drive systems



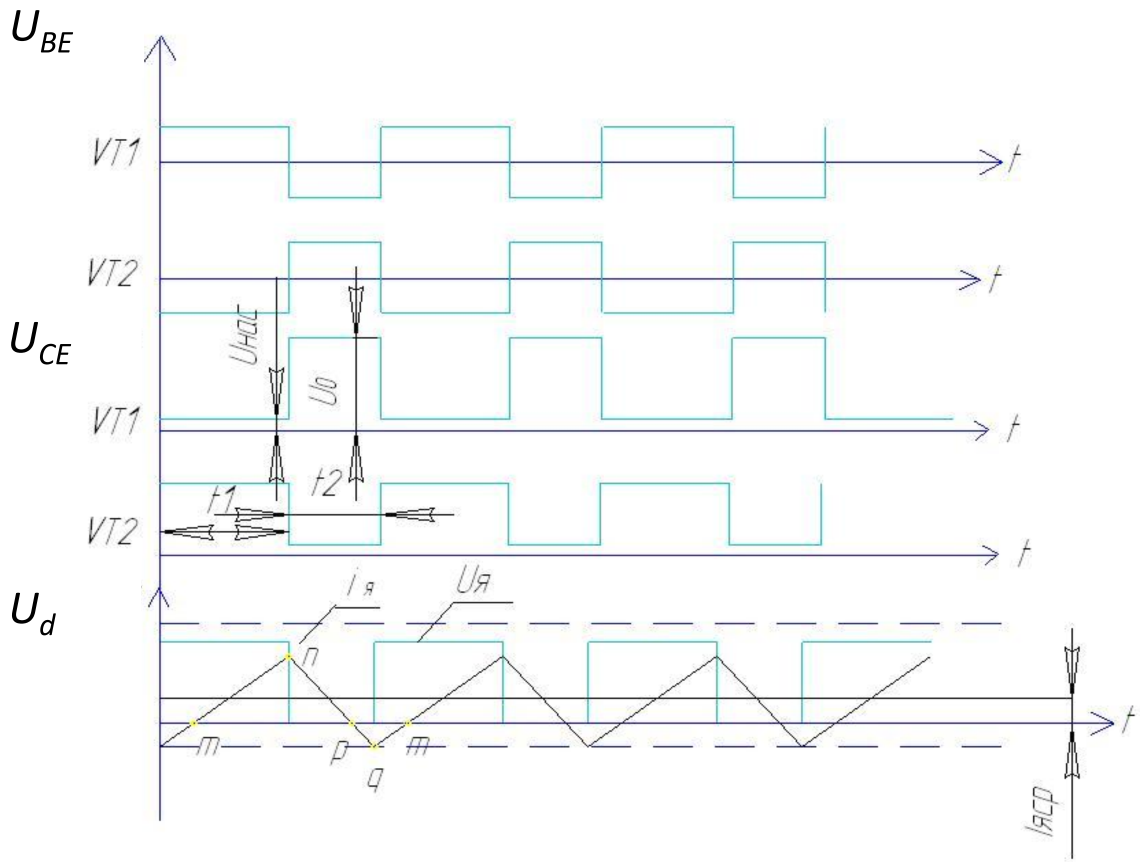
non-reversible circuitry providing

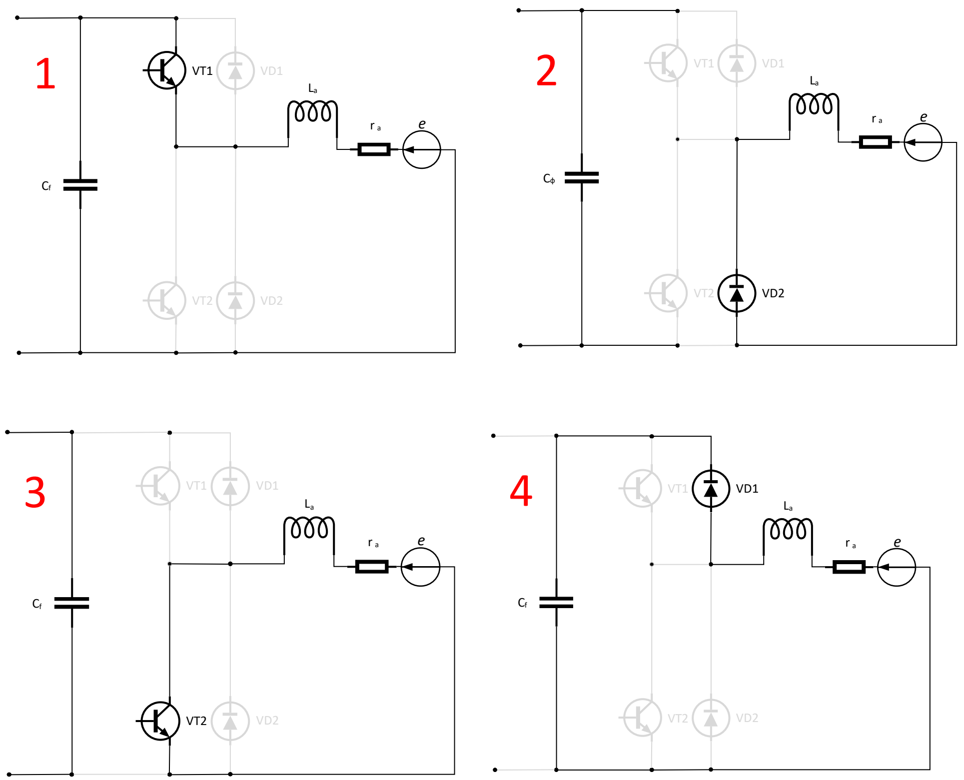
- dynamic braking mode
- return of the energy of the rotating parts of the machine to the power grid.

Transistors VT1 and VT2 are switched by sign-alternating pulses of reverse polarity, i.e.
when VT1 is switched on, VT2 is switched off and vice versa.

When VT1 is opened: the load circuit is connected to the power supply circuit.

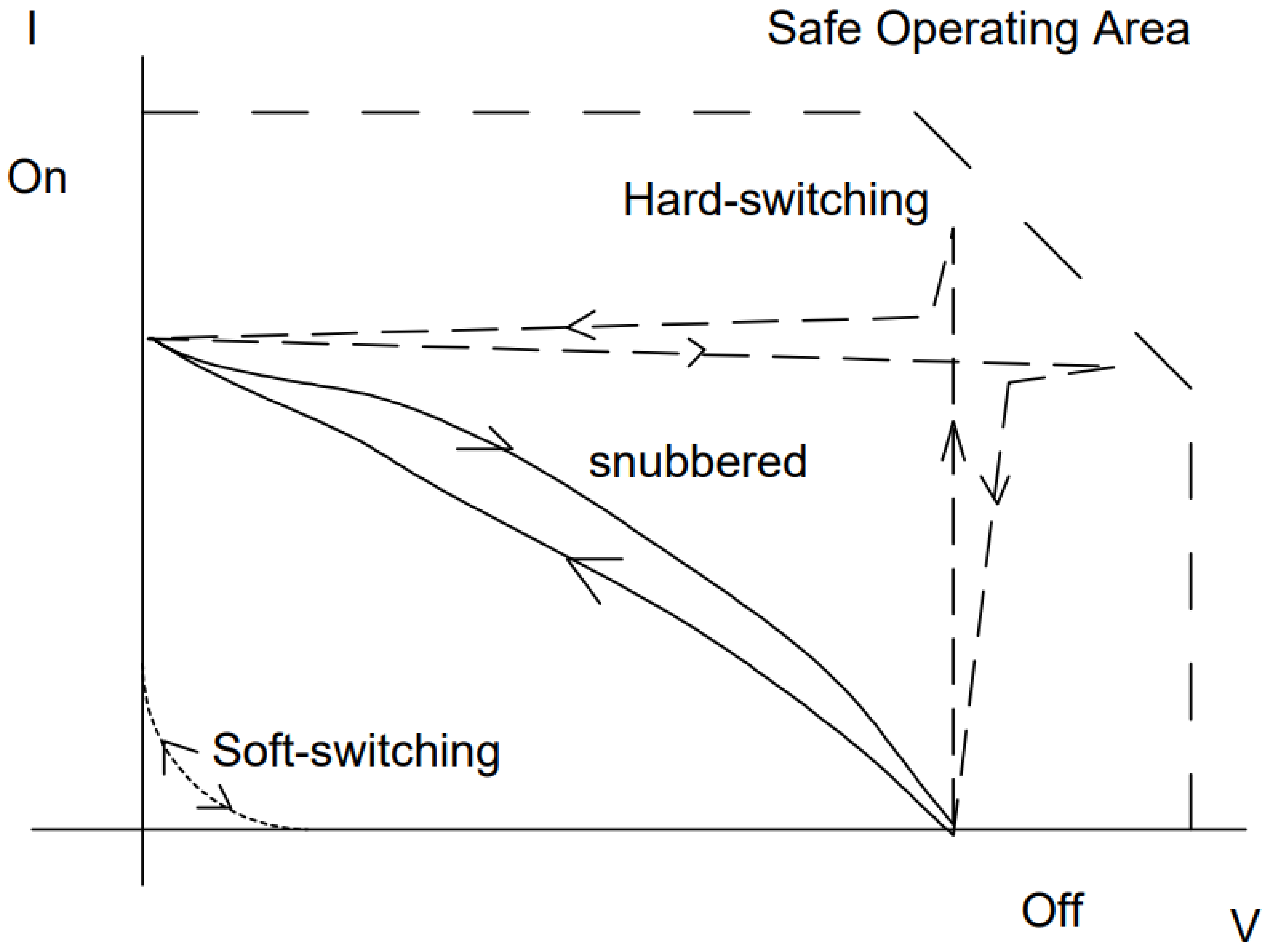
When VT1 is turned off and VT2 is turned on, the DC drive armature circuit is disconnected from the power supply circuit and shortened in the circuits formed either by the open VT2 or by the VD2 shunting it.





Mode 1. Through the open VT1 at the time interval m-n, the energy of the power supply is consumed by the machine, I_a=I_s.
Mode 2. When pulse t_1 ends, the load is disconnected from the power source.
Mode 3. At point p, the current changes direction under the action of the EMF of the armature.
Mode 4. At the end of time, t_2 turns on VT1 and closes VT2.

Hard and soft switching characteristics

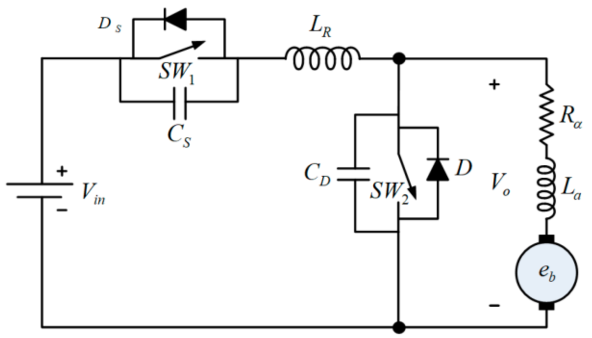


Soft-Switching Converters

- Usage of LC resonant circuits
- Increased number of switches
- Very low ripple current

- High switching frequency, above to 100 kHz
- Low ElectroMagnetic Interference (EMI)

- Very High Efficiency
- Complex Control Circuit



Zero-voltage multi-resonant converter fed DC motor drive

2Q-ZVMR Converter

- 2Q Operation
- Quite low switching losses
- Provides load variation and full ranges of voltage conversion

2Q ZVT Converter

- 2Q Operation
- Unity device current and voltage stress
- Zero voltage switching

2Q ZCT Converter

- 2Q Operation
- Zero current switching
- Minimum current and voltage stresses
- Switching frequency in the range of 50 kHz
- For medium-power DC motor applications in the range of few kW

4Q ZVT Converter

- 4Q Operation
- Unity current and voltage stress
- Zero voltage switching
- High power density

4Q ZCT Converter

- 4Q Operation
- Same characteristics as 2Q-ZCT
- Power up to 5 kW

Soft-Switching Converters

- Usage of LC resonant circuits
- Increased number of switches
- Very low ripple current

- High switching frequency, above to 100 kHz
- Low ElectroMagnetic Interference (EMI)

- Very High Efficiency
- Complex Control Circuit

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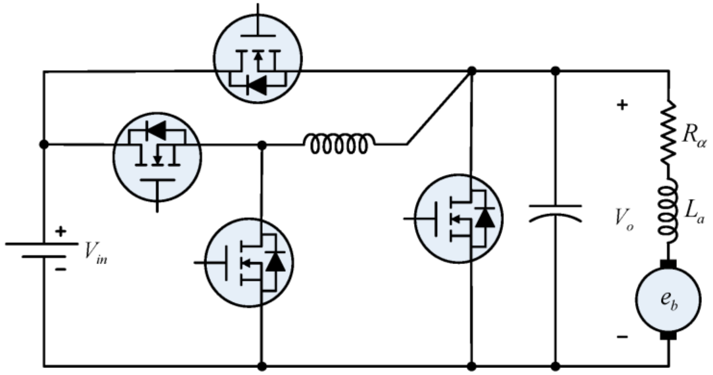

2Q Zero-Voltage-Transition (ZVT)
Zero-current-transition converter fed DC motor drive.

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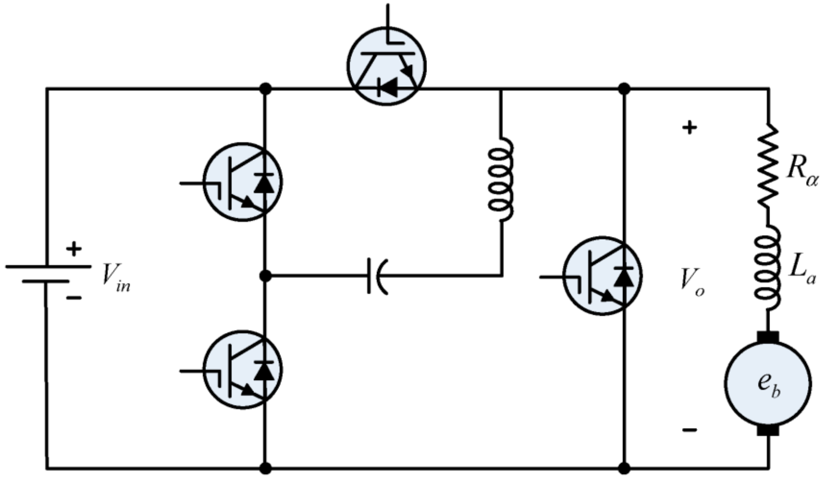

2Q Zero-Current-Transition (ZCT)

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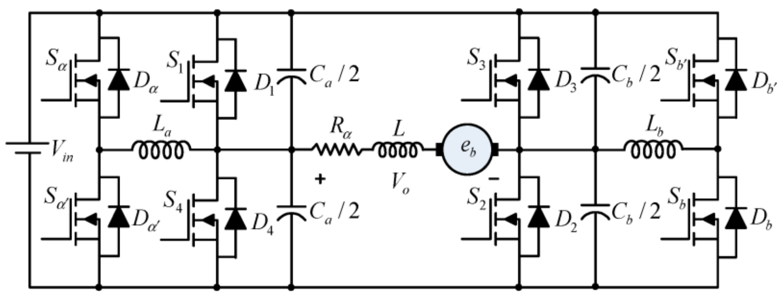

4Q-ZVT converter fed DC motor drive

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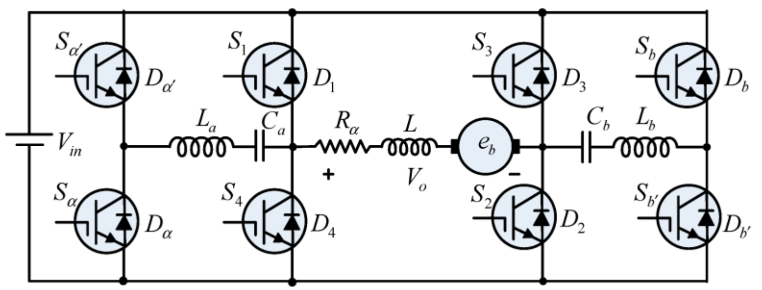

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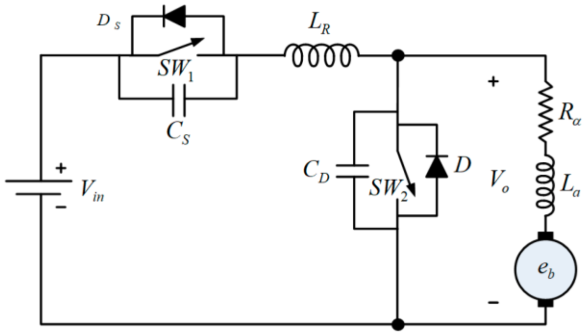
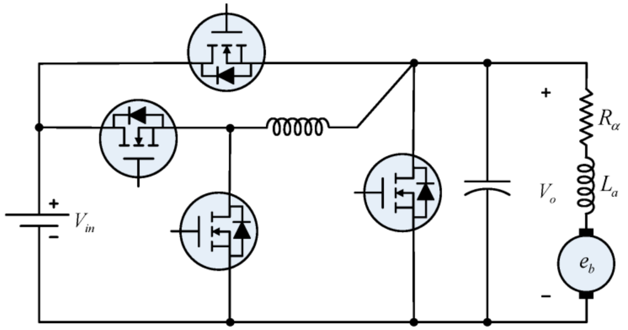
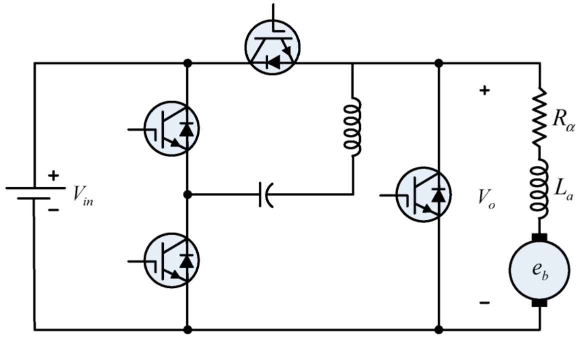


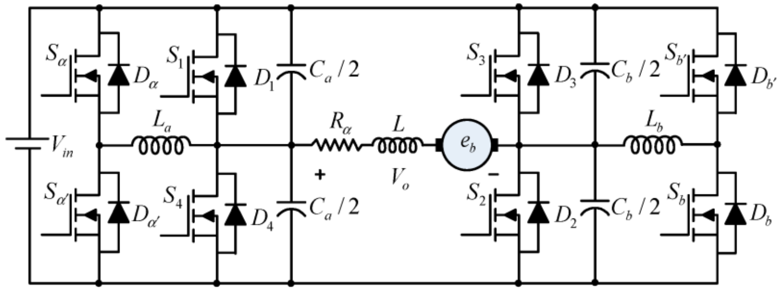
Zero-voltage multi-resonant converter fed DC motor drive



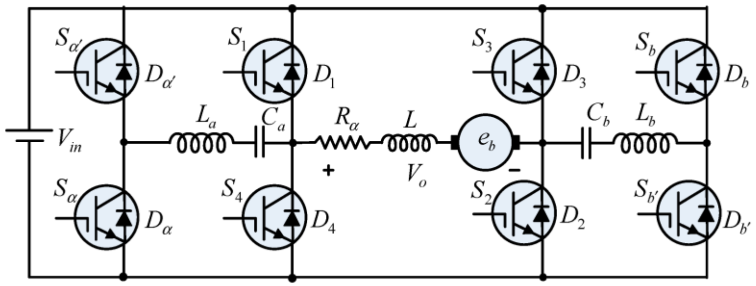
Zero-voltage-transition converter fed DC motor drive



Zero-current-transition converter fed DC motor drive.



4Q-ZVT converter fed DC motor drive



4Q-ZCT converter fed DC motor drive

ITMO

Actuators

Lection 9

H-bridge PWM algorithms

Asc. Prof. Nikolai Poliakov
Asc. Prof. Sergei Lovlin
Asc. Prof. Dmitry Lukichev