# Design Of Inverters

Shiburanj Thayale Veettil

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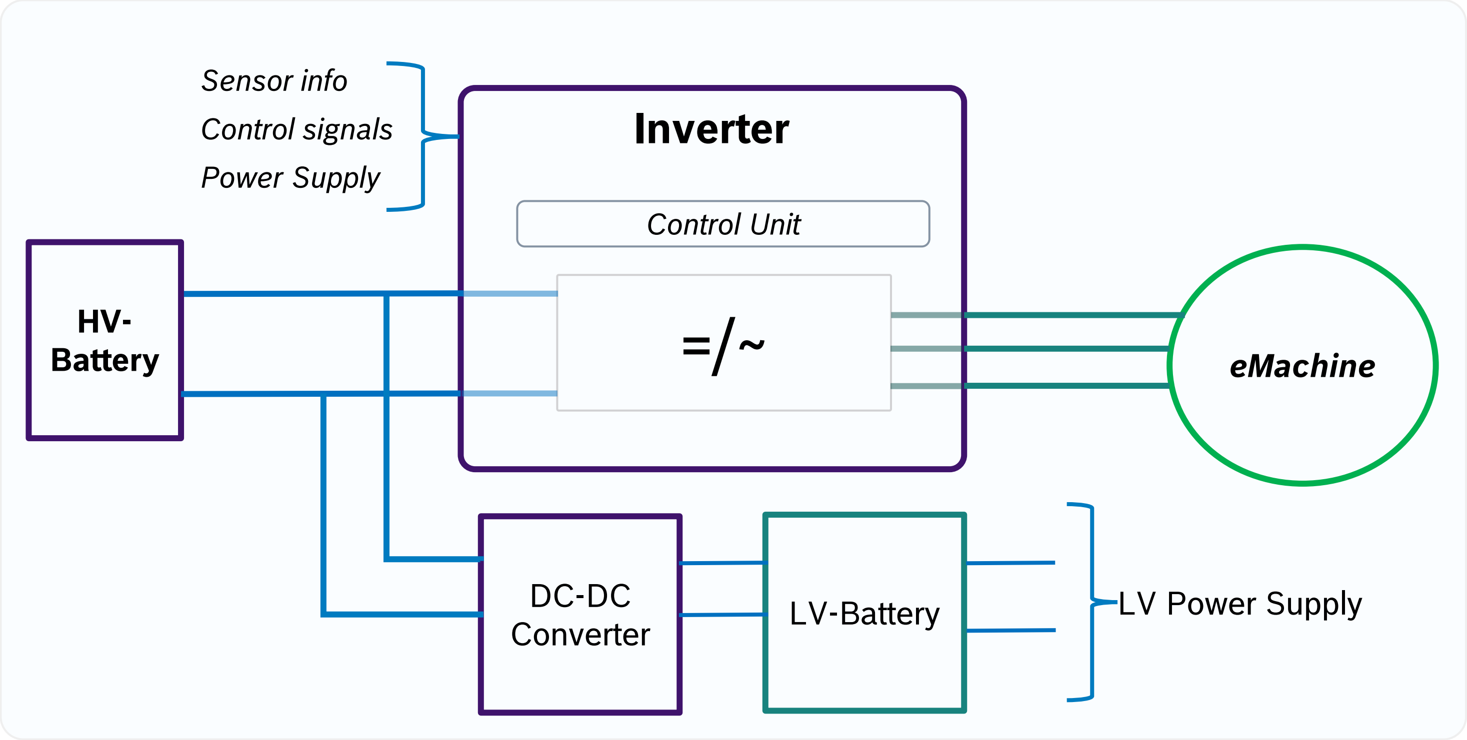
1. Introduction to Inverter
2. Building Blocks: EV Specific Inverter
3. Inverter Operation for BEV
4. Project

01

# Introduction to Inverter

# Introduction to Inverter
## System Overview: BEV





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02

# Building Blocks: EV Specific Inverter

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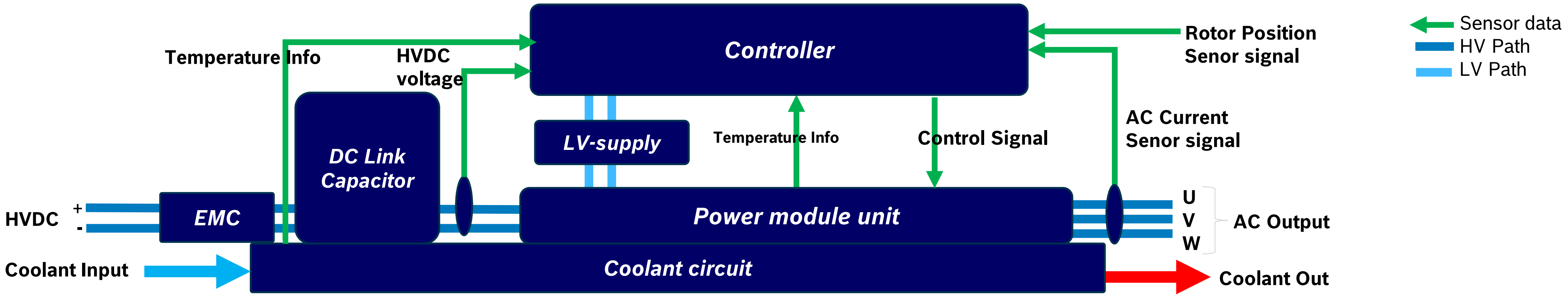
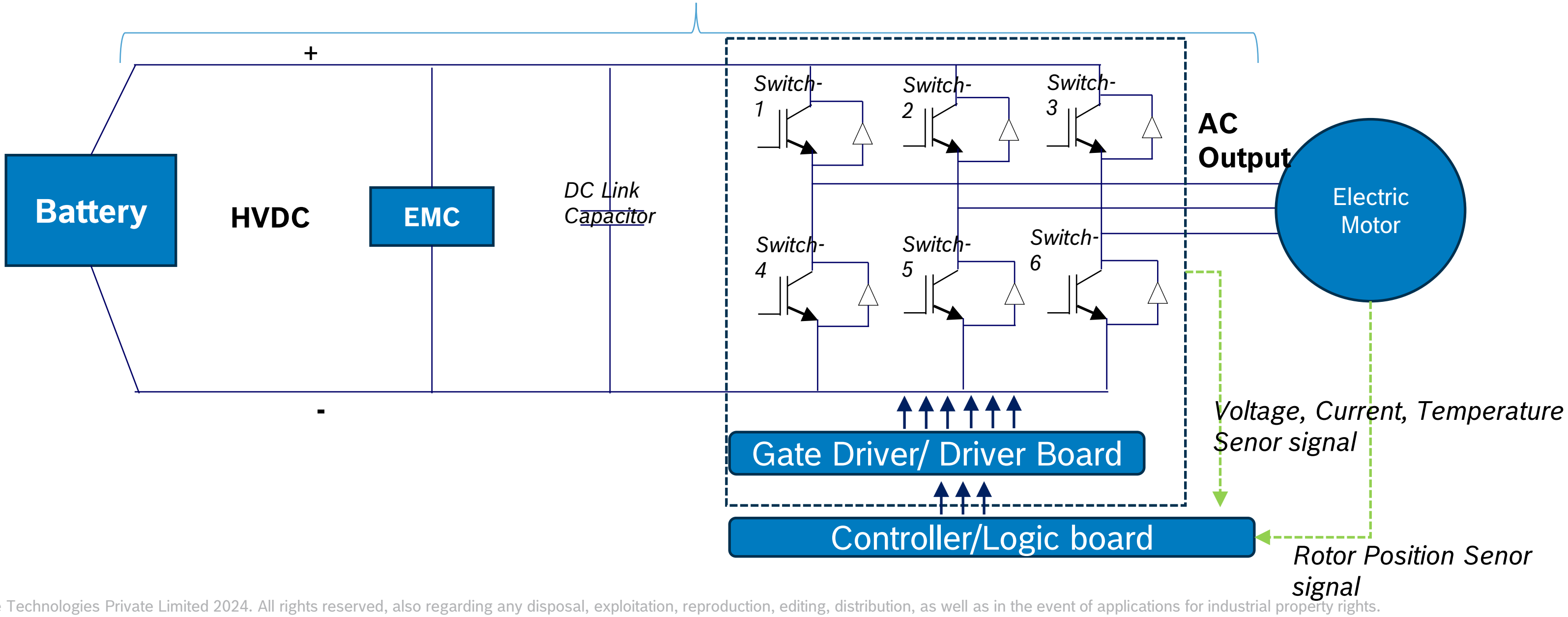
# Building Blocks: EV Specific Inverter

## Inverter Overview







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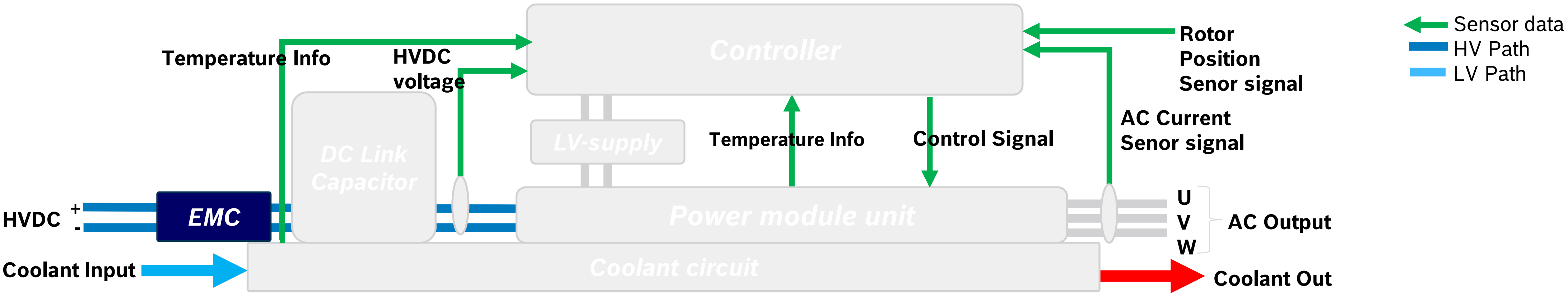
# Building Blocks: EV Specific Inverter

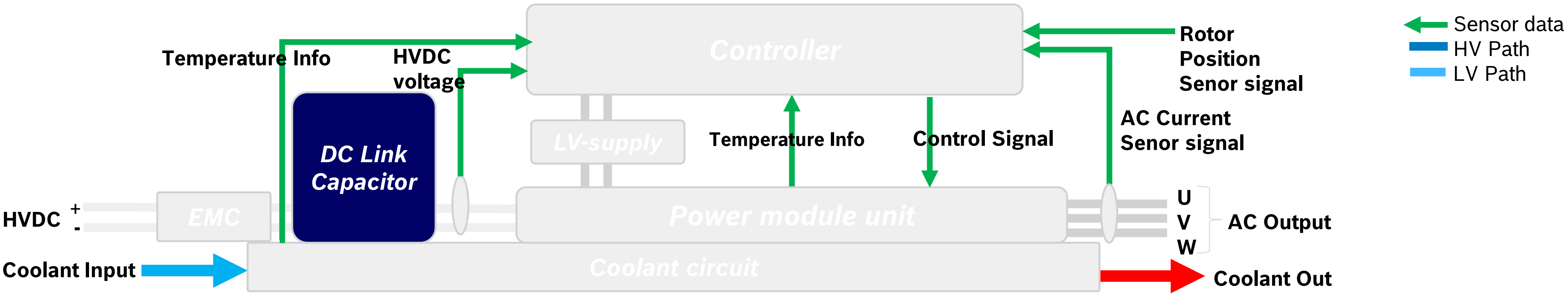
## Components




| Components | Feature | Factors affecting sizing |
|---|---|---|
| **DC Busbars:** | ➢ Used to provide the HVDC supply to DC link capacitor and to Power module.<br>➢ Material: Copper bars<br>    ➢ Electrical conductivity, high current carrying capacity and durability.<br>➢ Preferably indirect cooling. | ➢ Current density – area of conductor<br>➢ Thermal limit – Cooling mechanism<br>➢ Area availability. |
| **EMC Filter:** | ➢ Used to reduce the electromagnetic interference (radiation and emission).<br>➢ Focussing on conductive emission elimination: common-mode and differential-mode current elimination/reduction.<br>➢ The EMC filter will design in such a way that to eliminate the voltage frequency spectrum from 150KHz to 30MHz under the standards . | ➢ Target country legislation on emission (radiative and conductive).<br>➢ Target Frequency spectrum<br>    ➢ Switching frequency<br>    ➢ Power module type<br>    ➢ Elimination mechanism (SW/HW)<br>    ➢ Machine parameters |

# Building Blocks: EV Specific Inverter

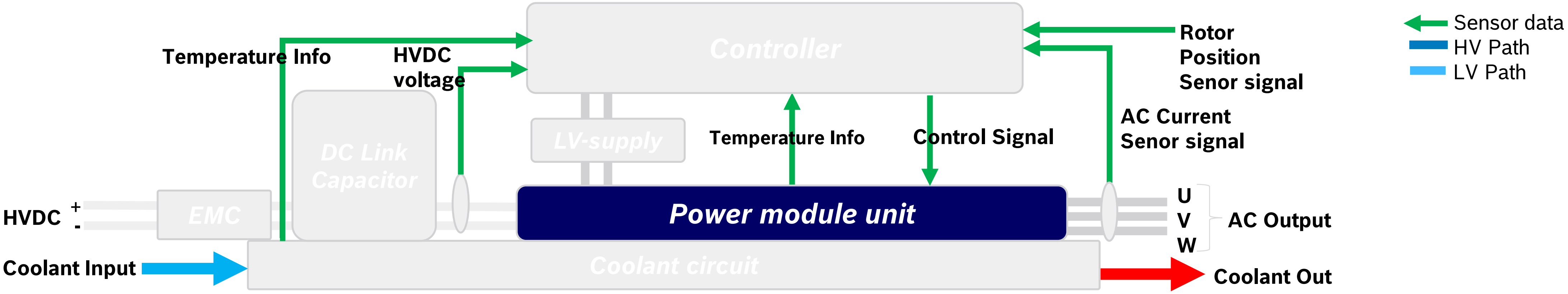
## Components




| Components | Feature | Factors affecting sizing |
|---|---|---|
| **DC Link Capacitor:** | ➢ DC Link capacitor is used to reduce voltage ripple caused by inverter switching and other voltage surges from external sources. | ➢ HVDC operational voltage<br>➢ Acceptable voltage ripple values during the inverter operation.<br>➢ Switching frequency and modulation methods<br>➢ Current limits.<br>➢ Space and cost targets.<br>➢ NVH |

# Building Blocks: EV Specific Inverter

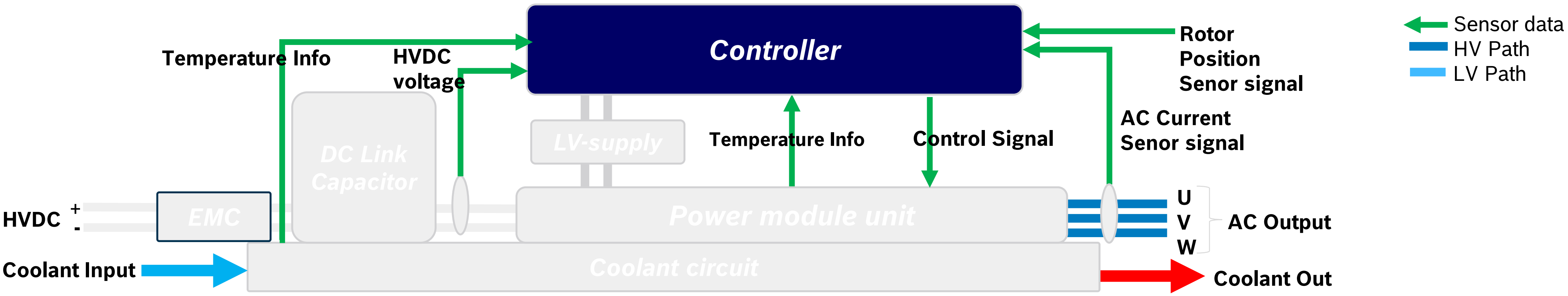
## Components




| Components | Feature | Factors affecting sizing |
|---|---|---|
| **Power module unit:** | ➢ Convert the DC power into AC power.<br>➢ Power module unit is with switches and gate driver module. | ➢ Switch type –<br>    ➢ IGBT, SiC-MOSFET.<br>➢ Cost<br>➢ HVDC voltage levels and Max peak voltage (transient)<br>➢ Maximum operational current and duration.<br>➢ Efficiency<br>➢ Switching frequency and Switch on/off time, minimum pulse width<br>➢ Gate voltage. |

# Building Blocks: EV Specific Inverter

## Components




| Components | Feature | Factors affecting sizing |
|---|---|---|
| **Controller Unit:** | ➢ Used to control the switching pulses to the switches in power module unit to produce required power/torque as output for defined e-Machine speed.<br>➢ Process all the sensor signals received and based on the torque request controller will calculate the turn on and off time for each switches in the Power Module Unit and communicate that to Power Module unit. | ➢ The HW will select based on safety standards and functionality required in the inverter.<br>➢ Response time of the system during fault and control.<br>➢ Computation power and resource capacity required |
| **AC Busbars:** | ➢ Used to provide AC supply to machine from inverter.<br>➢ Direct and indirect cooling is used for AC Busbar to reduce the thermal loading in AC busbars.<br>➢ Copper bars are used because of its electrical conductivity, high current carrying capacity and durability<br>➢ Sizing is based on the AC side current. | ➢ Thermal limit – Cooling mechanism<br>➢ Current density – area of conductor<br>➢ Voltage limit – Insulation class: cables |

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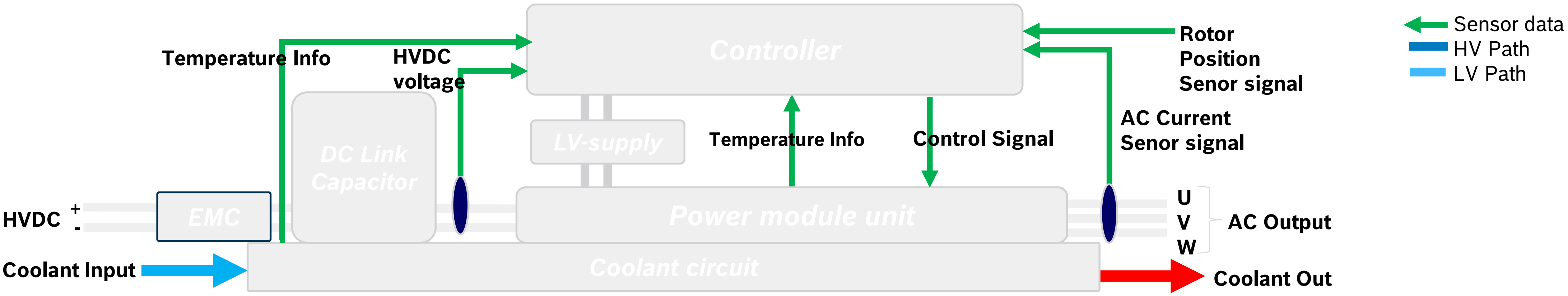
# Building Blocks: EV Specific Inverter

## Components




| Components | Feature | Factors affecting sizing |
|---|---|---|
| **DC Voltage sensor:** | ➢ Measure the HVDC Voltage .<br>➢ Used to define the desired current for defined Torque/power for eDrive system.<br>➢ Used the data to protect system from over or under voltage events. | ➢ The max voltage limit the Inverter/eDrive needs to measure.<br>➢ Accuracy needs to meet the torque and HV voltage safety. |
| **AC Current sensors:** | ➢ Used to measure AC current in Inverter Output (AC side).<br>➢ To protect the system from high current and avoid thermal incidents. | ➢ Max current value needs to measure.<br>➢ Accuracy level to meet the torque accuracy targets. |
| **Temperature sensors** | ➢ Used to measure the temperature values at different part of the inverter.<br>➢ To protect the system from thermal incidents.<br>➢ To provide the effective derating to the system and improve the life time and robust operation. | ➢ Temperature range needs to be measured.<br>➢ Accuracy needs to measure.<br>➢ Placement and cost for the sensor. |



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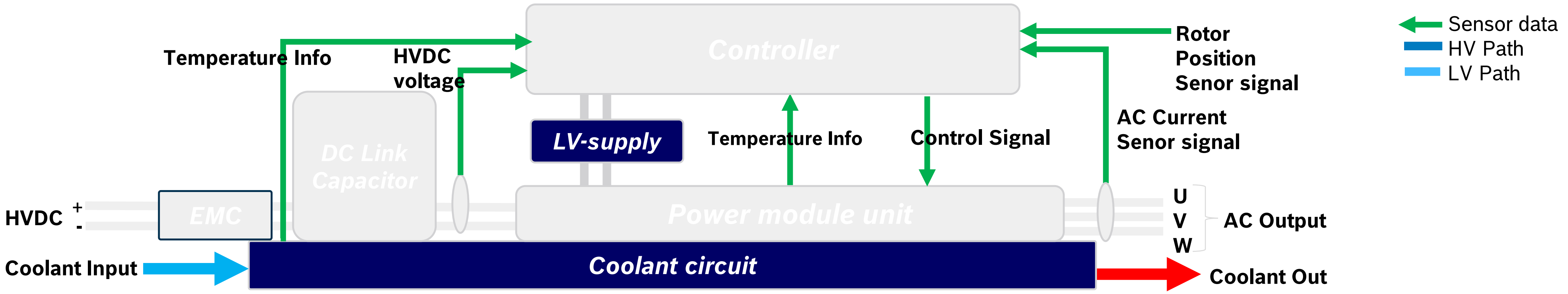
# Building Blocks: EV Specific Inverter

## Components




| Components | Feature | Factors affecting sizing |
|---|---|---|
| **Coolant Circuit** | ➢ To ensure a proper heat transfer in the system<br>➢ Make the component temperature below its threshold temperature limit by removing the excess heat generated as part of inverter operation. | ➢ Coolant medium and mixer(glycol+water).<br>➢ Space availability.<br>➢ Heat transfer capability and heat generation in different use cases.<br>➢ Coolant volume flow rate and temperature. |
| **LV Supply** | ➢ To provide the low voltage to microcontroller, ADC, Gate drivers and other electronic components used inside the Inverter.<br>➢ Regulates low voltage and power supply. | ➢ Depending on voltage and power required by each components such as gate driver, sensor modules, ADC, micro controller, protection circuits, etc<br>➢ Safety concepts and HW circuits/functionality. |

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# Inverter Operation: BEV

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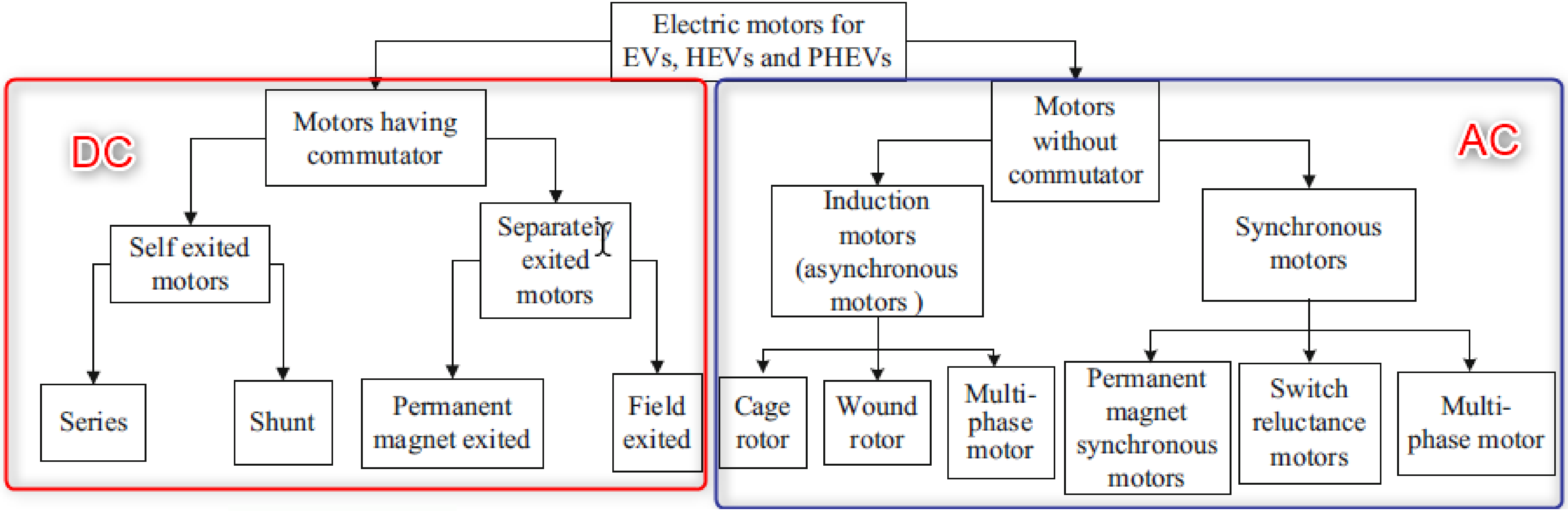
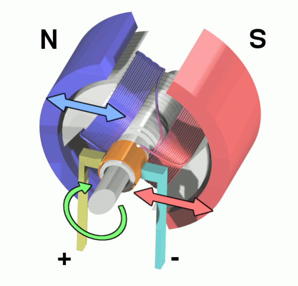
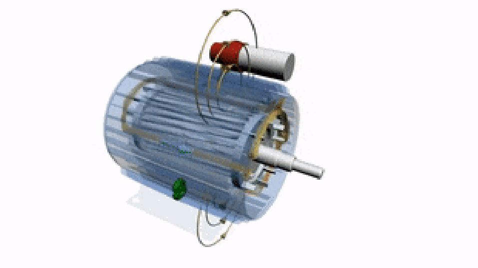
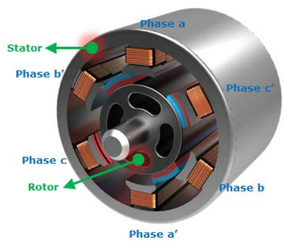
# Inverter Operation: BEV

## Basic Introduction to Different type of Machines







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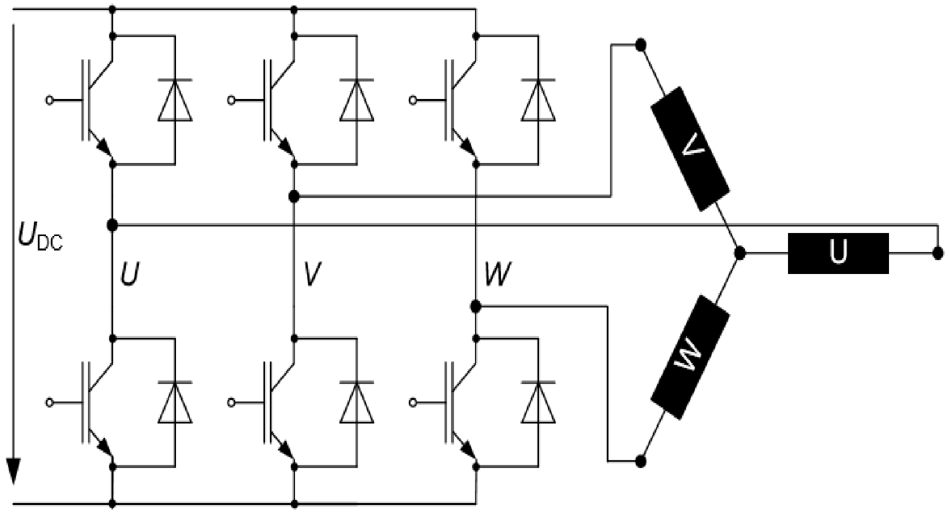
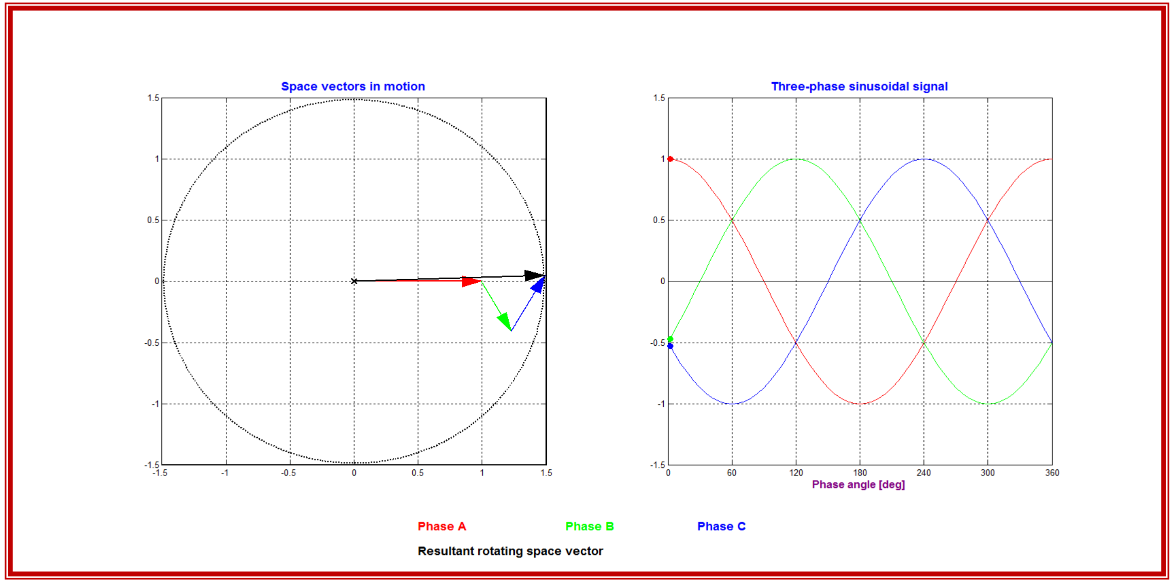
# EV Product Development Coursework
## Inverter Function

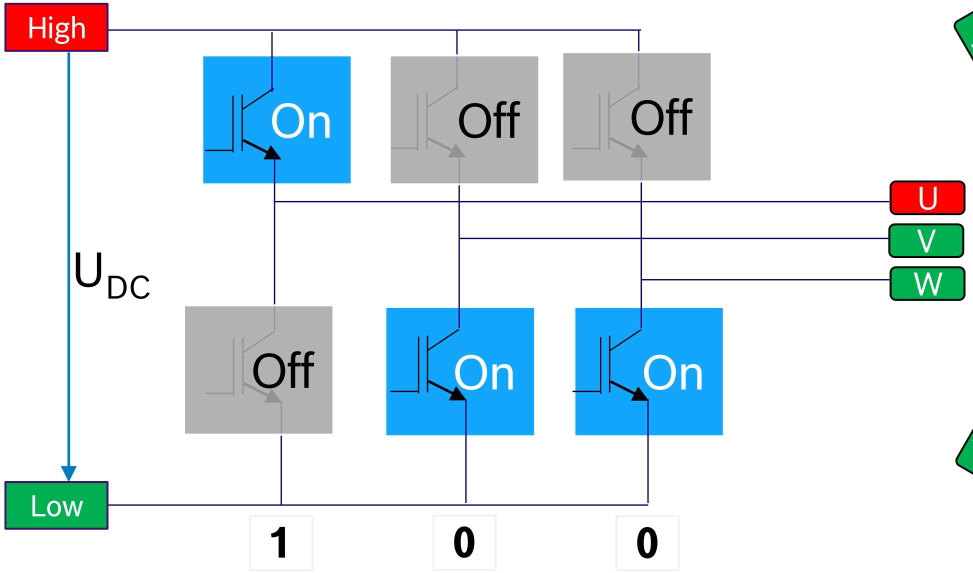


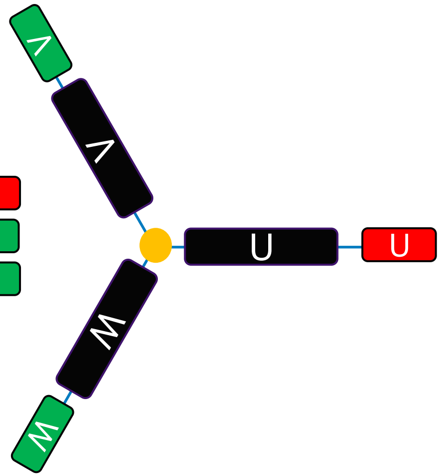



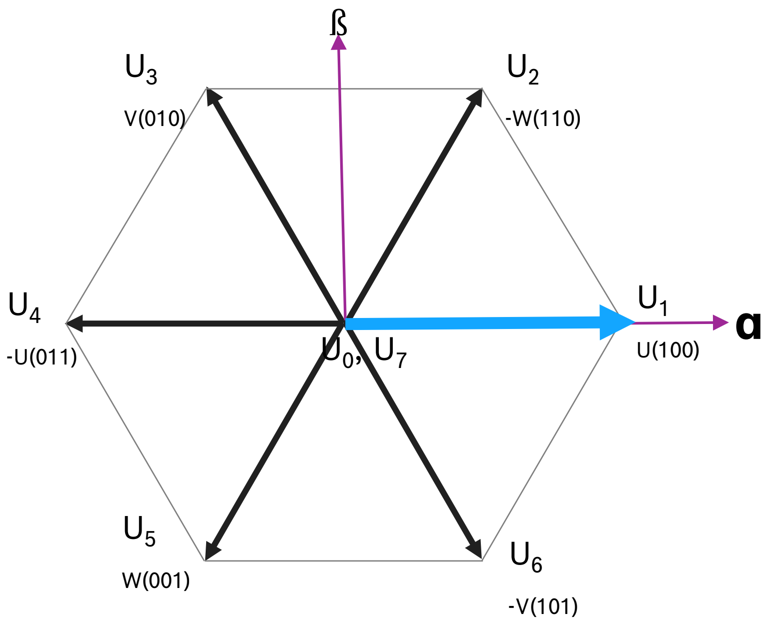

- The inverter generates 3 phase sinusoidal output voltages → Feed machine with distributed windings
- Voltages are phase shifted with 120°, Machine windings are shifted by 120°
- The resulting phasors are rotating synchronous to the rotor angle

- $B_{res} = B_m \cos(\theta) \cos(\omega t) + B_m \cos(\theta - 120) \cos(\omega t - 120) + B_m \cos(\theta - 240) \cos(\omega t - 240)$
- $B_{res} = 3/2\ (B_m \cos(\theta - \omega t))$

# Introduction to Inverter
## Voltage modulation




- ✓ At a time, one switch in the leg will be ON, the other OFF.
- ✓ 6 Active Vectors + 2 Zero vectors
- ✓ Resultant Space vector for **phase voltage**:

$$UR = (2/3)*[U_{UN}(t) + U_{VN}(t)* e^{(j2\pi/3)} + U_{WN}(t)* e^{(j4\pi/3)}]$$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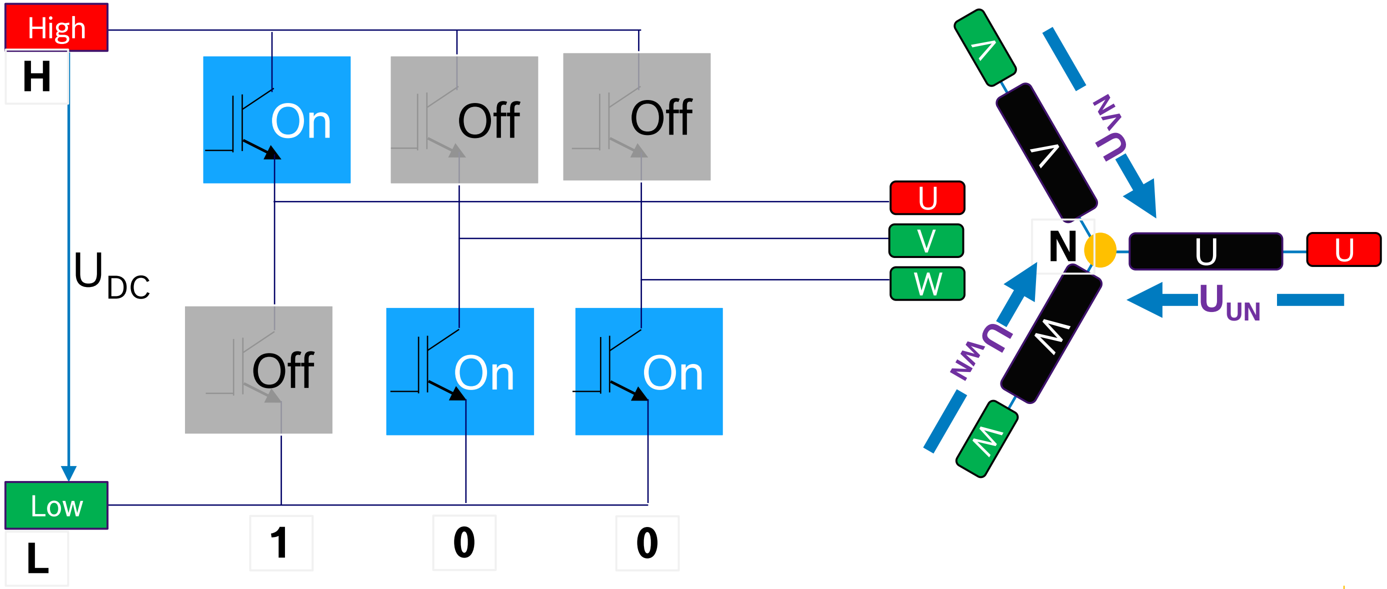
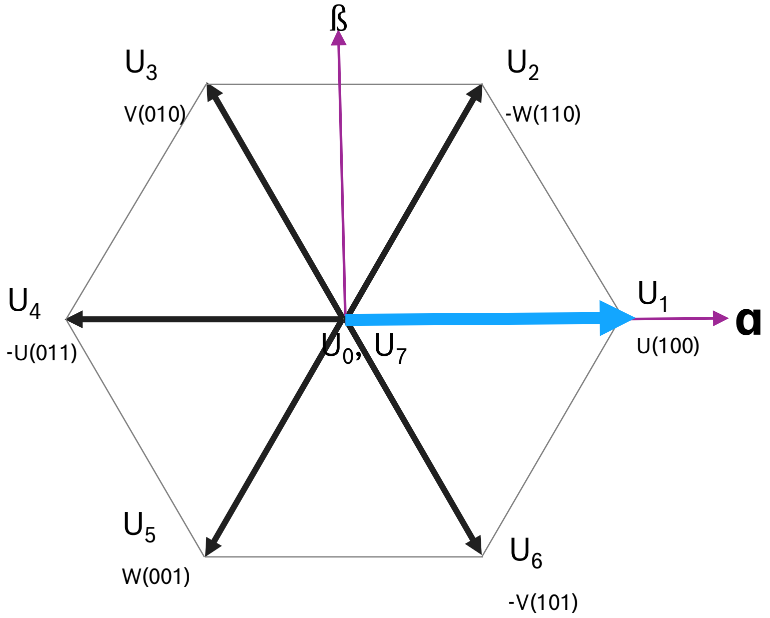
# Introduction to Inverter
## Voltage modulation




$U_{UN} = U_{UL} + U_{LN}$
$U_{VN} = U_{VL} + U_{LN}$
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$U_{LN} = -1*(U_{UL} + U_{VL} + U_{WL})/3$

$U_{UN} = (2/3)U_{UL} - (1/3)U_{VL} - (1/3)U_{WL}$
$U_{VN} = (2/3)U_{VL} - (1/3)U_{UL} - (1/3)U_{WL}$
$U_{WN} = (2/3)U_{WL} - (1/3)U_{UL} - (1/3)U_{VL}$

$\boldsymbol{UR} = (2/3)*[U_{UN}(t) + U_{VN}(t)* e^{(j2\pi/3)} + U_{WN}(t)* e^{(j4\pi/3)}]$
$\boldsymbol{=(2/3)*U_{DC}}$


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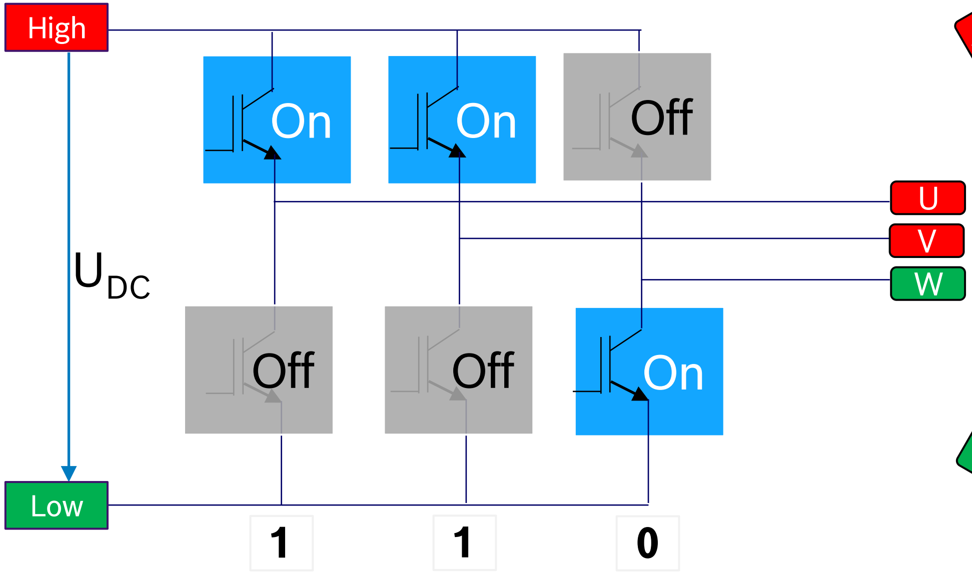
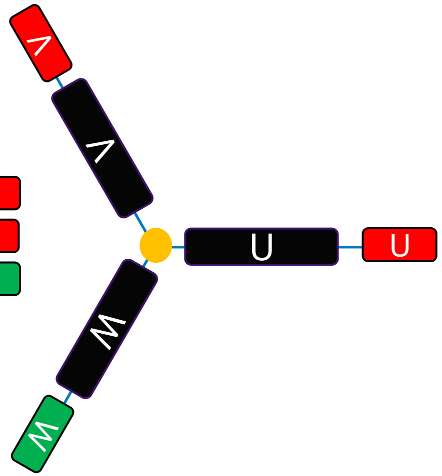
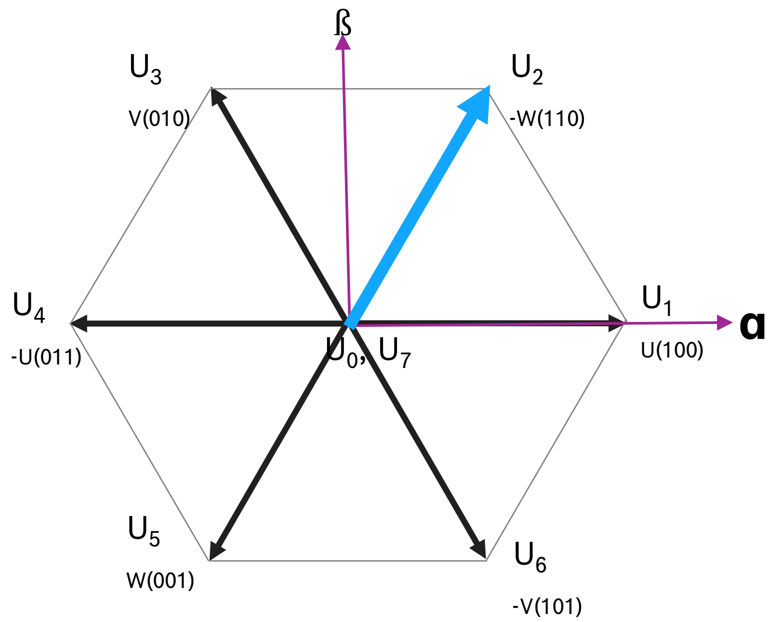
# Introduction to Inverter

## Voltage modulation

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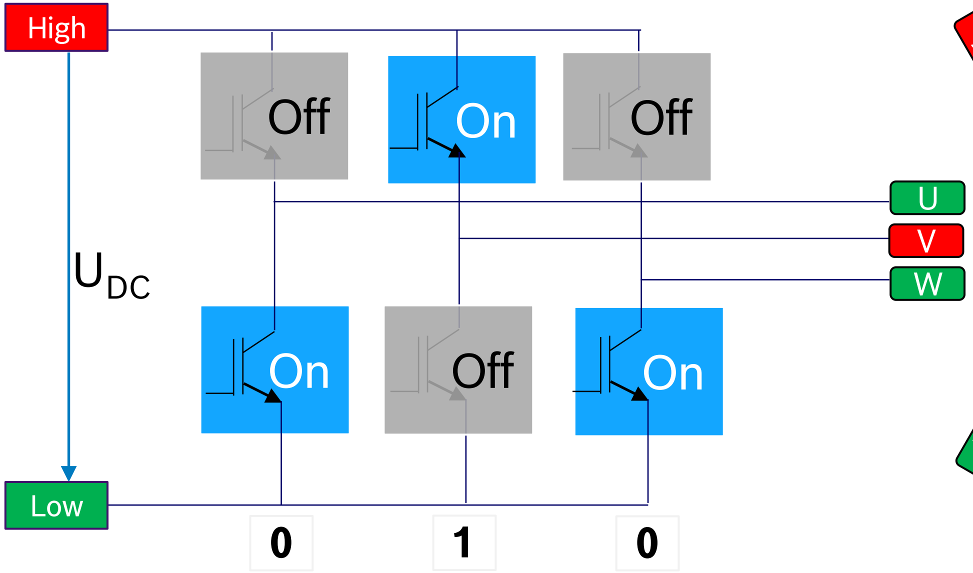
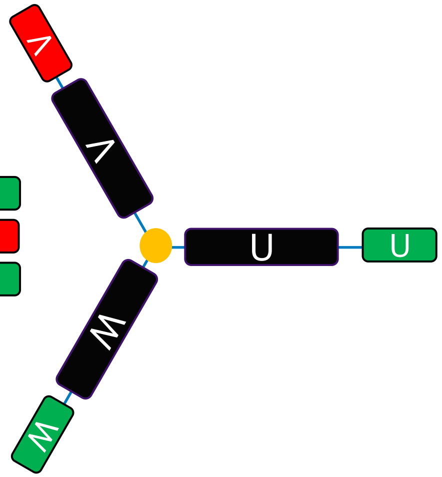
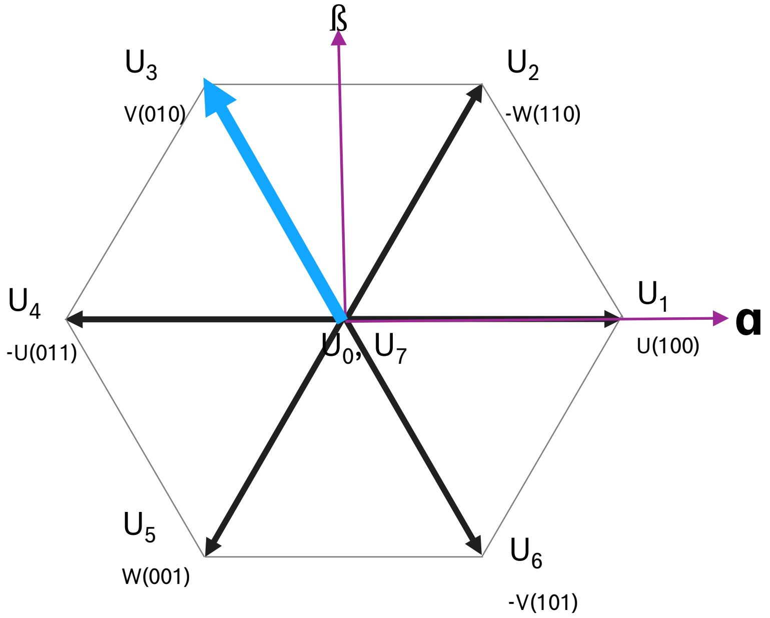
$$U_{WN} = (2/3)U_{WL} - (1/3)U_{UL} - (1/3)U_{VL}$$

$$\boldsymbol{UR} = (2/3)*[U_{UN}(t) + U_{VN}(t)*\, e^{(j2\pi/3)} + U_{WN}(t)*\, e^{(j4\pi/3)}]$$
$$\boldsymbol{= (2/3)*U_{DC}*e^{(j\pi/3)}}$$

# Introduction to Inverter
## Voltage modulation

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$$\boldsymbol{UR} = (2/3)*[U_{UN}(t) + U_{VN}(t)*e^{(j2\pi/3)} + U_{WN}(t)*e^{(j4\pi/3)}]$$
$$= \boldsymbol{(2/3)*U_{DC}*e^{(j2\pi/3)}}$$


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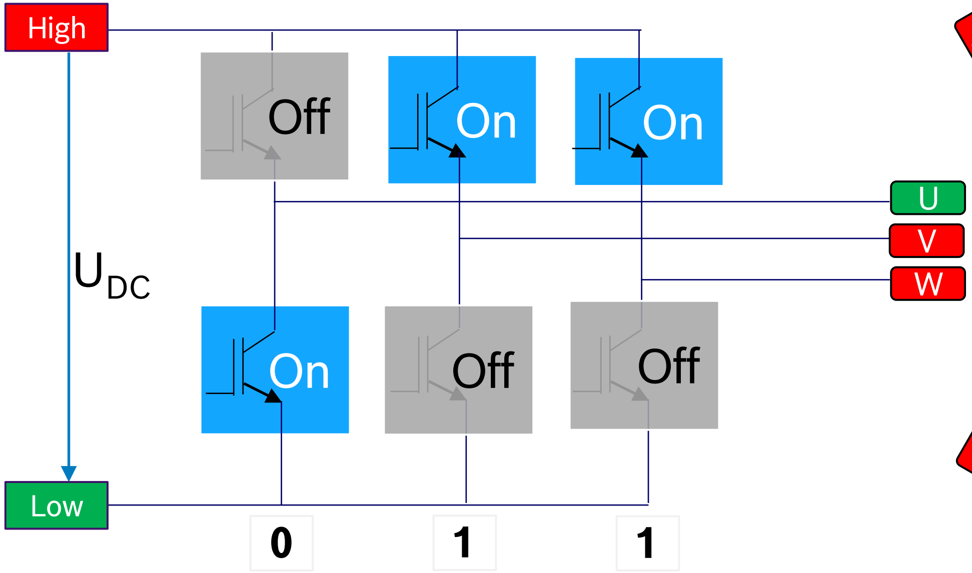
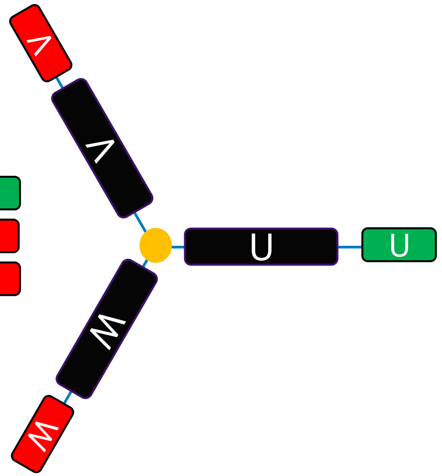
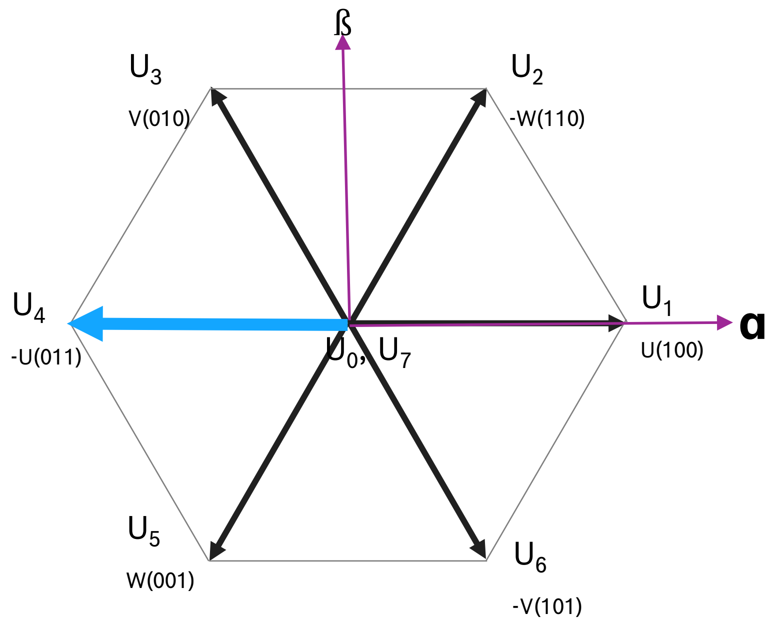
# Introduction to Inverter
## Voltage modulation

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$$\boldsymbol{UR} = (2/3)*[U_{UN}(t) + U_{VN}(t) * e^{(j2\pi/3)} + U_{WN}(t) * e^{(j4\pi/3)}]$$
$$\boldsymbol{= (2/3) * U_{DC} * e^{(j\pi)}}$$


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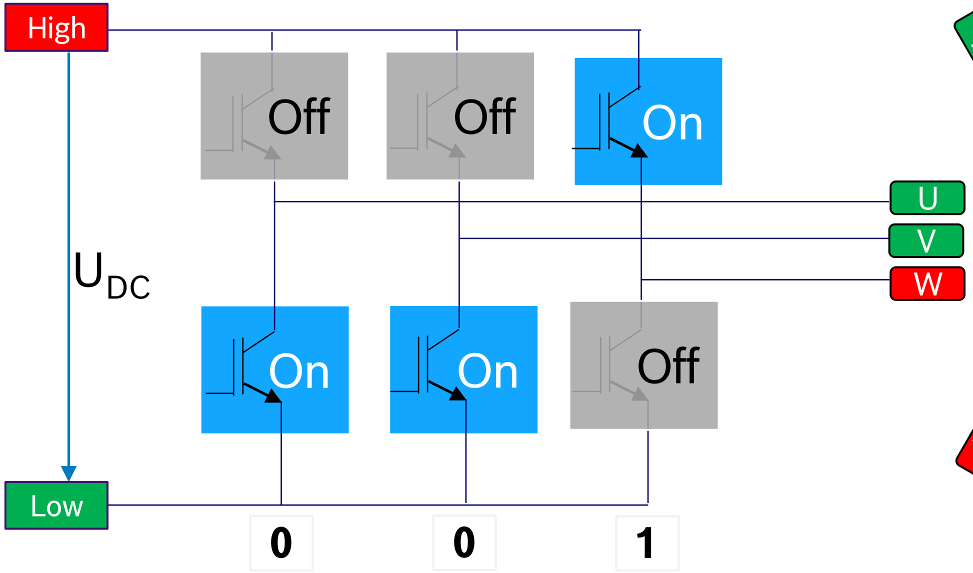
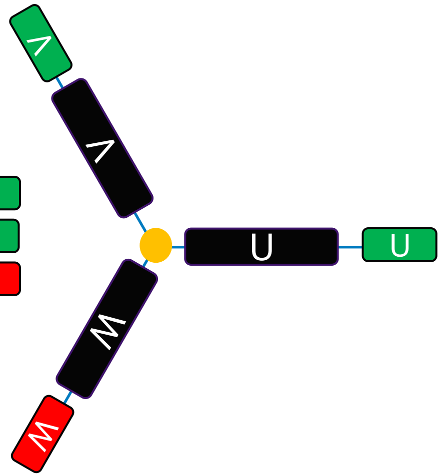
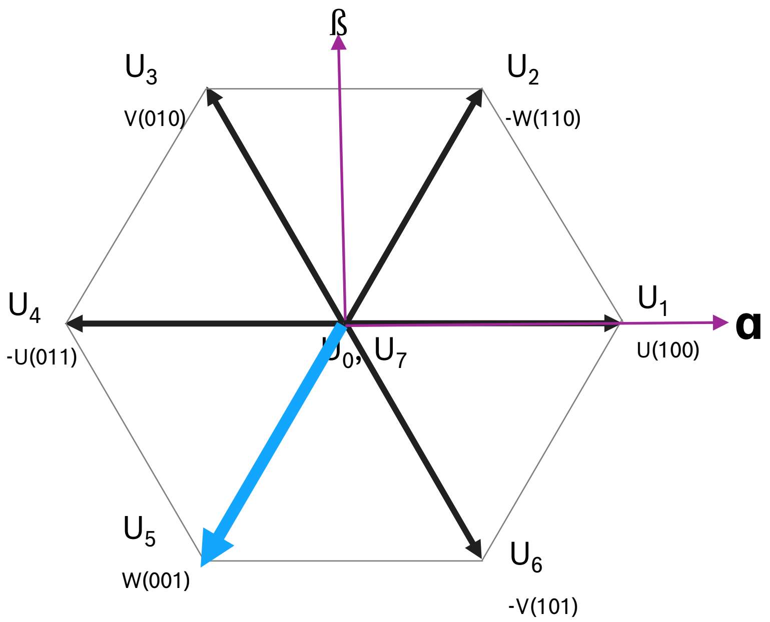
# Introduction to Inverter
## Voltage modulation

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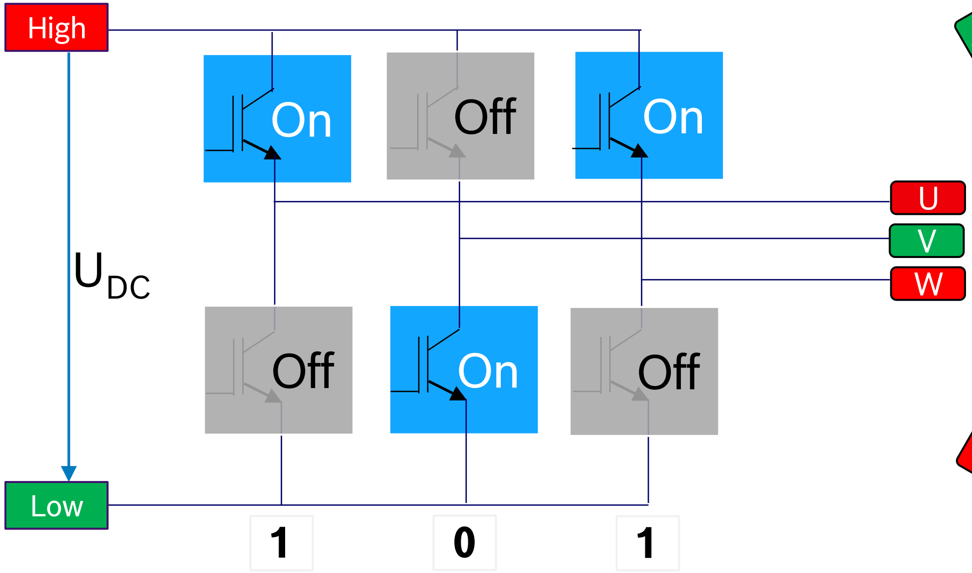
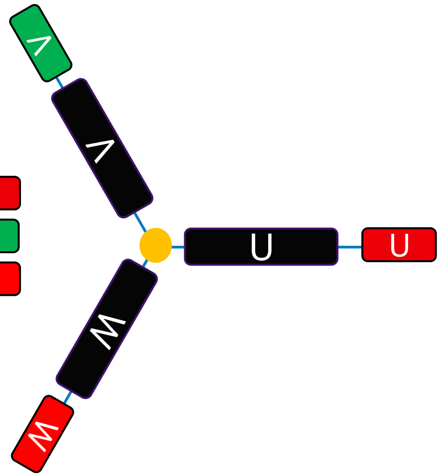
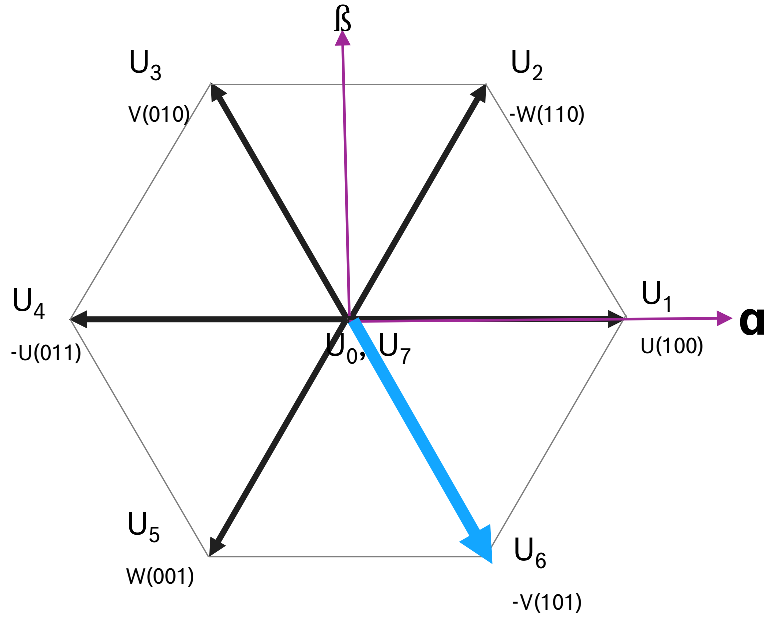
$= (2/3)*U_{DC}*e^{(j4\pi/3)}$

# Introduction to Inverter
## Voltage modulation

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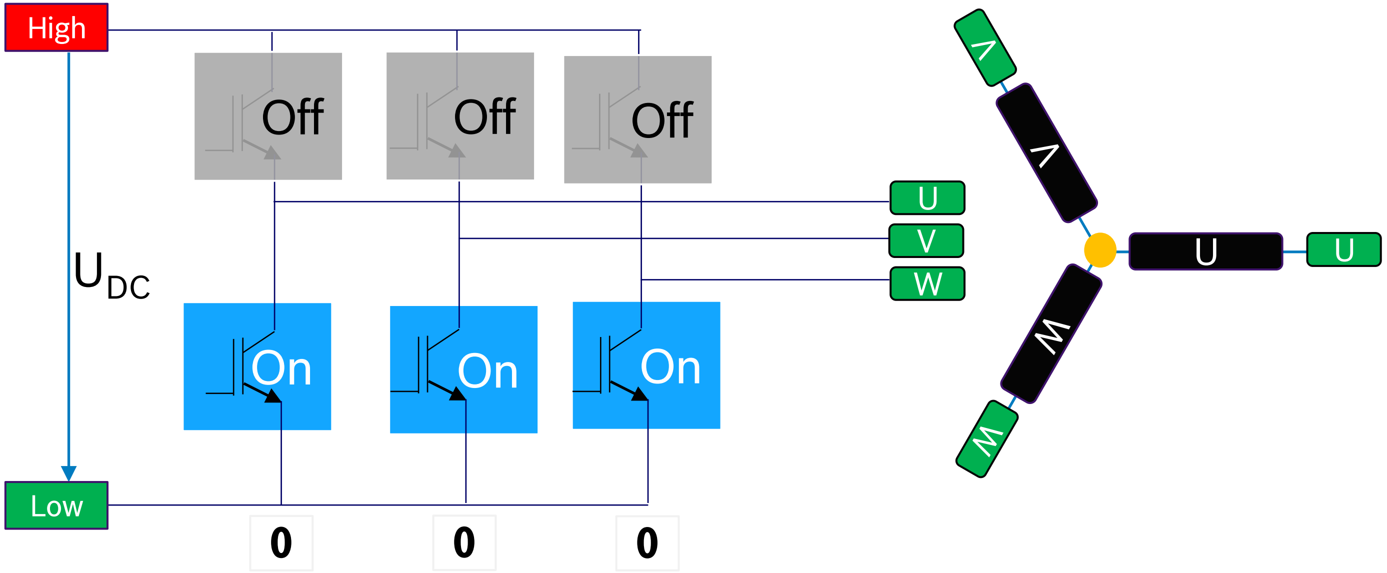
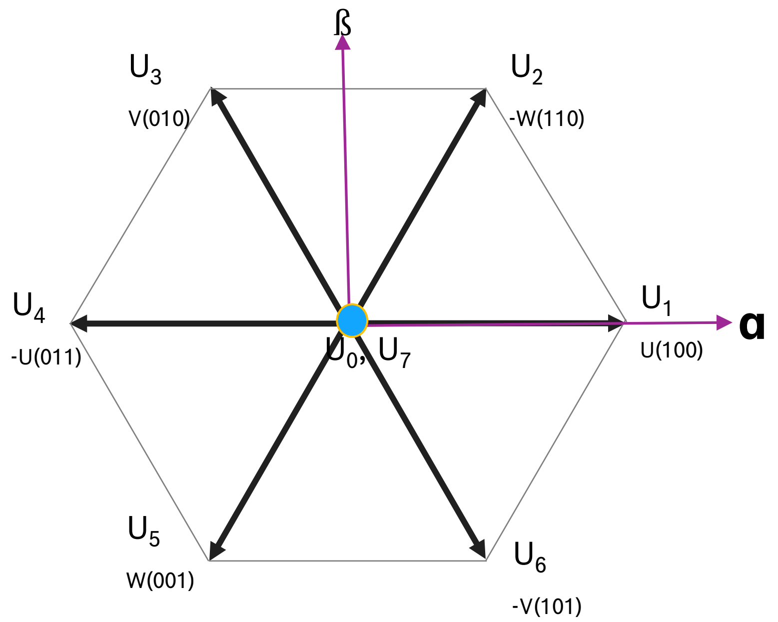
$$\boldsymbol{=(2/3)*U_{DC}*e^{(j5\pi/3)}}$$

# Introduction to Inverter
## Voltage modulation




- ✓ At a time, one switch in the leg will be ON, the other OFF.
- ✓ 6 Active Vectors + 2 Zero vectors

$$\boldsymbol{UR} = (2/3)*[U_{UN}(t) + U_{VN}(t) * e^{(j2\pi/3)} + U_{WN}(t) * e^{(j4\pi/3)}]$$
$$= \boldsymbol{0}$$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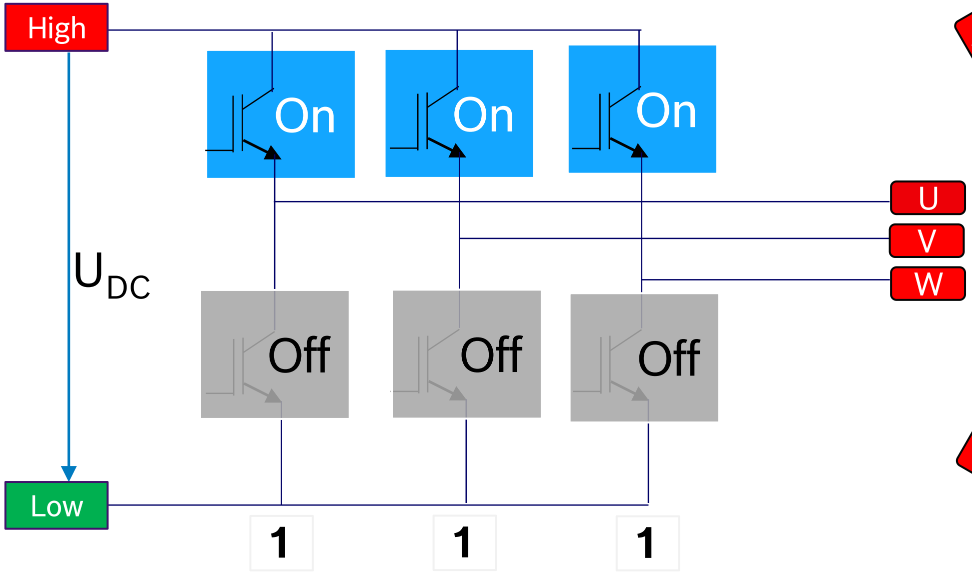
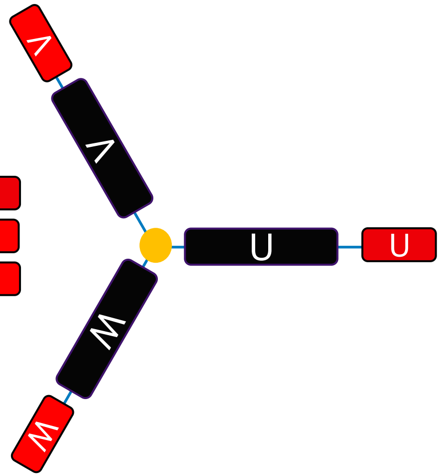
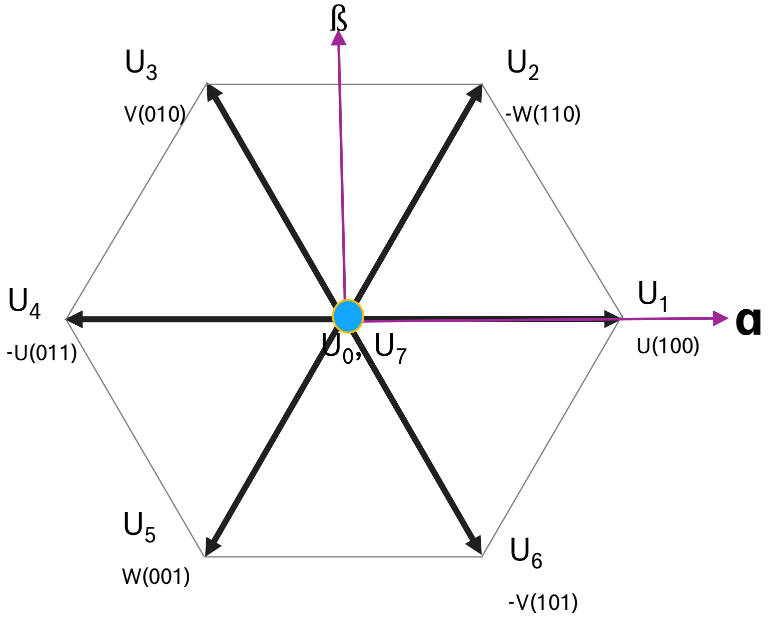
# Introduction to Inverter
## Voltage modulation

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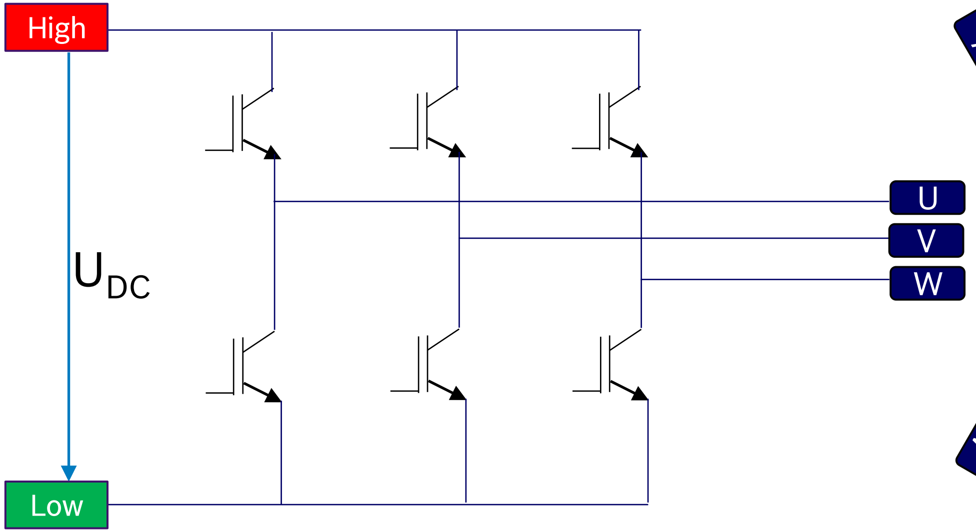
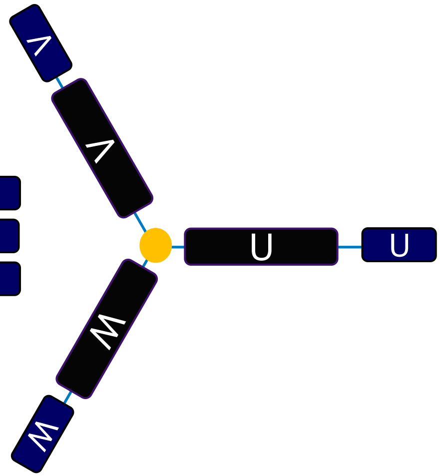
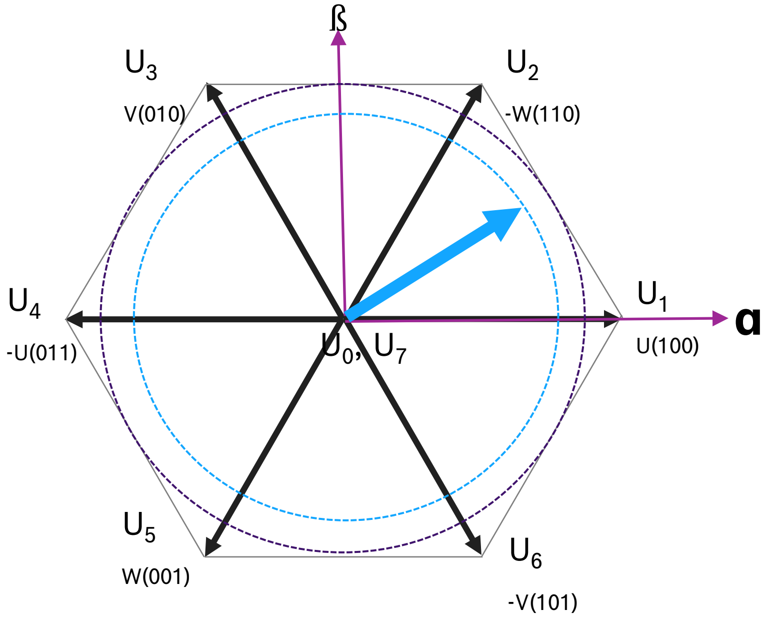
# Introduction to Inverter

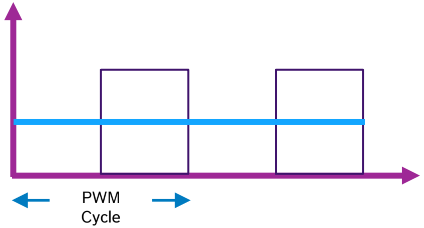
## Voltage modulation




Modulation Depth(**m**) $= U_R/(U_{DC}/2)$
Max m,SVPWM($m_{Max}$) $= [(2/3)*U_{DC}*(sqrt(3)/2)]/[(U_{DC}/2)]$
$= 1.1547$




$U_R T_S = U_1 T_1 + U_2 T_2 + \mathbf{U_0 T_0}$

$= U_1 T_1 + U_2 T_2 + \mathbf{U_0 T_{01} + U_0 T_{07}}$

$= \mathbf{U_0(T_0/2)} + U_1 T_1 + U_2 T_2 + \mathbf{U_7(T_0/2)}$

**$U_0$ = 000**
**$U_1$ = 100**
**$U_2$ = 110**
**$U_7$ = 111**

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**$U_2$ = 110**
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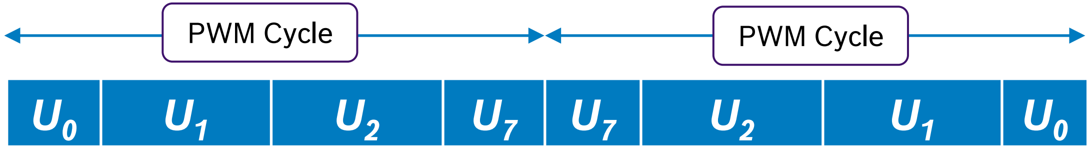
**$U_0$ = 000**



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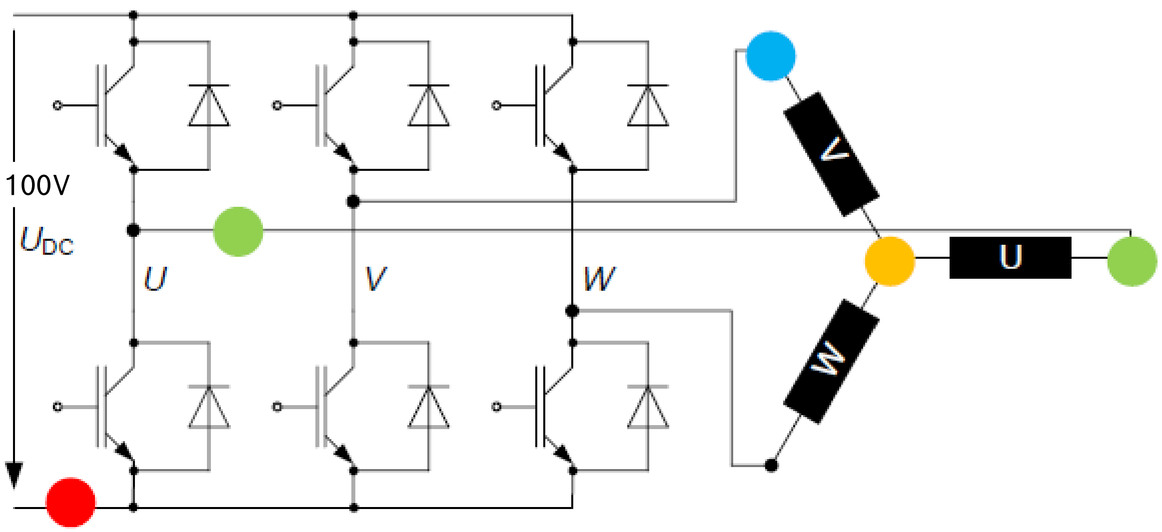
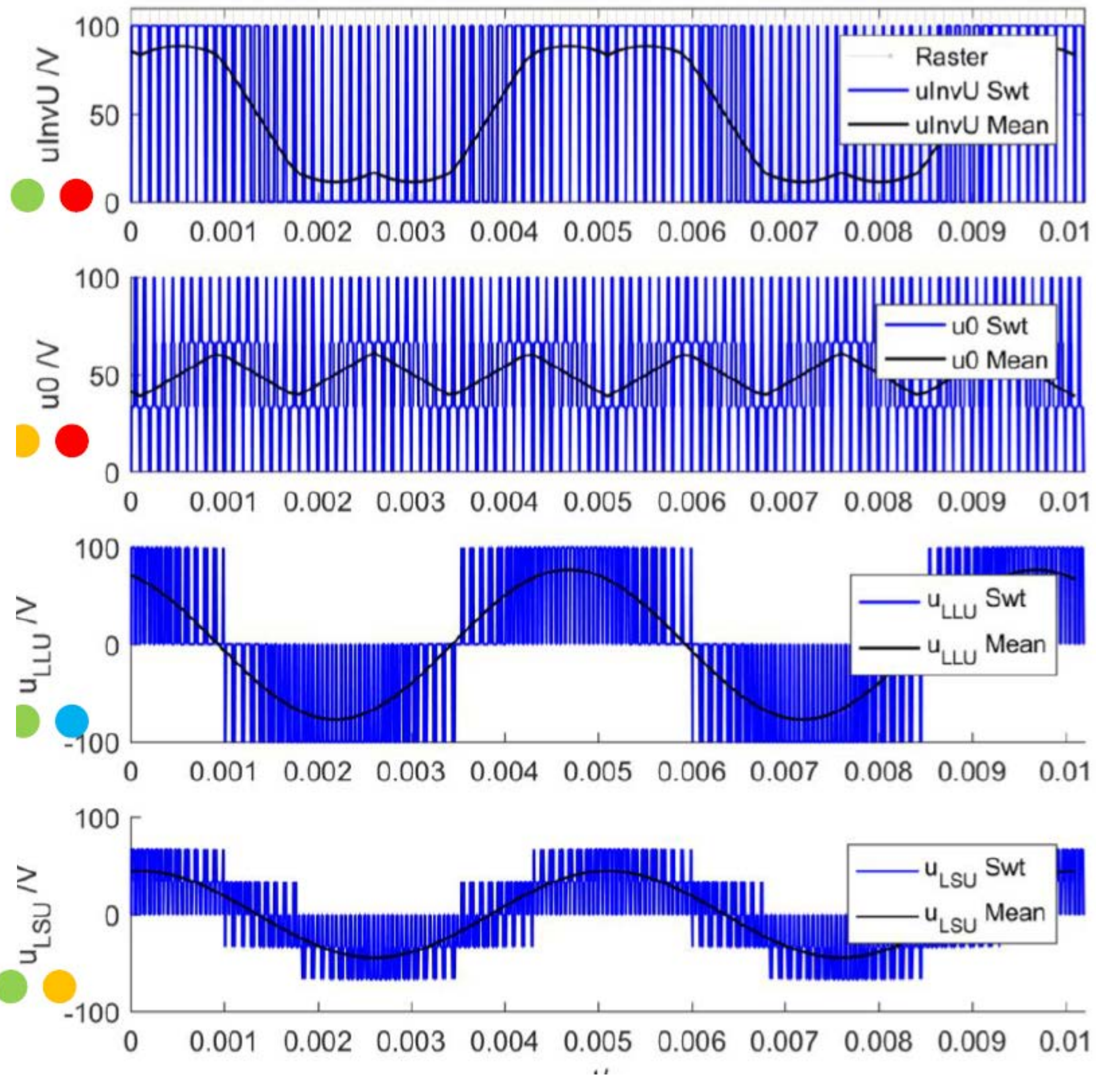
# Introduction to Inverter
## Voltage modulation

uDC = 100V
m = 0.8913
Elc Frq = 200Hz

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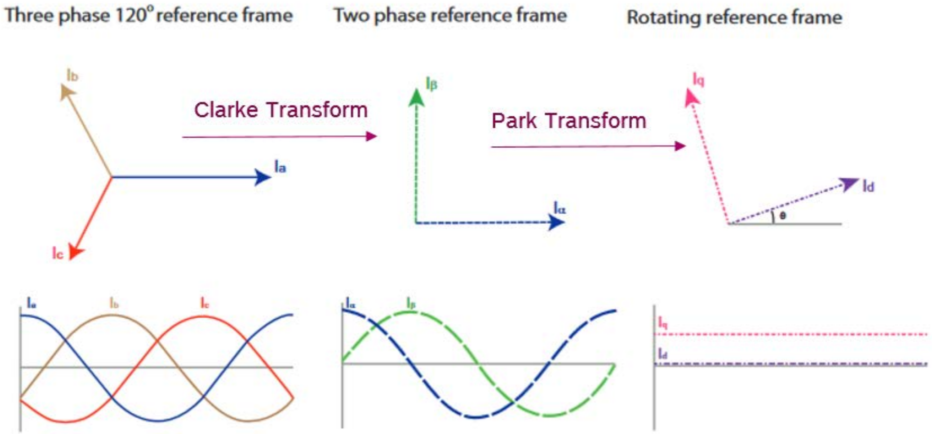
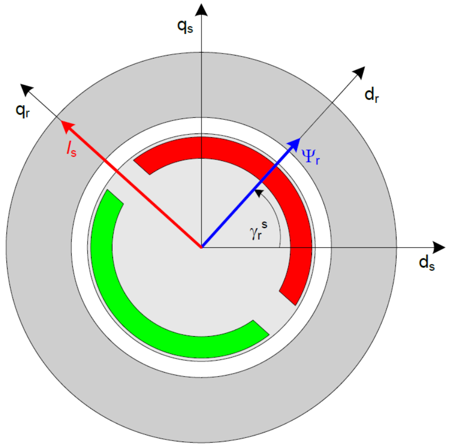
# Introduction to Inverter

## Park Transform

*All values are effective values*

**Park Transform:** Link *(Two-reaction theory of synchronous machines generalized method of analysis-part I, 1929)*




- ➢ Permanent Magnet Synchronous Machine:
- ▪ Stator with cupper windings
- • Rotor with permanent magnets
- ➢ Field oriented coordinate system:
- ▪ Rotor flux $\boldsymbol{\Psi}$ (flxExct)d-direction

**PSM(DQ)**

$$T_{Em} = 3p\, iQa\left(\Psi_E + \underbrace{\left(L_d - L_q\right) iDa}_{\Psi_{Reluc}}\right)$$

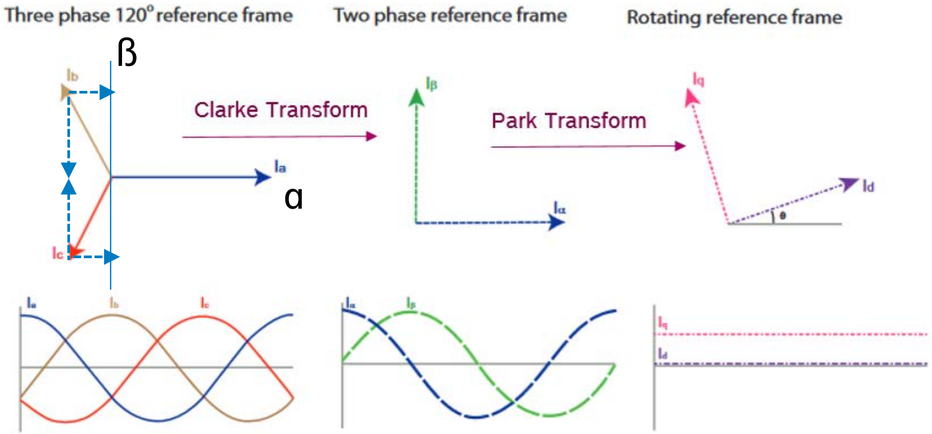
$$uDa = R\, iDa + \frac{d}{dt}\left(L_d iDa\right) - \omega_{\mathrm{Flx}} L_q iQa$$

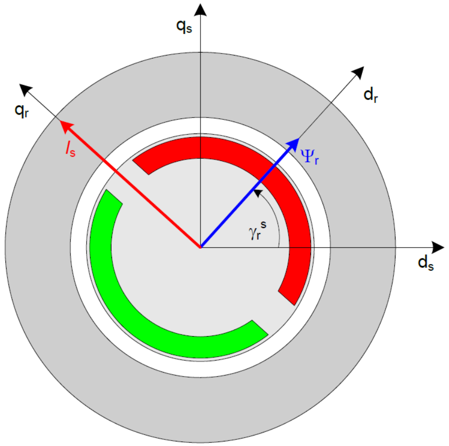
$$uQa = R\, iQa + \frac{d}{dt}\left(L_q iQa\right) + \omega_{\mathrm{Flx}} L_d iDa + \omega_{\mathrm{Flx}} \Psi_E$$

*All values are effective values

# Introduction to Inverter
## Park Transform

**Park Transform:** Link *(Two-reaction theory of synchronous machines generalized method of analysis-part I, 1929*)




- Permanent Magnet Synchronous Machine:
  - Stator with cupper windings
  - Rotor with permanent magnets
- Field oriented coordinate system:
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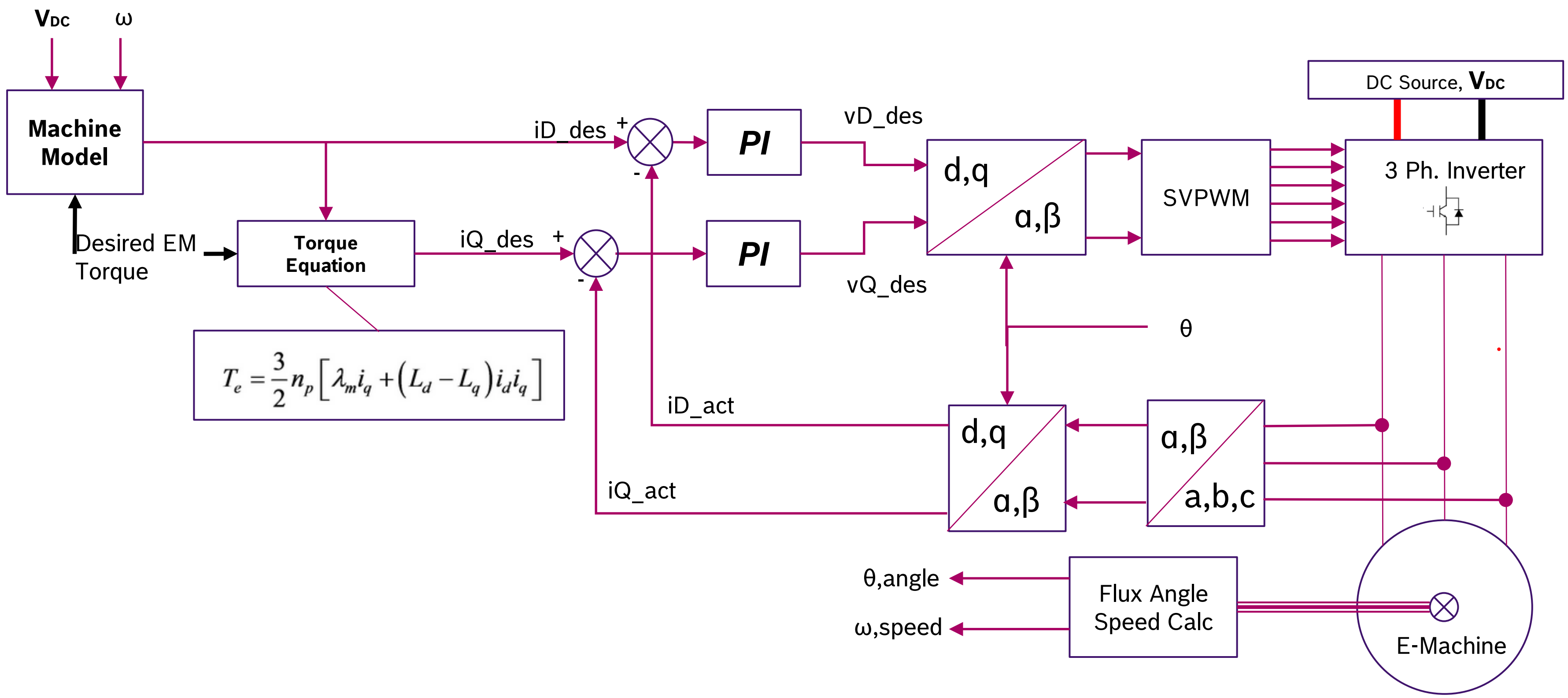
# EV Product Development Coursework

## Field Oriented Control – Mostly used



04

# Project

# Introduction to Inverter

## Design a Controller for PMSM(Interior Magnet) Machine

- Design a Controller for PMSM machine with SvPWM
  - Explore different control mechanism
  - Design a controller for a stable control operation with following torque dynamics.
    - Peak Overshoot 10% of desired torque.
    - Steady state torque error 6%(average torque)
    - Settling time 250mSec
    - Rise time 50mSec
    - Torque ripple  3% desired torque.
- Estimate the Capacitance value for the defined Inverter spec.:
  - Ref: Link *(Analytical calculation of the RMS current stress on the DC link capacitor of voltage DC link PWM converter systems)*