Motor controller

Pre-internship Assignment Infineon

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Introduction

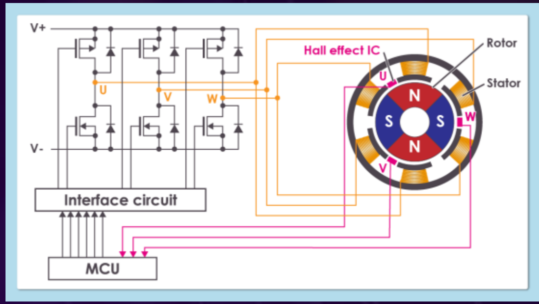
Our aim is design, build, and test a compact controller for a brushless DC (BLDC) motor suitable for driving the joint of a cobot

- Theory
- Research
- Implementation
- Further works

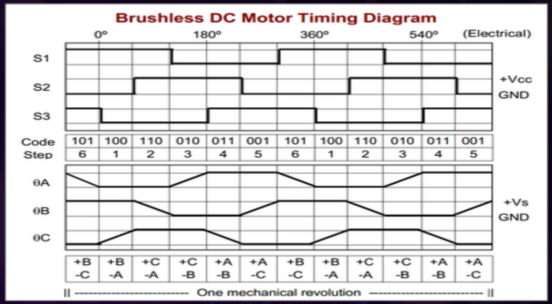
Theory

Let’s first have a look at Brushless Motor, types of commutation and controlling BLDC motors and why GaNs. We will also see what is switching losses and how to minimize them in GaNs section.

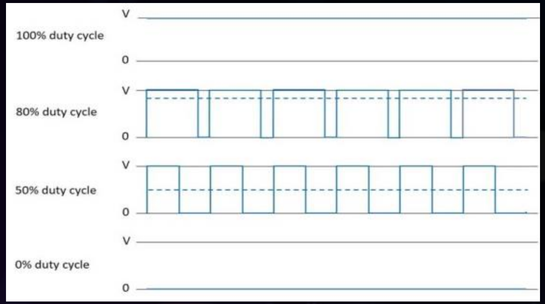
Brushless Motor



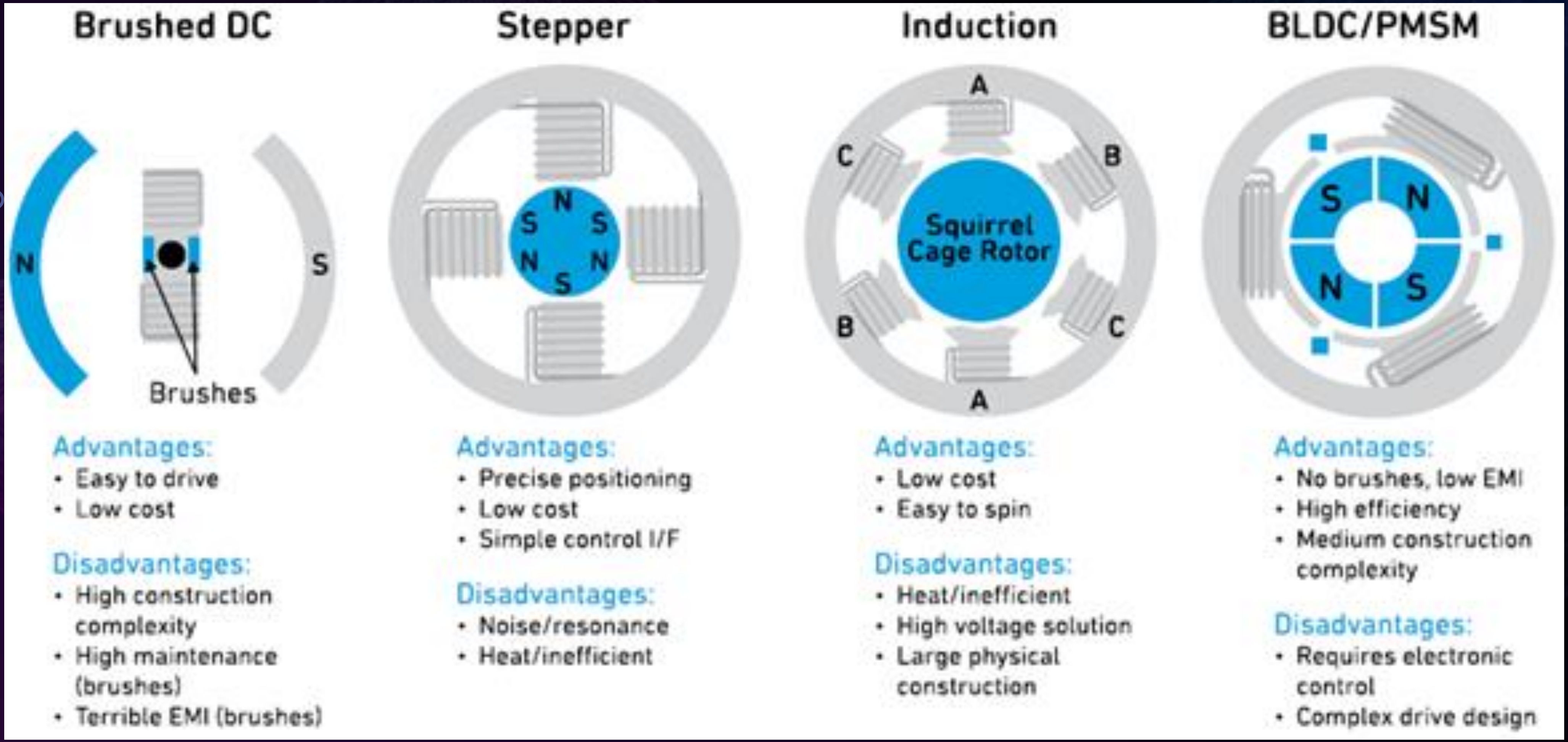
Types of Commutation



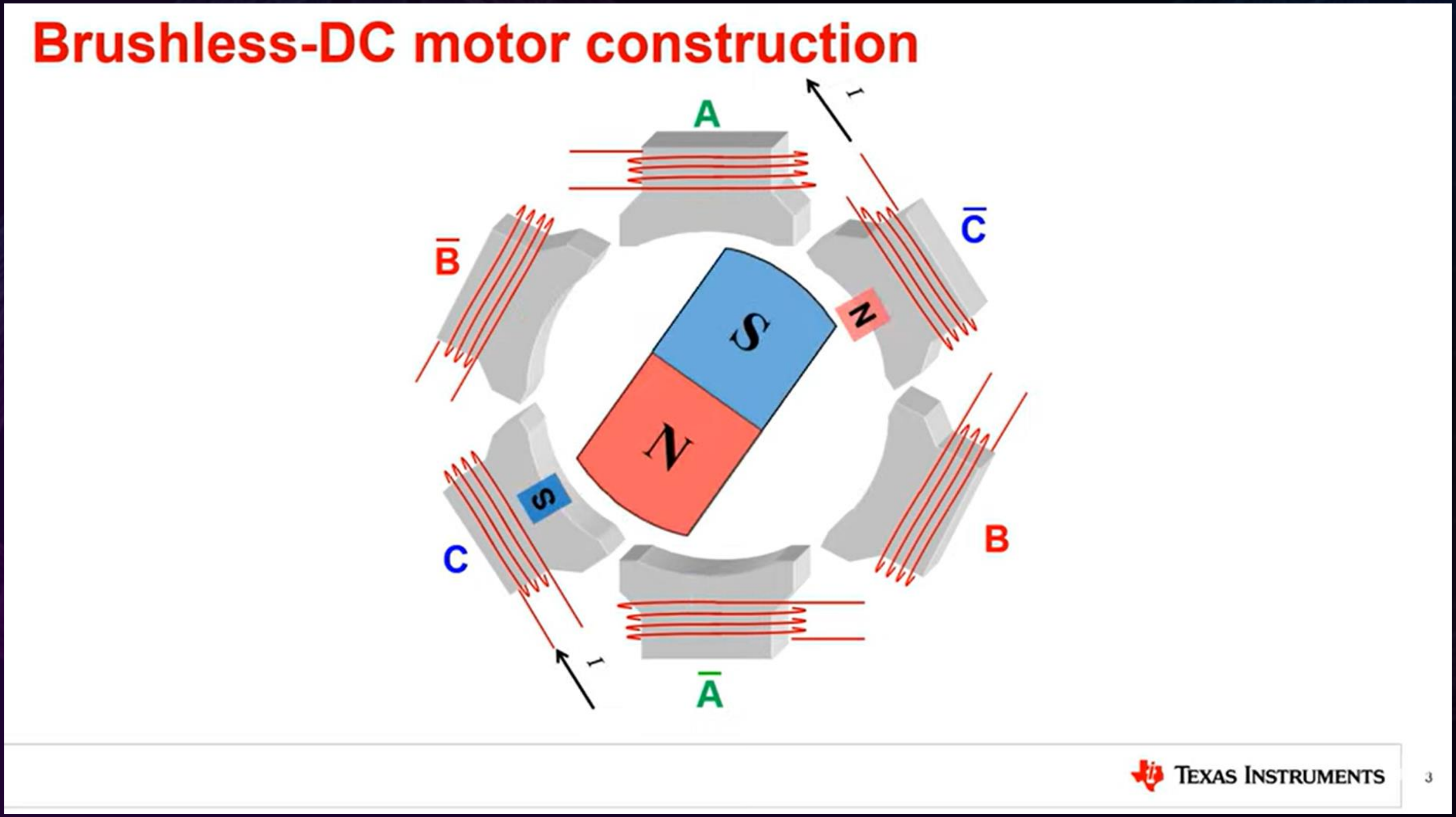
Why GaNs



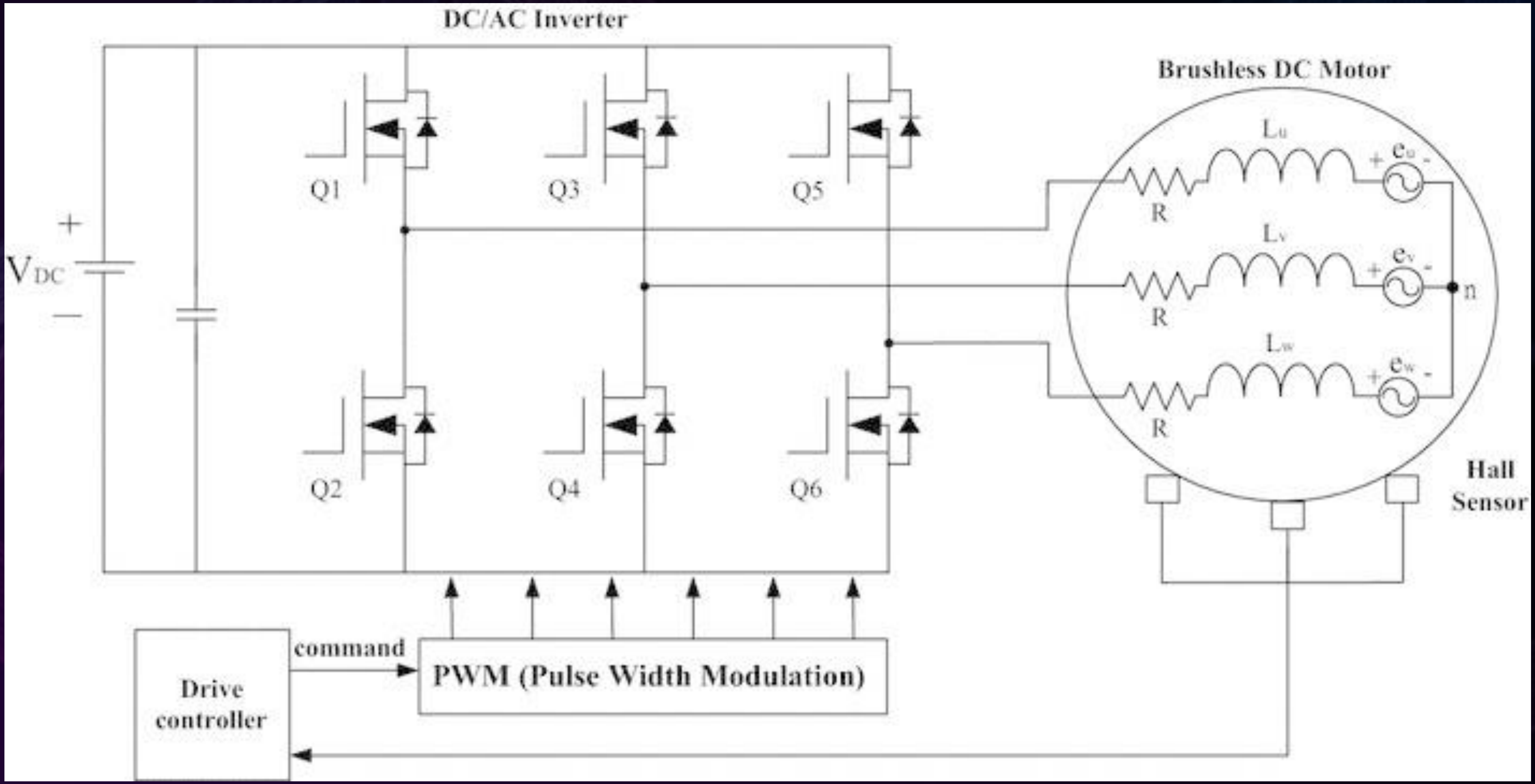
Few Types of Motors



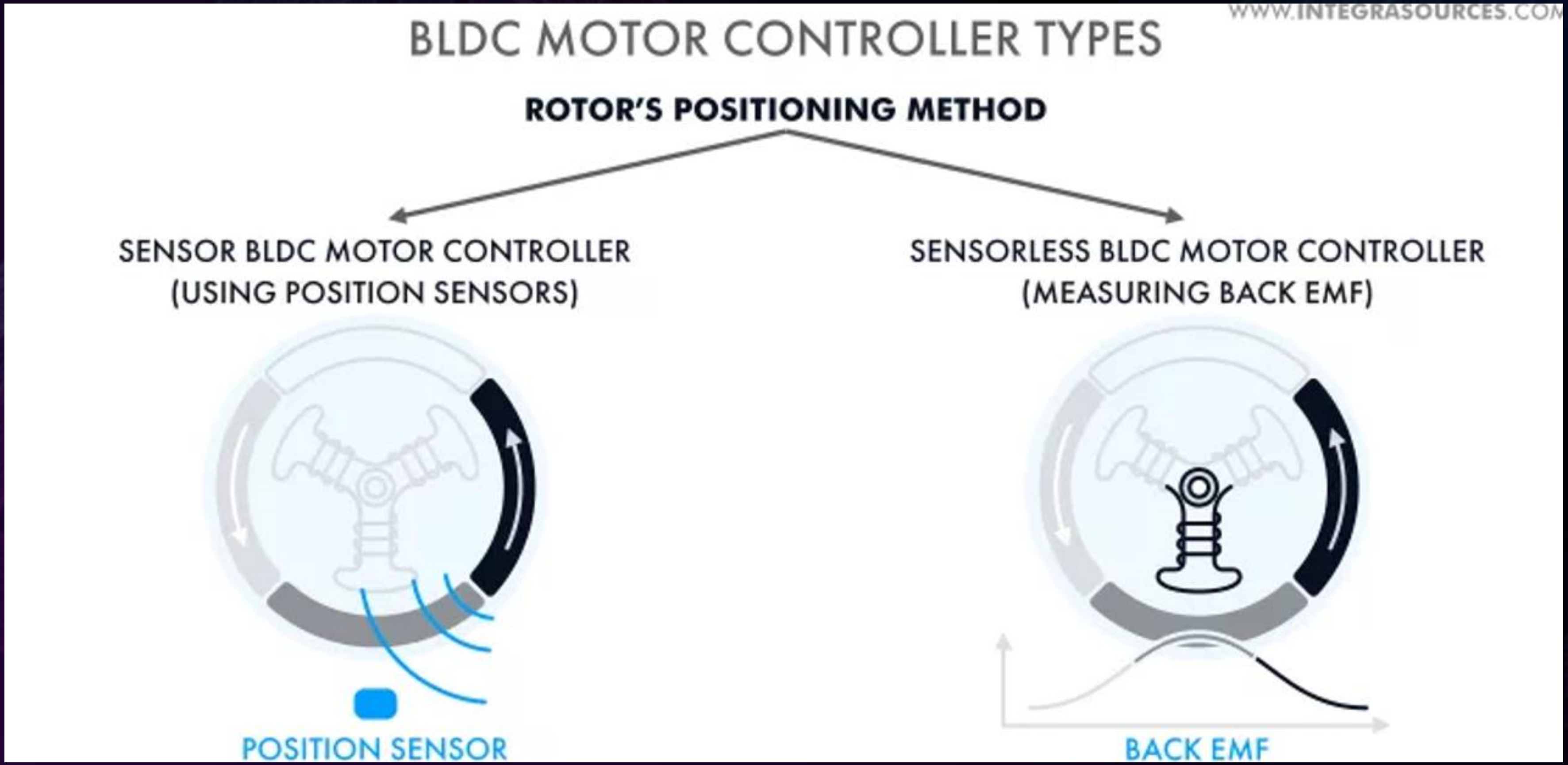
Brushless Motor



Three Phase H-Bridge Inverter



Position Feedback



Motor Params

Given specs:

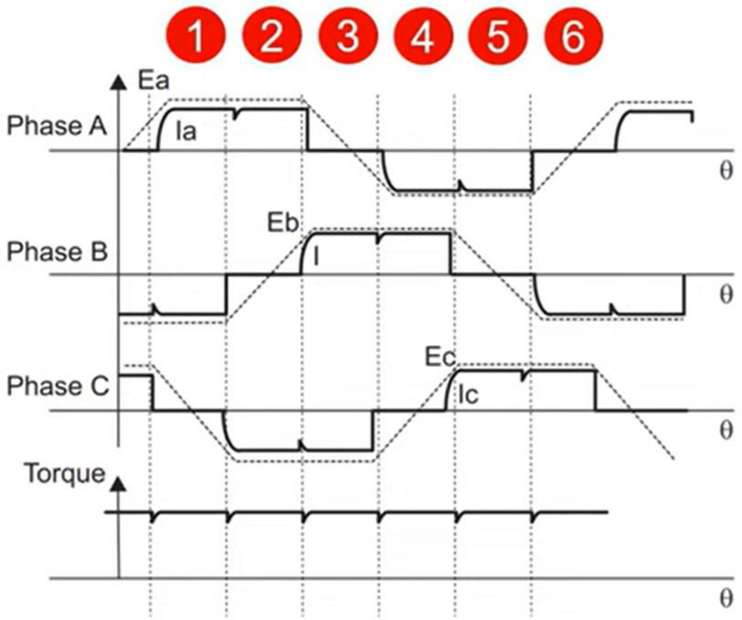
4-5s (13.6V - 21V)
Motor : Turnigy Aerodrive SK3 -4240-740kv
Poles : 14 V/Hz : 0.045420136
Resistance (ohm) : 0.0151
Kv (rpm/V) : 660.5
Inductance (uH) : 11.85833333
Torque constant (Nm/A): 0.011276989
Rated current (A) : 50
Desired torque (Nm) : 0.3
Operating current (A): 26.60284548
Operating speed (rpm) : 3000
Operating power (W) : 94.24777961
Coil reactance (ohm) : 0.003725405

What we want:

Motor RPM: 0-3000RPM **Gearbox :** 100:1 **Torque :** 30Nm **Input :** 48-60V min.40V Min. size and weight of power cables internal to the cobot

Trapezoidal commutation

Trapezoidal commutation



Difficulty: Low

Advantages:

- Simple control scheme (6 states)
- High speed and high torque
- Low switching losses (1xPWM)

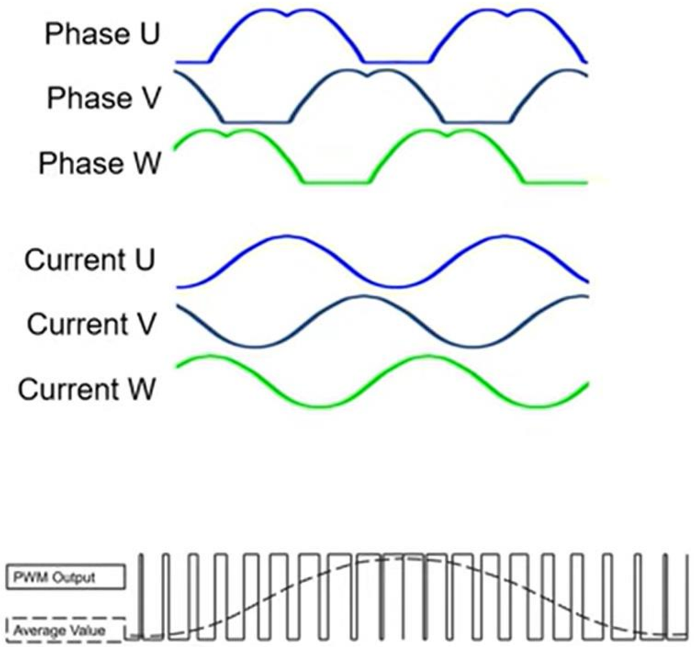
Disadvantages:

- High torque ripple
- High audible electrical noise
- Not maximizing torque output and motor efficiency

Used widely in brushless motor ESCs

Sinosoidal commutation

Sinusoidal commutation (180°)



Difficulty: Medium

Advantages:

- Low audible noise
- High motor efficiency
- Low torque ripple for stable loads

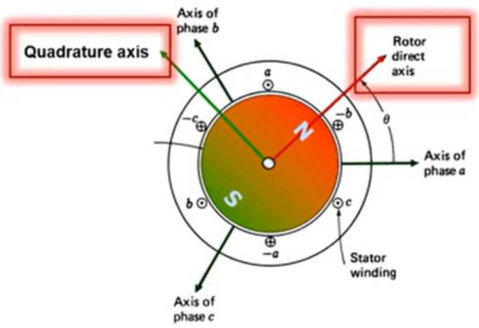
Disadvantages:

- High switching losses (3x PWM)
- More complex control vs trapezoidal
- High torque ripple for dynamic loads
- Not maximizing torque output and motor efficiency

Texas Instruments 5

Field Oriented Control(FOC)

Field-Oriented Control (FOC)



Difficulty: High

Advantages:

- Highest torque and motor efficiency
- Lowest audible noise and torque ripple
- High motor speed (+field weakening)

Disadvantages:

- High switching losses (3x PWM)
- Complex control and real-time calculations needed from MCU

TEXAS INSTRUMENTS

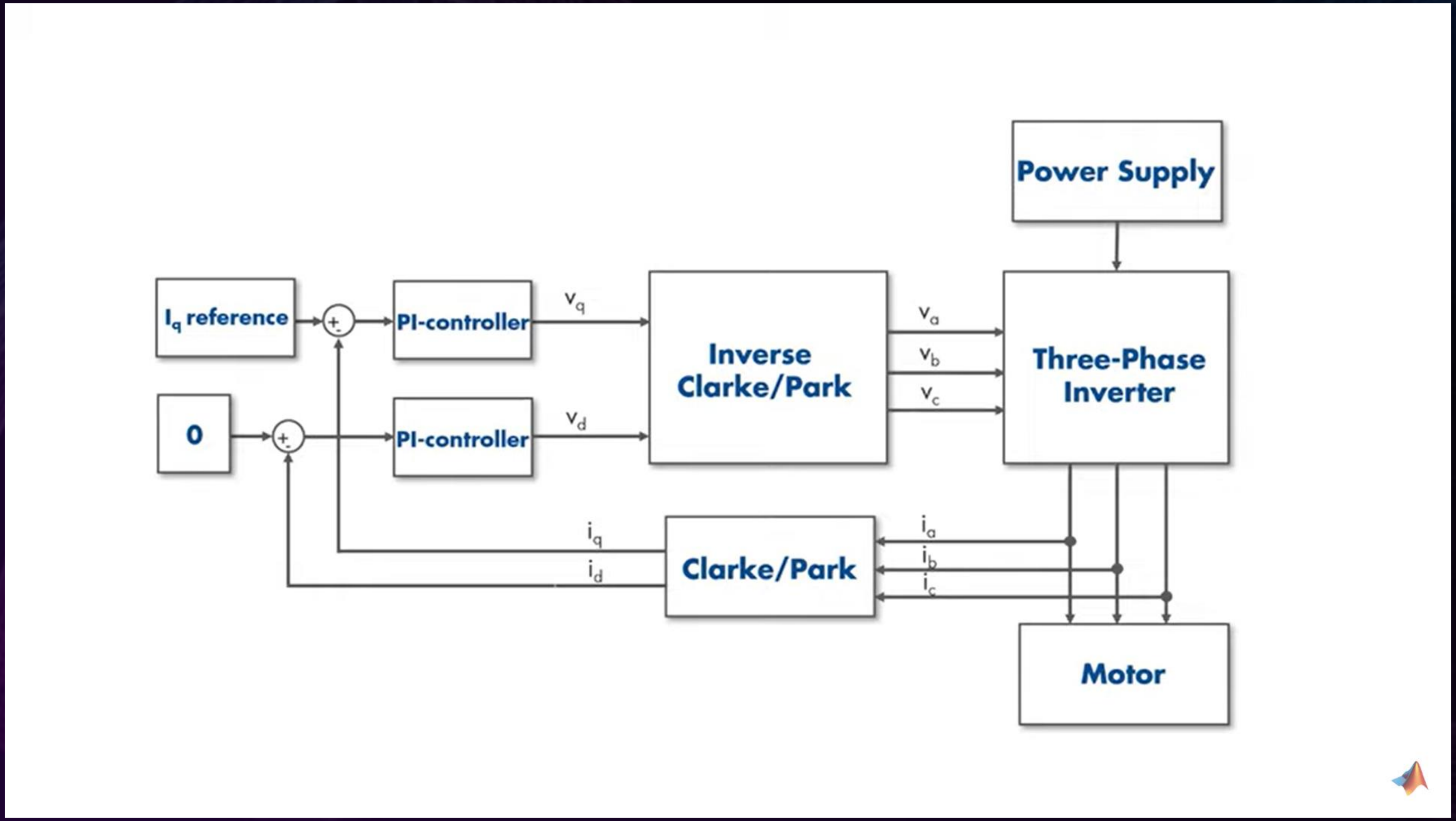
FOC applications

Method	Control Implementation	Noise	Motor efficiency	Switching Loss	Comments
Trap	Look-up table (simple)	High	Low	Low	Best for high-torque or high-speed applications
Sine	Look-up table (complex)	Low	High	High	Not the best for dynamic torque
FOC	Real-time calculation (complex)	Lowest	Highest	High	Highest torque and efficiency, best torque ripple

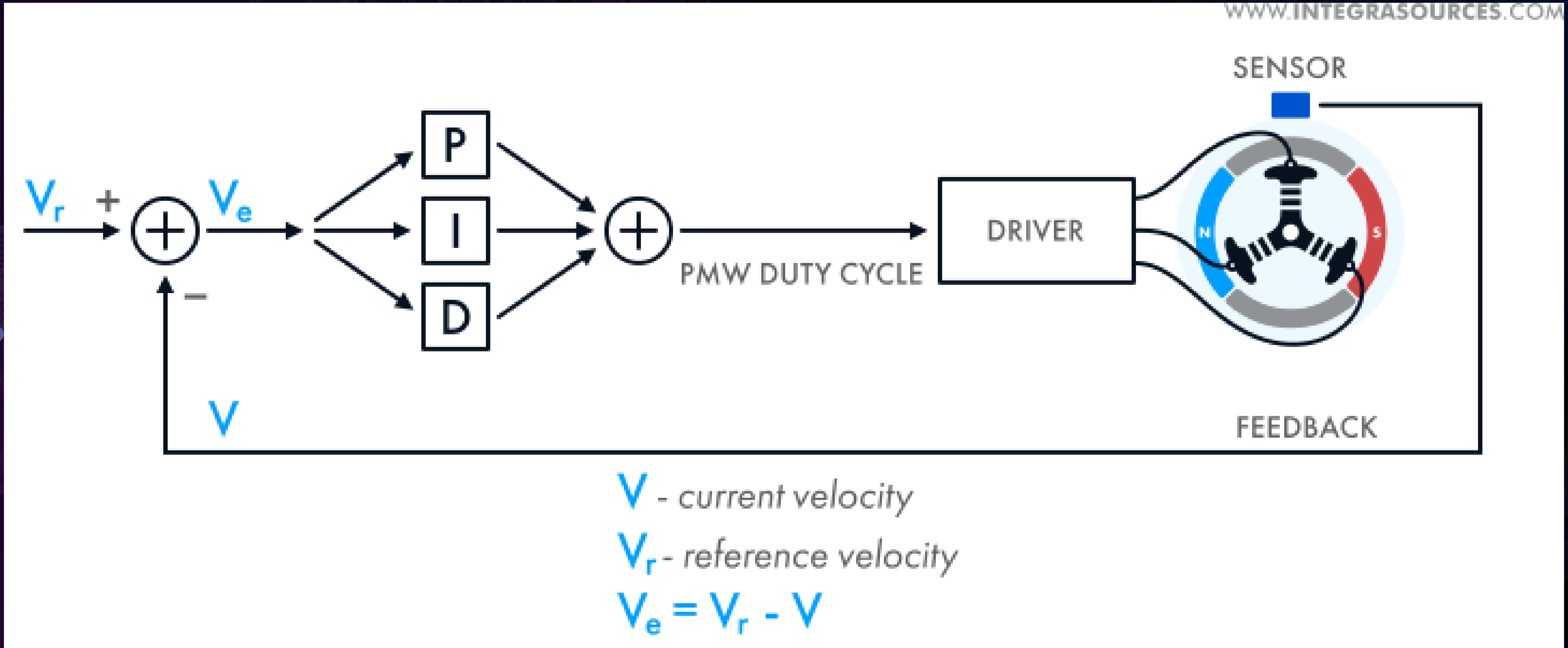
- Torque ripple
  - Quiet operation (fans, air purifiers)
  - Smooth dynamic operation in full speed range (robotic servos, washing machines)
- Motor efficiency
  - Longer battery life
  - Lower power consumption (cost savings)
- Motor speed
  - Increased speed performance through field-weakening technique (robot vacuums)

TEXAS INSTRUMENTS 12

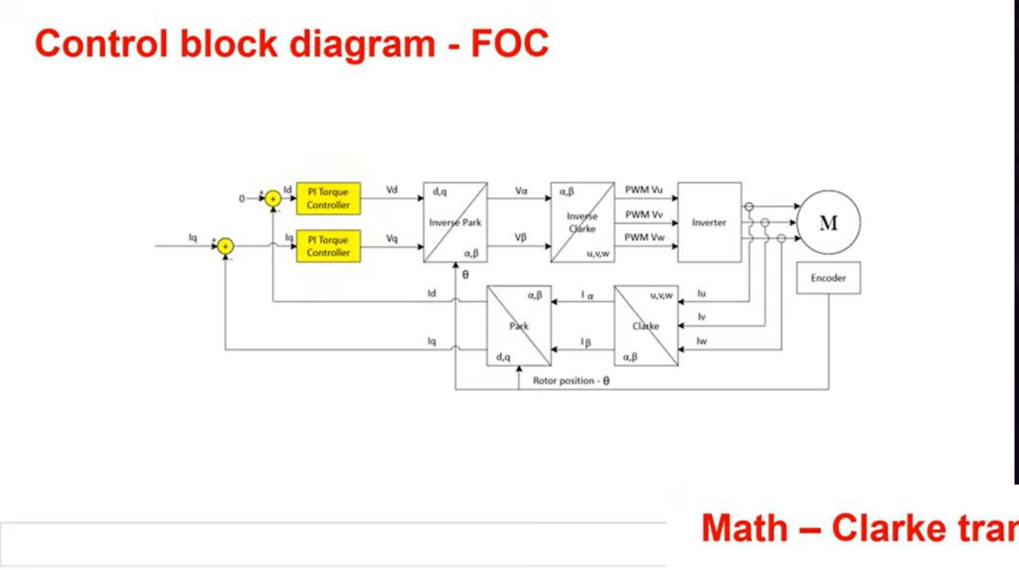
Field Oriented Control(FOC)

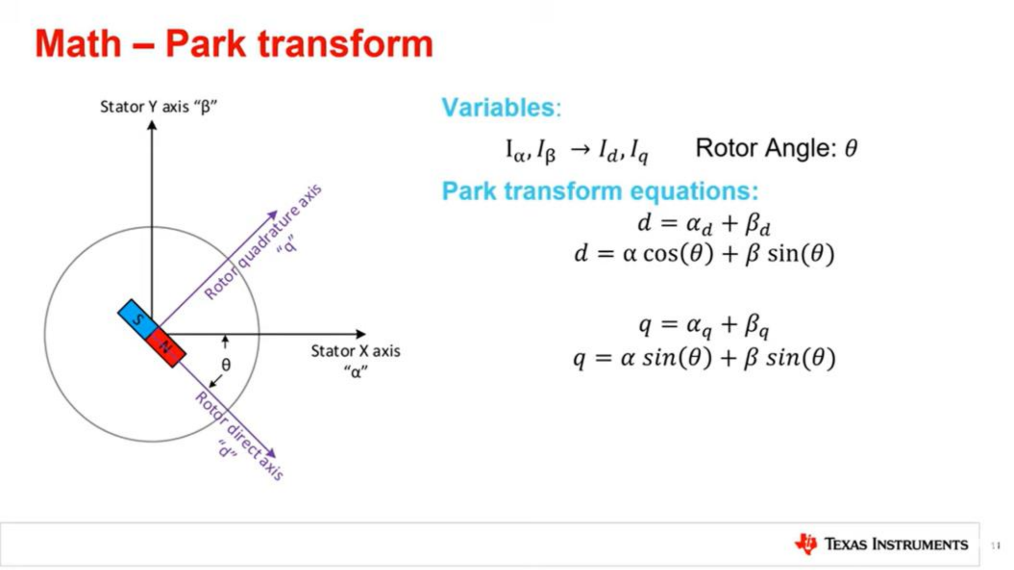


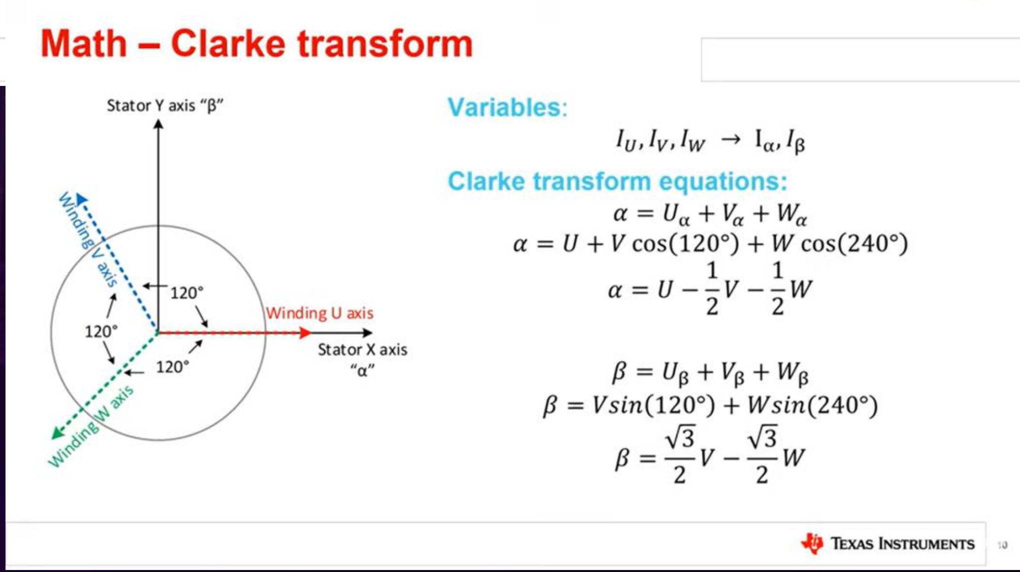
How to implement PID/PI control loop



Calculations and Controls in Field Oriented Control(FOC)







Why GaNs: PWM and frequency

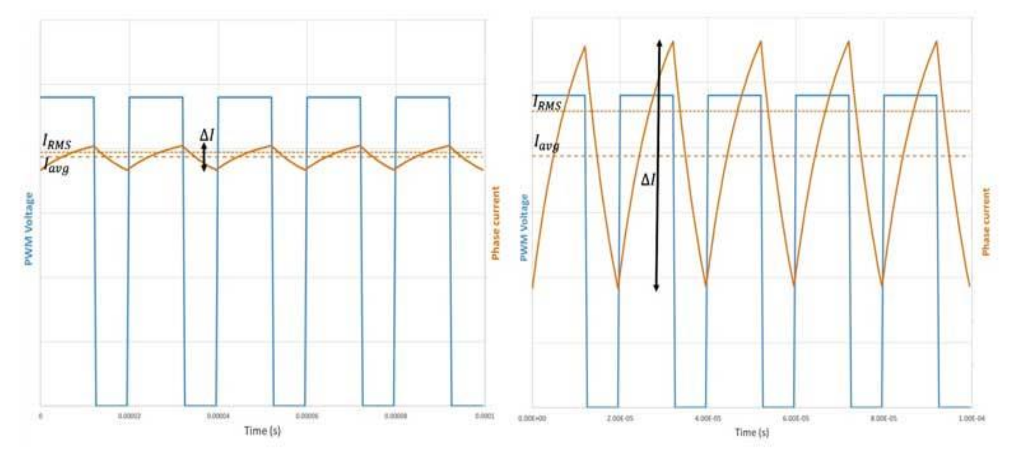
PWM used for current and voltage control (Duty cycle)

The torque of a DC motor is proportional to the average current, as illustrated by the formula:

$$T_{motor} = k_t \, I_{avg} \quad \text{EQ. 1}$$

Joules losses: The current ripple will increase the RMS (Root Mean Square) current value, which is the value considered for joules losses calculation. The ripple will simply generate additional heating, without increasing the average current, hence without increasing the torque. Notice that it is a square variation in function to the RMS current.

$$P_{Joules} = R \, I_{RMS}^2 \quad \text{EQ. 2}$$



The maximum value of the ripple is obtained when the duty cycle is 50%, meaning D=0.5:

$$\Delta I_{max} = \frac{U_{PWM}}{4 \, L \, f_{PWM}} \quad \text{EQ. 16}$$

From equation Eq. 15, there are several parameters influencing:

- The power supply U_{PWM}
- The duty cycle D
- The PWM frequency f_{PWM}
- The inductance L

Why GaNFETs: PWM and frequency

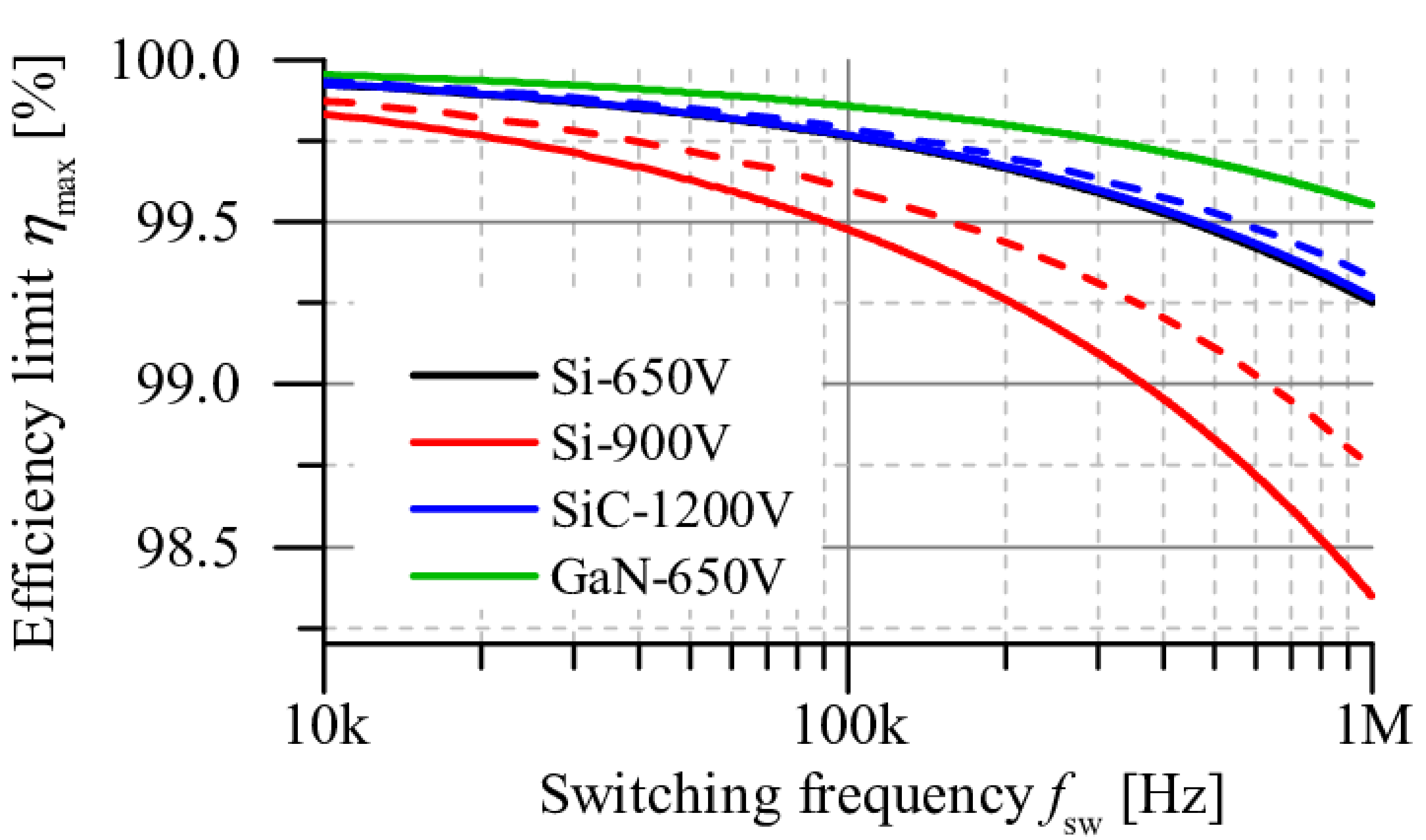
Determining the PWM (Pulse Width Modulation) frequency for a brushless motor involves considering several factors including motor characteristics, drive circuitry, and control requirements.

1. **Motor Characteristics**: The PWM frequency should be high enough to ensure smooth motor operation and minimize audible noise, especially at low speeds. However, it should not be excessively high to avoid increasing switching losses in the motor driver circuitry.
2. **Switching Losses**: Higher PWM frequencies result in increased switching losses in the motor drive circuitry, which can reduce overall efficiency and increase heat generation. Therefore, the PWM frequency should strike a balance between minimizing switching losses and ensuring smooth motor operation.
3. **Control System Requirements**: The PWM frequency should be compatible with the control system's sampling rate and response time requirements. Choosing a PWM frequency that aligns with the control system's dynamics can help optimize motor performance and response.
4. **Drive Circuitry**: The drive circuitry, including the motor driver ICs and power transistors, may have recommended or maximum PWM frequency specifications. It's important to ensure that the selected PWM frequency is within the limits specified by the drive circuitry to prevent damage and ensure reliable operation.
5. **Noise Considerations**: PWM frequency can affect electromagnetic interference (EMI) and audible noise produced by the motor and drive electronics. Selecting a PWM frequency that minimizes EMI and audible noise interference is important, especially in applications where electromagnetic compatibility (EMC) is critical.
6. **Application Requirements**: Consider the specific requirements and constraints of the application, such as speed range, torque control, and dynamic response. The PWM frequency should be selected to meet the performance and efficiency requirements of the application.

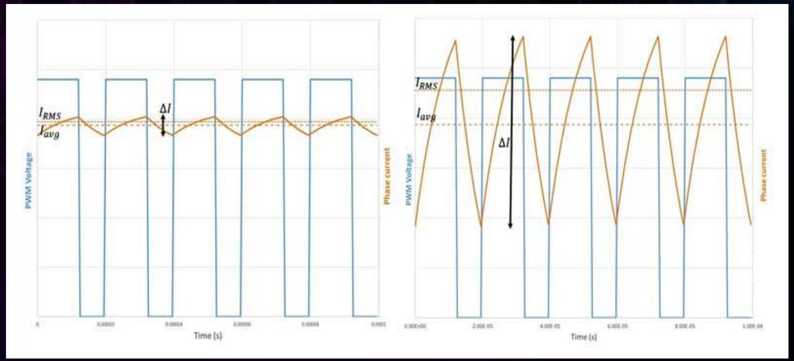
In normal ESCs, with SiC MOSFETs, PWM frequency of 50-80kHz is used

Why GaNFETs: PWM and frequency

In normal ESCs, with SiC MOSFETs, PWM frequency of 80kHz is used



- We can use 200kHz PWM frequency for similar switching loses using GaNs instead of commonly used SiC (An SiC MOSFET e.g. is attached at the bottom with characteristics similar to selected GaNFET)
  - 150% increase in frequency
  - 60% reduction in ripple currrent



› IPB65R190CFD7A	Buy Online	active and preferred	Automotive	650 V	190 mΩ	14 A	55 A

Why GaNs: PWM and frequency

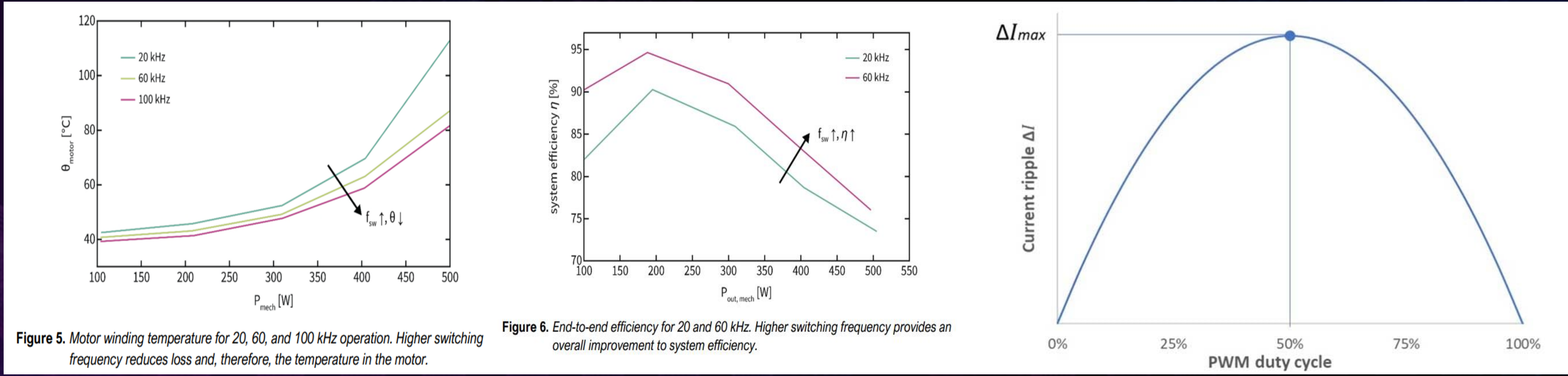


Figure 5. *Motor winding temperature for 20, 60, and 100 kHz operation. Higher switching frequency reduces loss and, therefore, the temperature in the motor.*

Figure 6. *End-to-end efficiency for 20 and 60 kHz. Higher switching frequency provides an overall improvement to system efficiency.*

- PWM Duty Cycle:
  - MAX: 19/40=0.475 (47.5% @ Min Voltage)
  - MIN: 19/60=0.3167 (31.7% @ Max Voltage)

Selected GaNFET

<u>Options Infineon Provided</u>:

- 4 GaNs: -IGO60R070D1 -IGOT60R070D1 -IGLD60R070D1 -IGT60R070D1

  (All have the similar Electrical Characteristics, just footprints are different)
- We will be using IGT60R070D1

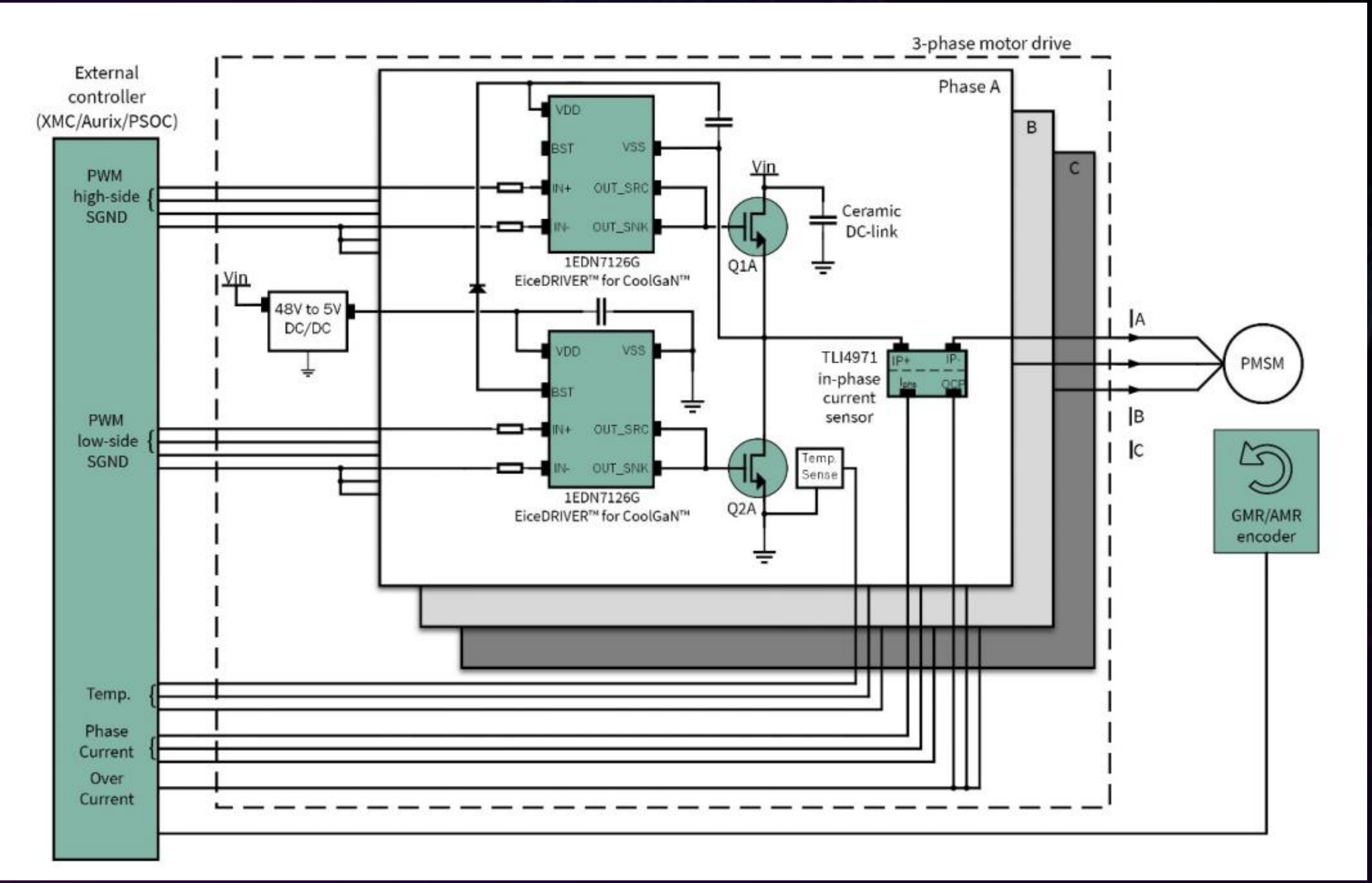
Table 1 Key Performance Parameters at T_j = 25 °C

Parameter	Value	Unit
$V_{DS,max}$	600	V
$R_{DS(on),max}$	70	mΩ
$Q_{G,typ}$	5.8	nC
$I_{D,pulse}$	60	A
Q_{oss} @ 400 V	41	nC
Q_{rr}	0	nC

Turn- on delay time	$t_{d(on)}$	-	10	-	ns
Turn- off delay time	$t_{d(off)}$	-	14	-	ns

Max Frequency supported: 41.67 MHz

Recommended Circuit by Infineon



- Recommended GaNFET driver:
  - 1EDN7126G (EiceDriver for CoolGaN)
- Recommended Current sensor:
  - TLI4971
- Recommended MCUs or Controllers:
  - XMC
  - Aurix
  - PSOC
- Recommended encoder
  - GMR
  - AMR

GaNFET driver

What is Gate Driver?

- A gate driver is a power amplifier that accepts a low power input from a controller IC and produces the appropriate high current gate drive for a power device. It is used when a PWM controller cannot provide the output current required to drive the gate capacitance of the associated power device.

- Recommended GaNFET driver - 1EDN7126G (EiceDriver for CoolGaN)

- This driver along with GaNFETs can be used in motor drive applications, such as those used for robotics, drones, automotive, and industrial machinery where high switching frequencies enable higher power density, increased efficiency, higher performance, and reduced EMI. These benefits can make GaN-based motor drive systems more compact, reliable, and cost-effective than silicon-based systems.

- Turn on, off propagation delay= 75ns impulse blanking time = 40ns(min time pulse on)
  - Max frequency= 1/((10+14+75+75+40)*10^-9) = 4.673MHz

GaNFET driver

Parametrics	1EDN7126G
Channels	1
Configuration	High-side
Output Current (Source)	1.5 A
Output Current (Sink)	1.5 A
Output Current	1.5 A
Turn Off Propagation Delay	75 ns
Turn On Propagation Delay	75 ns
Voltage Class	200 V

2.6 Active Miller clamp

The sink output of the gate driver has an active Miller clamp feature to provide high immunity to spurious turn-on events. During a turn-off transition, the peak sinking current and equivalent pull-down resistance is defined according to the product variant. However, once the driver detects that the gate voltage (at the sink output) has fallen below 0.4 V, the active Miller clamp is engaged within 3 ns, increasing the strength of the Sink output significantly. With the clamp engaged, all four product variants can sink up to 5 A, with an equivalent pull-down resistance of 0.3 Ω. This feature allows the designer to optimize the turn-off speed without sacrificing the driver's "keep-off" strength. If an external gate resistor is placed at the sink output, the effectiveness of the active Miller clamp is reduced.

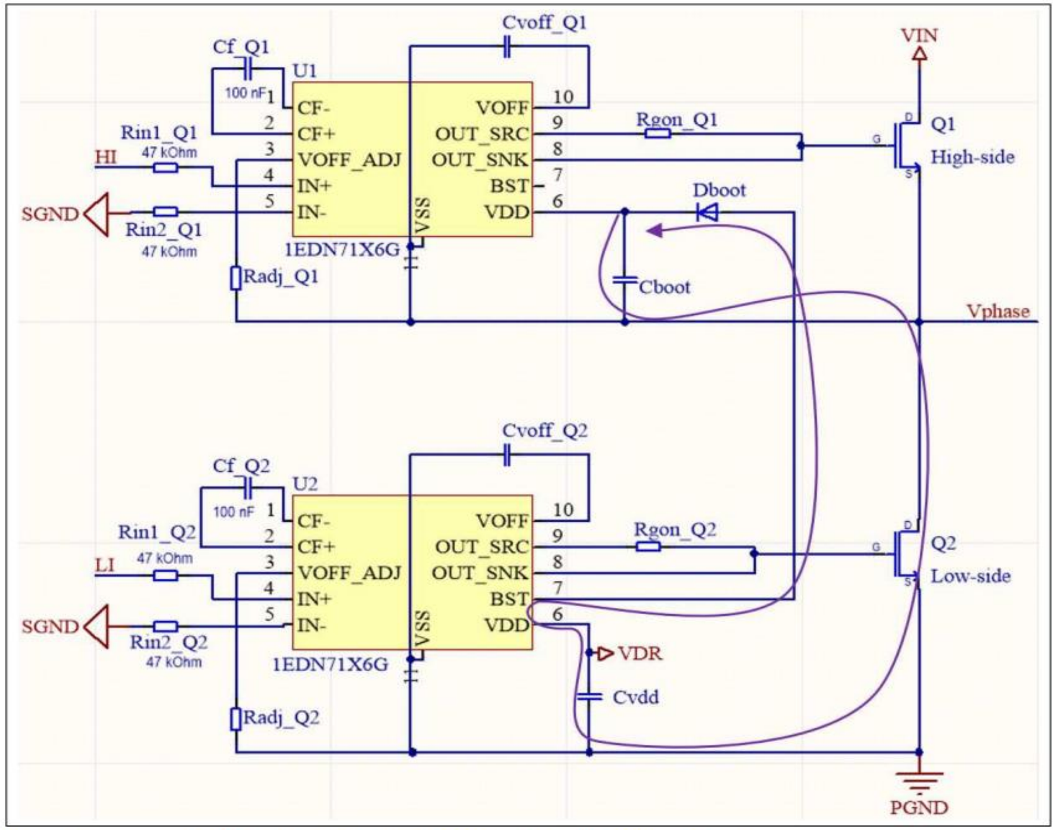
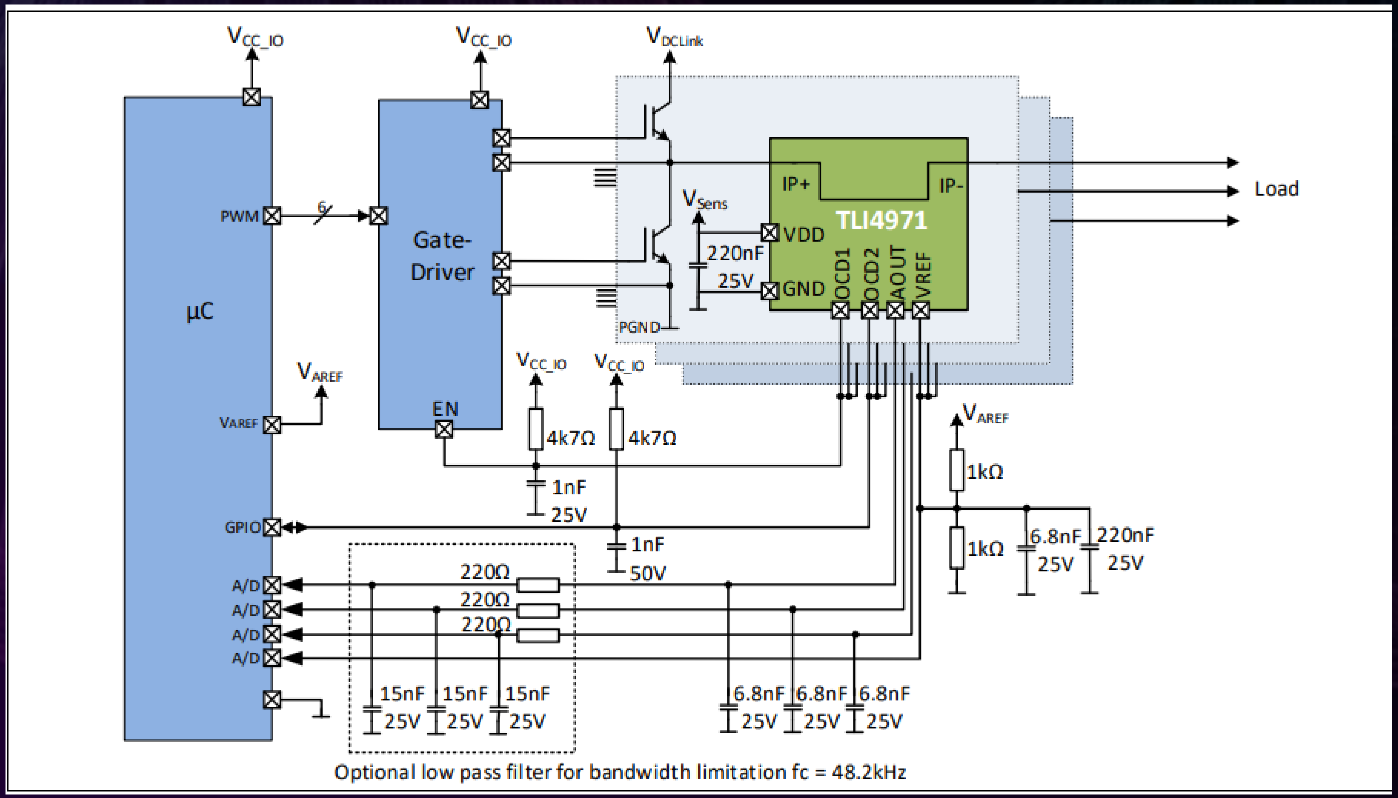


Figure 5 Half-bridge with active bootstrap clamping (CP enabled)

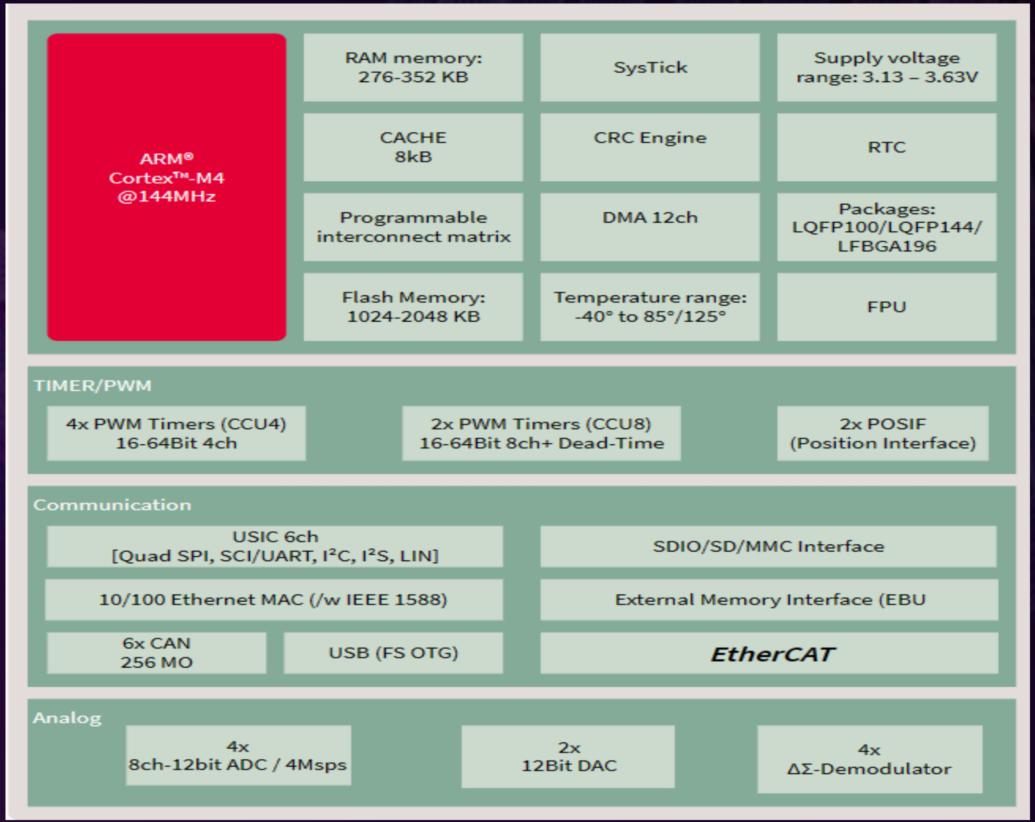
Current Sensor

- The XENSIV™ TLI4971 Hall effect sensor avoids potential common-mode transient immunity (CMTI) issues with differential amplifiers. A well-isolated in-phase current sensor is more immune to voltage transients and provides accurate readings for field-oriented control of the motor.



MCU

- XMC4800-F100K2048 AA 144MHz
  - More than 9bits of PWM accuracy



Summary of Features

- ARM ® Cortex ®-M4 @ 144MHz
- 2048kB Flash, 352kB RAM
- Data and IP Protection on Flash
- Supply voltage range: 3.13 - 3.63V
- EtherCAT ® node
- 6 x CAN nodes
- EthernetMAC, USB-OTG, SD/MMC
- 6 channel USIC (configurable to SPI, UART, IIC, IIS)
- External Bus Unit
- 4 x 12-bit ADC, 18 input channels, 4 x parallel sampling and conversion
- 2 channel 12bit DAC
- 4 channel ΔΣ Demodulator
- 24 x 16-bit special purpose timers, dead time generation
- 2 x Position Interface
- Watch Dog Timer, Real Time Clock
- XMC4000 Functional Safety Package
- Package: LQFP100
- Temperature range: -40 - 125°C
- SDIO/SD/MMC Interface

Alternative MCU

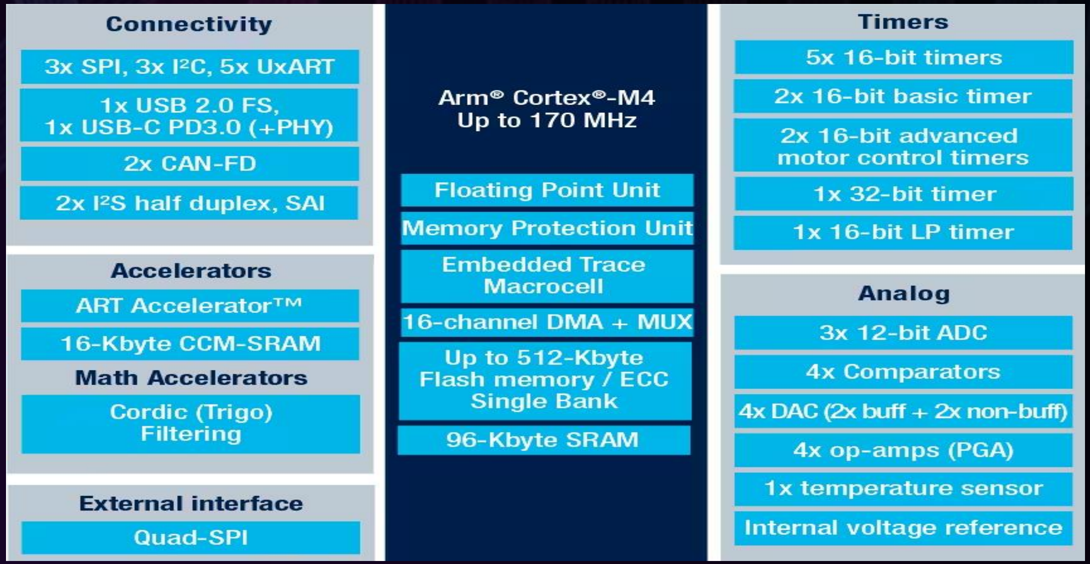
- STM32G491RE ARM Microcontroller 170MHz, more than 9bits of PWM accuracy (Even more than XMC4800-F100K2048)

- Core: Arm® 32-bit Cortex®-M4 CPU with FPU, Adaptive real-time accelerator (ART Accelerator) allowing 0-wait-state execution from Flash memory, frequency up to 170 MHz with 213 DMIPS, MPU, DSP instructions

They offer three fast 12-bit ADCs (5 Msps), four comparators, four operational amplifiers, four DAC channels (2 external and 2 internal), an internal voltage reference buffer, a low-power RTC, one general-purpose 32-bit timers, three 16-bit PWM timers dedicated to motor control, seven general-purpose 16-bit timers, and one 16-bit low-power timer.

- 15 timers:
  - 1 x 32-bit timer and 2 x 16-bit timers with up to four IC/OC/PWM or pulse counter and quadrature (incremental) encoder input
  - 3 x 16-bit 8-channel advanced motor control timers, with up to 8 x PWM channels, dead time generation and emergency stop
  - 1 x 16-bit timer with 2 x IC/OCs, one OCN/PWM, dead time generation and emergency stop
  - 2 x 16-bit timers with IC/OC/OCN/PWM, dead time generation and emergency stop
  - 2 x watchdog timers (independent, window)
  - 1 x SysTick timer: 24-bit downcounter
  - 2 x 16-bit basic timers
  - 1 x low-power timer

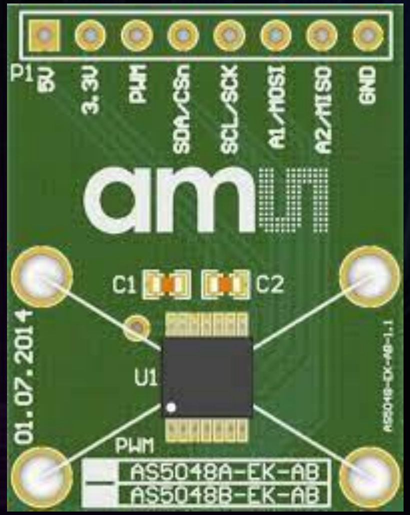
- V_{DD}, V_{DDA} voltage range: 1.71 V to 3.6 V



Encoder

- Recommended encoder: Infineon XENSIV™ TLE5012 magnetic angle sensors with 0.01° resolution
  - In applications where a sensored FOC scheme is preferred, this encoder can be used for precise positioning.
  - Uses SPI protocol

- Used Magnetic encoder: ams AS5048B
  - Used this because of SPI pin limitation on Arduino(PWM+SPI pin)
  - Magnetic encoder, no moving parts
  - 0.02197 deg resolution
  - 14 bit resolution
  - Used I2C protocol

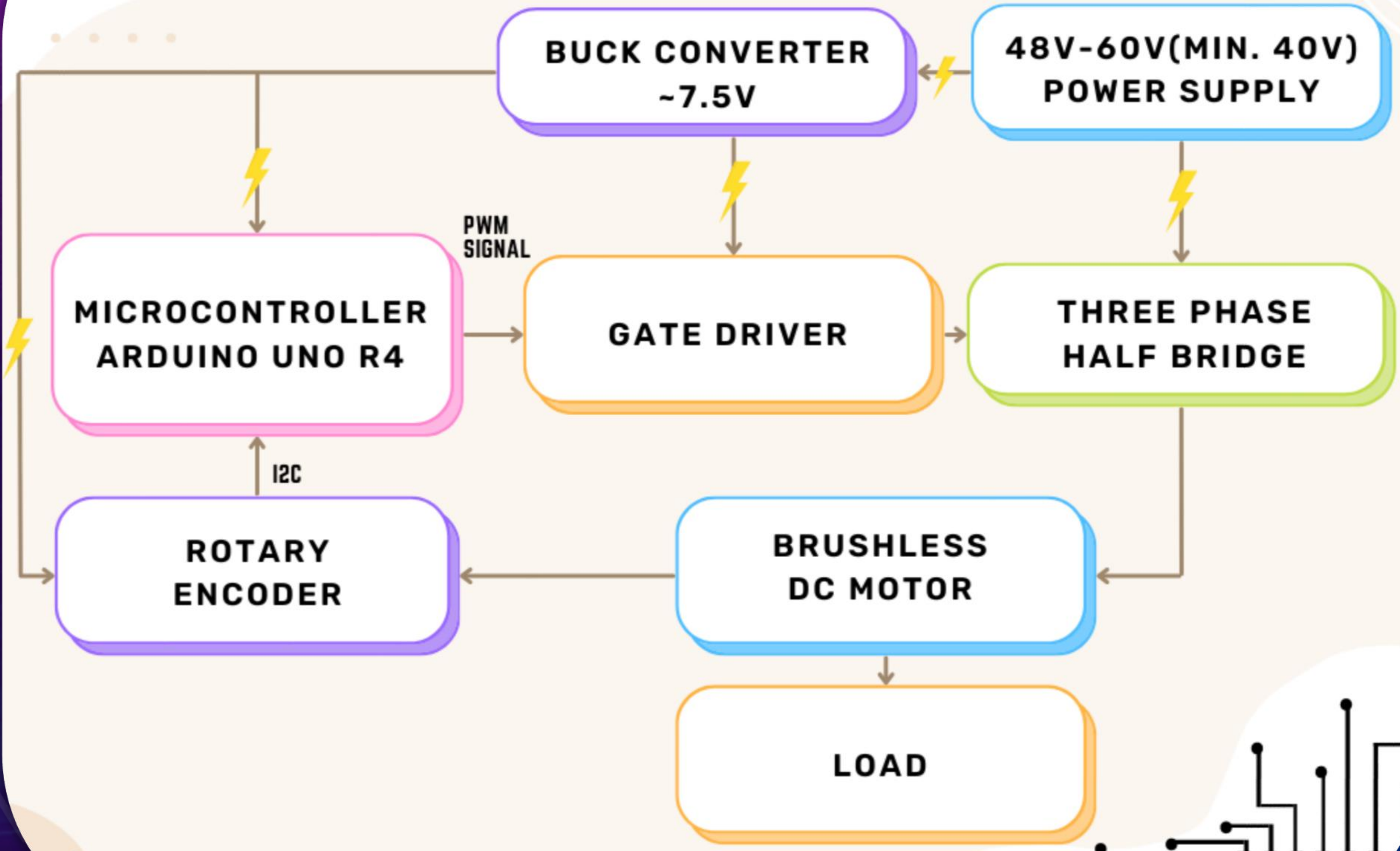


MCU board to be used for testing and Additional Component Details

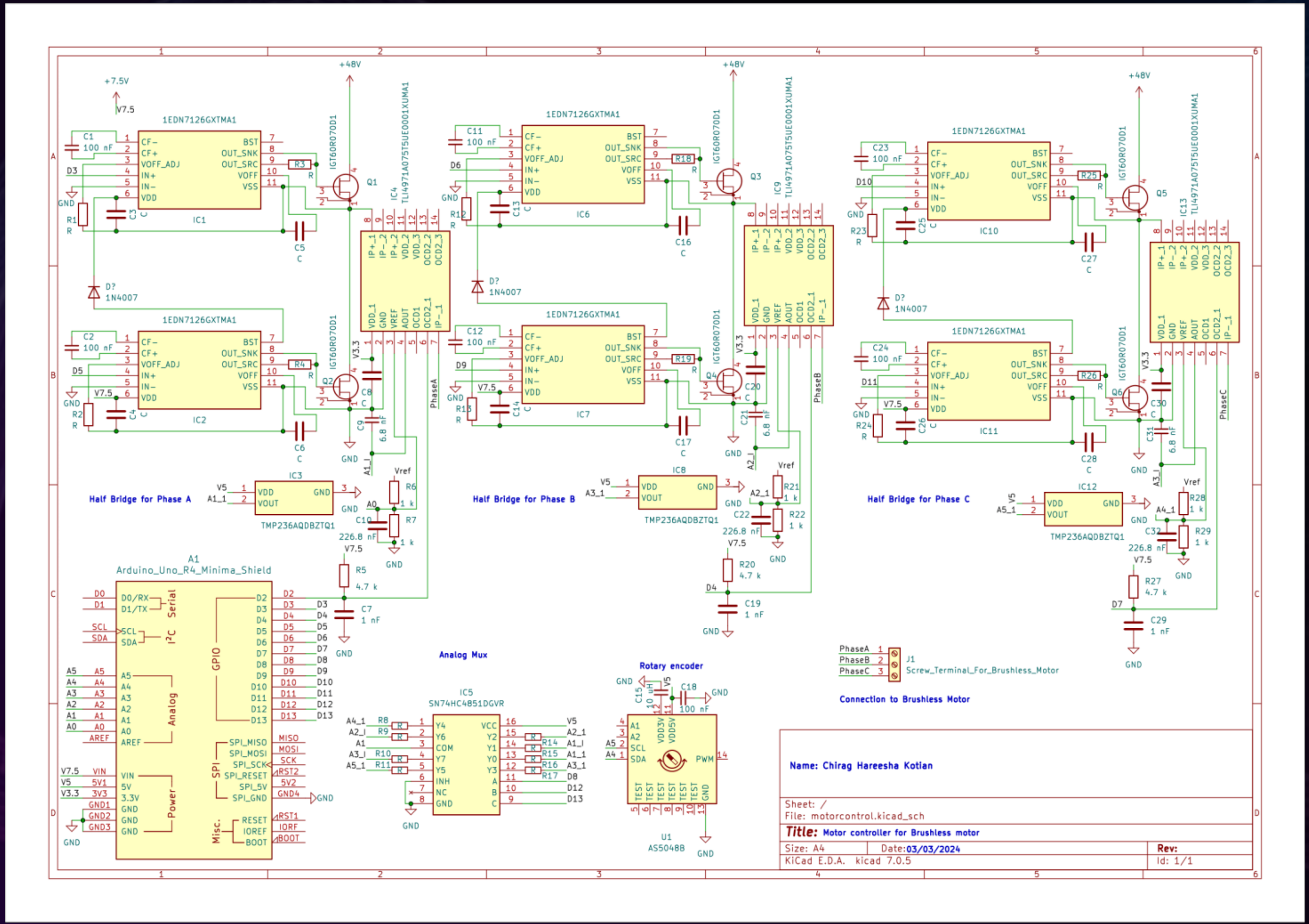
- **Arduino unoR4 minima:**
  - 48Mhz Clock speed
    - 8 bit resolution -> 200kHz (240)
      - voltage control resolution= 0.234375V @60V and 0.15625V @ 40V
      - PWM: D3,D5,D6,D9,D10,D11
      - A/D C: A0,A1,A2,A3,A4,A5 (Used by Temperature, Vref, Current)
      - OverCurr: D2,D4,D7

- **Analog Mux:** SN74HC4851 8channel (D8,D12,D13)
- **For buck convertor:** 7.5V, we can use LM5117
- **For temperature sensor:** TMP236
  - ±2.0°C analog output temperature sensor, with 19.5mV/°C gain

BLOCK DIAGRAM OF THE SYSTEM



Circuit Schematic



- Made using open-source KiCAD

Bill of Materials

Source:	D:\PROJECTS\prima innotech\motorcontoller\KiCad\motorcontrol\motorcontrol.kicad_sch								
Date:	###								
Tool:	Eeschema 7.0.5								
Generator:	E:\kicad\New folder\7.0\bin\scripting\plugins/bom_csv_grouped_by_value_with_fp.py								
Component Count:	86								
Ref	**Qnty**	**Value**	**Cmp name**	**Footprint**	**Description**	**Vendor**	**Rate**	**Cost**	**DNP**
A1	1	Arduino_Uno_R4_Minima_Shield	Arduino_Uno_R4_Minima	PCM_arduino-library:Arduino_Uno_R4_Minima	Arduino Uno R4 Minima which will be brain for the system	Robu	1399	1399	
C1, C2, C11, C12, C18, C23, C24	7	100 nF	C_Small		Unpolarized capacitor, small symbol	Electronics Cor	2.2	15.4	
C3, C4, C5, C6, C8, C13, C14, C16, C17, C20, C25, C26, C27, C28, C30	15	C	C		Unpolarized capacitor	Electronics Cor	2.2	33	
C7, C19, C29	3	1nF	C		Unpolarized capacitor	Electronics Cor	2.2	6.6	
C9, C21, C31	3	6.8 nF	C_Small		Unpolarized capacitor, small symbol	Electronics Cor	2.2	6.6	
C10, C22, C32	3	226.8 nF	C		Unpolarized capacitor	Electronics Cor	4.4	13.2	
C15	1	10 uH	C_Small		Unpolarized capacitor, small symbol	Electronics Cor	2.2	2.2	
D1, D2, D3	3	1N4007	1N4007	Diode_THT:D_DO-41_SOD81_P10.16mm_Horizontal	1000V 1A General Purpose Rectifier Diode, DO-41	Electronics Cor	1	3	
IC1, IC2, IC6, IC7, IC10, IC11	6	1EDN7126GXTMA1	1EDN7126GXTMA1	1EDN7126GXTMA1	Gate Drivers INT. POWERSTAGE/DRIVER	Mouser	98.77	592.62	
IC3, IC8, IC12	3	TMP236AQDBZTQ1	TMP236AQDBZTQ1	SOT95P237X112-3N	Board Mount Temperature Sensors Automotive grade, ±0.5°C analog output temperature sensor with 19.5 mV/°C gain 3-SOT-23 -40 to 125	Mouser	67.81	203.43	
IC4, IC9, IC13	3	TLI4971A075T5UE0001XUMA1	TLI4971A075T5UE0001XUMA1	TLI4971A075T5UE0001XUMA1	Infineon TLI4971A075T5UE0001XUMA1	Mouser	400.89	1202.67	
IC5	1	SN74HC4851DGVR	SN74HC4851DGVR	SOP40P640X120-16N	8-Channel Analog Multiplexer/Demultiplexer with Injection-Current Effect Control	Mouser	68.89	68.89	
J1	1	Screw_Terminal_For_Brushless_N	Screw_Terminal_01x03		Generic screw terminal, single row, 01x03, script generated (kicad-library-utils/schlib/autogen/connector/)	Robu	100	100	
Q1, Q2, Q3, Q4, Q5, Q6	6	IGT60R070D1	IGT60R070D1	Package_TO_SOT_SMD:Infineon_PG-HSOF-8-3_ThermalVias	31A Id, 600V Vds, 70mOhm, N-Channel GaN MOSFET, HSOF-8	Mouser	955.33	5731.98	
R1, R2, R3, R4, R8, R9, R10, R11, R12, R13, R14, R15, R16, R17, R18, R19, R23, R24, R25, R26	20	R	R		Resistor	Electronics Cor	2	40	
R5, R20, R27	3	4.7 k	R		Resistor	Electronics Cor	2	6	
R6, R7, R21, R22, R28, R29	6	1k	R		Resistor	Electronics Cor	2	12	
U1	1	AS5048B	AS5048B	Package_SO:TSSOP-14_4.4x5mm_P0.65mm	Magnetic position sensor, 14-bit, PWM output, I2C Interface, TSSOP-14	Mouser	755.3	755.3	
							Total	10191.9	

Open-source FOC library with many features

- SimpleFOC
  - https://simplefoc.com/

SimpleFOCproject

Arduino Compatible Open Source Field Oriented Control (FOC) project

Features

- **Easy install**:
  - Arduino IDE: Arduino Library Manager integration
  - PlatformIO
- **Open-Source**: Full code and documentation available on github
- **Goal**:
  - Support as many sensor + motor + driver + current sense combination as possible.
  - Provide the up-to-date and in-depth documentation with API references and the examples
- **Easy to setup and configure**:
  - Easy hardware configuration
  - Each hardware component is a C++ object (easy to understand)
  - Easy tuning the control loops
  - *SimpleFOCStudio* configuration GUI tool
  - Built-in communication and monitoring
- **Cross-platform**:
  - Seamless code transfer from one microcontroller family to another
  - Supports multiple MCU architectures:
    - Arduino: UNO R4, UNO, MEGA, DUE, Leonardo, Nano, Nano33 ....
    - STM32
    - ESP32
    - Teensy
    - many more ...

Next Steps

Completing the schematic

Simulation, Improvement, PCB designing

Assembly and Testing

Reference Links

- https://www.portescap.com/en/newsroom/whitepapers/2021/10/understanding-the-effect-of-pwm-when-controlling-a-brushless-dc-motor
- https://www.portescap.com/en/newsroom/whitepapers/2021/10/understanding-the-effect-of-pwm-when-controlling-a-brushless-dc-motor
- https://ams.com/documents/20143/36005/AS5147_DS000307_3-00.pdf
- https://www.controleng.com/articles/understanding-the-effect-of-pwm-when-controlling-a-brushless-dc-motor/
- https://www.infineon.com/cms/en/product/microcontroller/32-bit-industrial-microcontroller-based-on-arm-cortex-m/32-bit-xmc4000-industrial-microcontroller-arm-cortex-m4/
- https://www.infineon.com/cms/en/product/microcontroller/32-bit-tricore-microcontroller/
- https://www.infineon.com/cms/en/product/microcontroller/32-bit-psoc-arm-cortex-microcontroller/
- https://github.com/simplefoc/Arduino-FOC
- https://www.youtube.com/watch?v=Y5kLeqTc6Zk
- https://www.youtube.com/watch?v=zSdetJsSeNw
- https://www.youtube.com/watch?v=Nhy6g9wGHow
- https://www.youtube.com/watch?v=YPD1_rcXBIE
- https://github.com/byDagor/Janus-Controller
- https://github.com/maakbaas/mbldc
- https://github.com/qwertpas/O32controller
- https://www.youtube.com/watch?v=VdkloigaxZo
- https://github.com/SheffieldEcoMotorsports/motor-controller
- https://simple-circuit.com/arduino-sensorless-bldc-motor-controller-esc/
- https://www.instructables.com/BLDC-Motor-Control-with-Arduino-salvaged-HD-motor/
- https://simple-circuit.com/arduino-sensorless-brushless-motor-bldc/
- https://simple-circuit.com/arduino-bldc-brushless-dc-motor-control/
- https://www.youtube.com/watch?v=_6-_jvZe7iA

Thank you

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