Introduction to BLDC Motor Control
Using Freescale MCU

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Accelerating Your Success™

Agenda

- Introduction to Brushless DC Motors
- Motor Electrical and Mechanical Model
- Motor Speed Control Hardware Design
- Motor Speed Control Software Tasks
- Motor Speed Control Challenges

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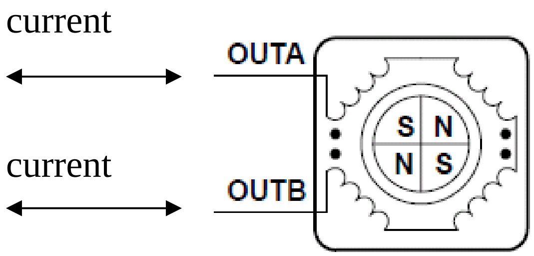
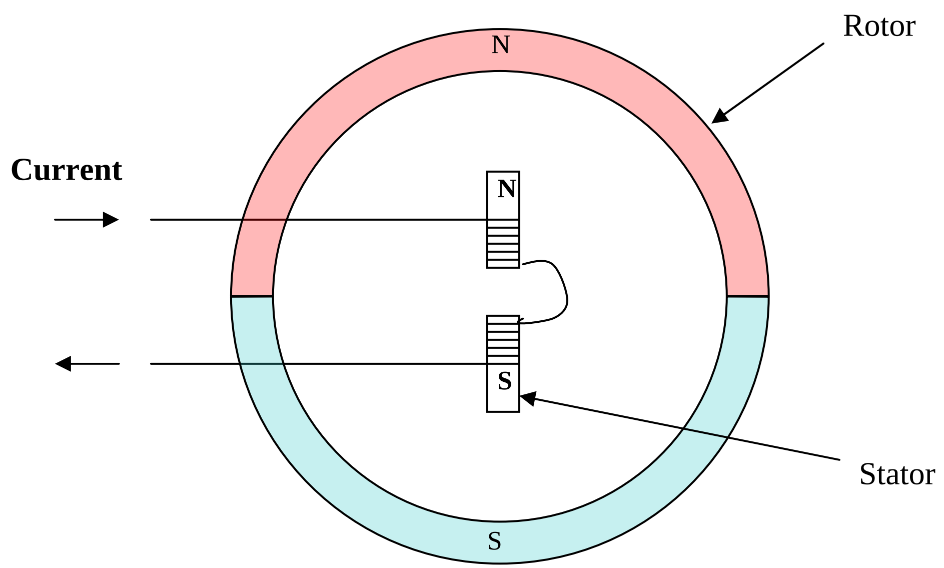
Theory of Operation



Structure of a single-phase 2 pole-pair BLDC motor

- Based on attraction and repulsion of magnetic poles.
- Rotating magnetic field of stator rotates rotor
- Rotation of magnetic field must be in phase with rotation of rotor.
- Rotation of magnetic field is achieved by changing direction of current through the stator coil.
- Speed Control achieved by controlling the average current flowing into stator coil.
- Hall Sensor used to detect rotor position.

Theory of Operation



Operation of a single-phase 1 pole-pair BLDC motor

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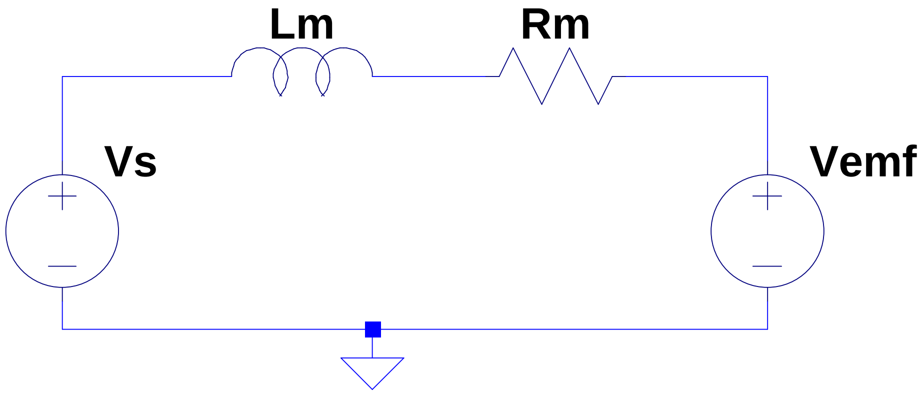
Motor Mechanical Model

- Mechanical model:
- Mechanical Drive Torque generated T is expressed as follows:
  - $T = K_T.i.\sin(N.\theta+C) = J.d\omega/dt + L.\omega + T_{ext}$
- where:
  - K_T = torque constant
  - i = current through coil
  - N = Number of pole pairs
  - θ = phase angle of rotor
  - C = phase offset due to motor phases
  - J = moment of inertia of rotor
  - ω = angular speed of rotor = $d\theta/dt$
  - L = constant associated with speed-related losses (damping, eddy current, friction)
  - T_{ext} = other external mechanical load

Motor Electrical Model



- Electrical model:
  - $V_s = L_m.di/dt + i.R_m + K_T.\omega$
- where:
  - V_s = supply voltage
  - L_m = motor coil inductance
  - R_m = motor coil resistance
  - ω = rotor speed
  - $K_T.\omega$ = back-emf induced voltage

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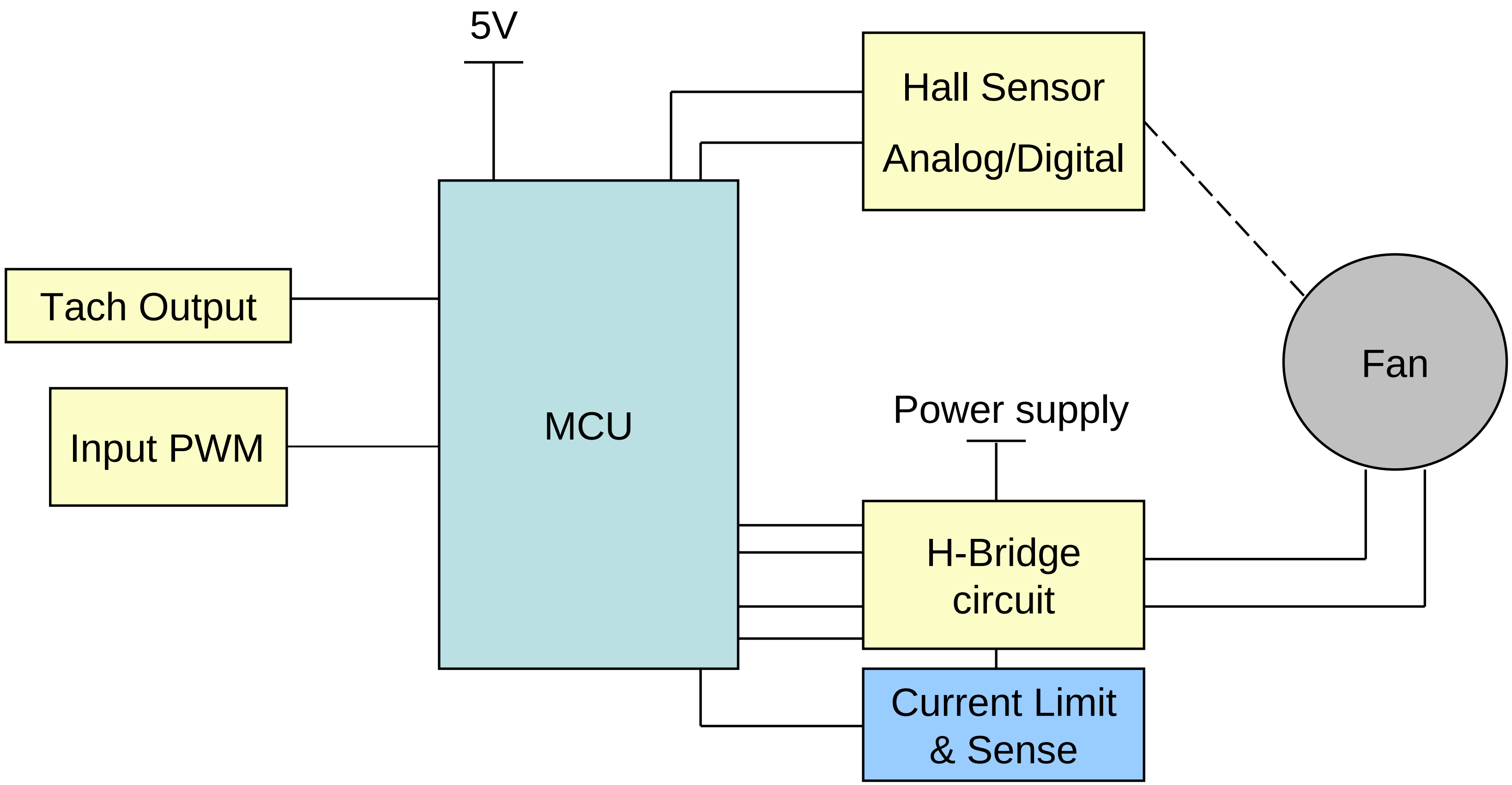
Motor Speed Control Hardware Block Diagram



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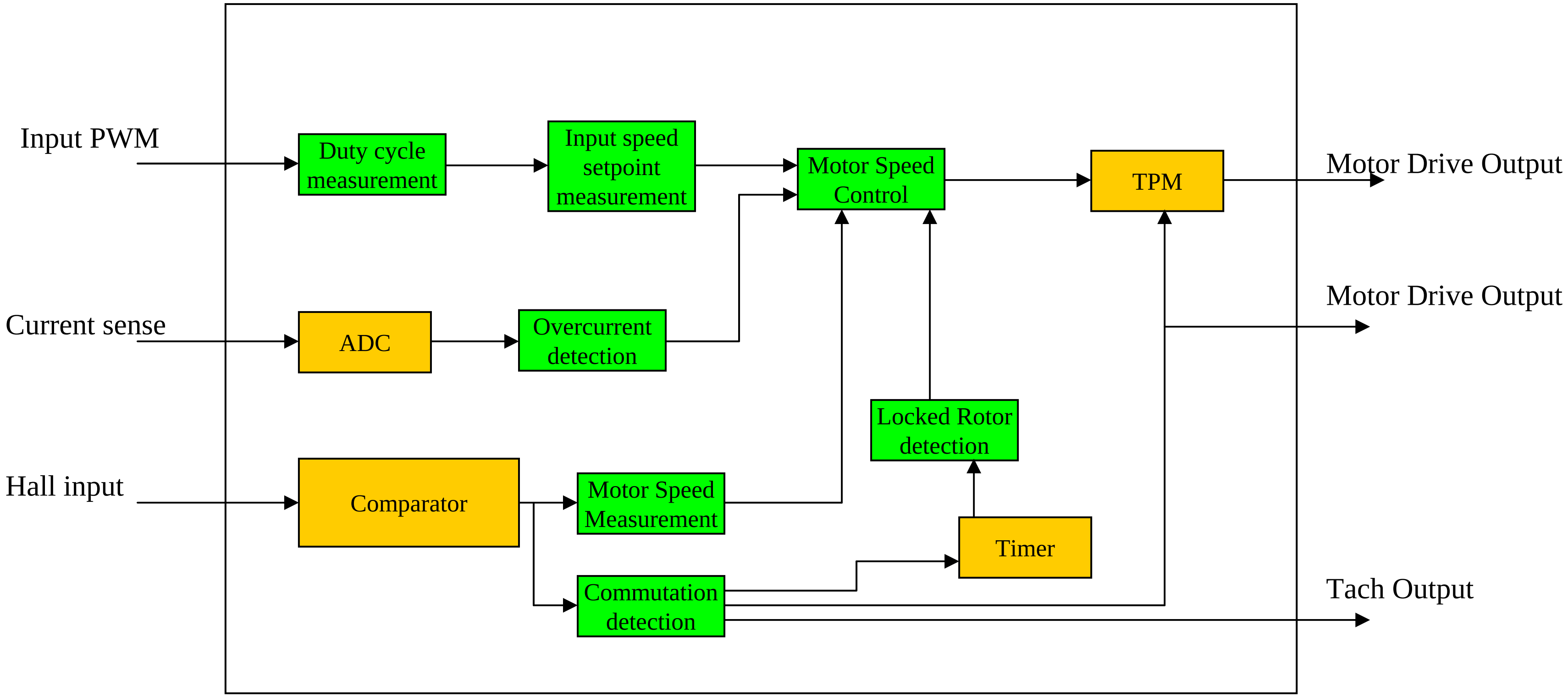
MC9S08SH4 Task and Resource Scheduling



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Motor Speed Control Challenges

- Phase commutation efficiency
- Reduce in-rush current
- Over-current limit
- Speed Control Accuracy
- Tuning motor speed curve

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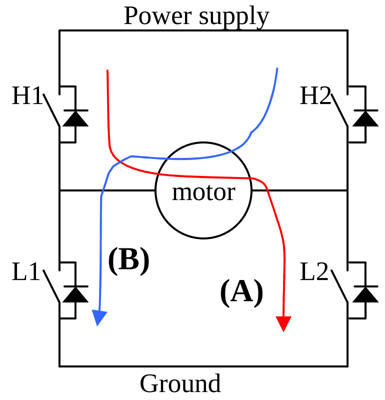
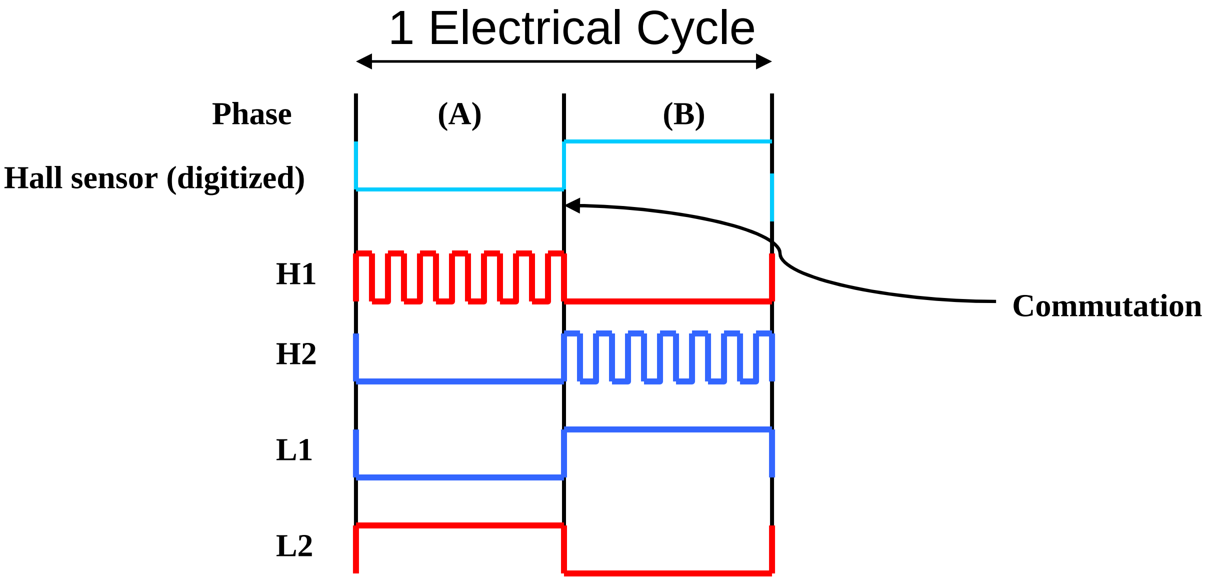
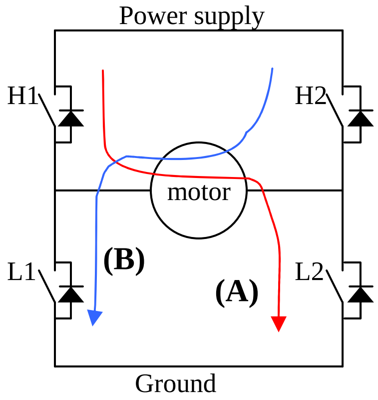
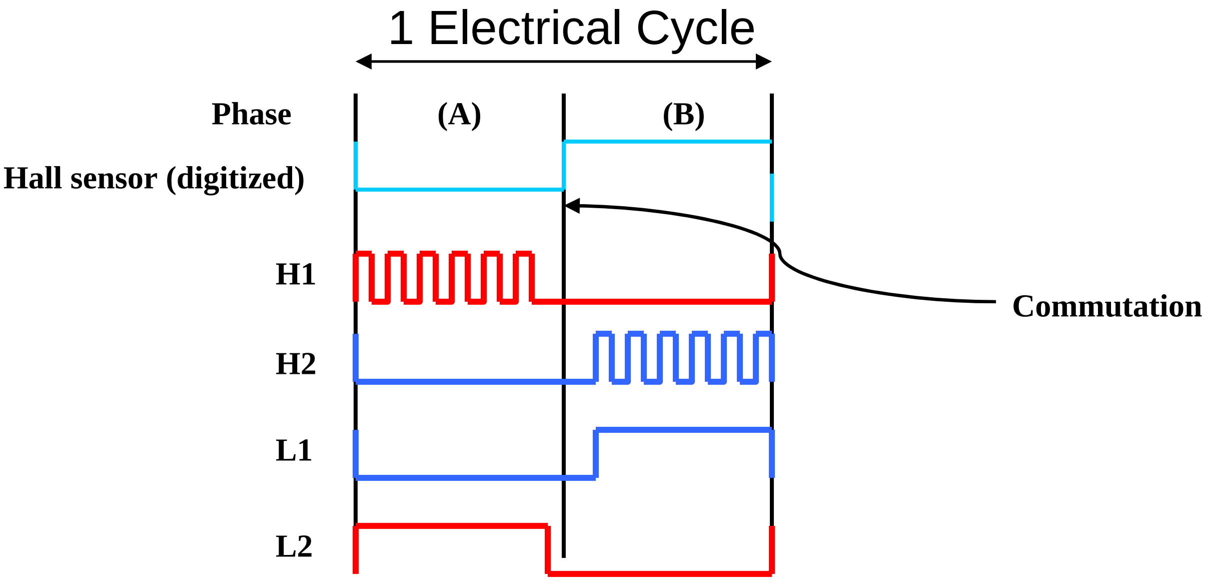
H-Bridge (Driving Sequence)





H-Bridge (Efficient Driving Sequence)





Motor Speed Control Challenges

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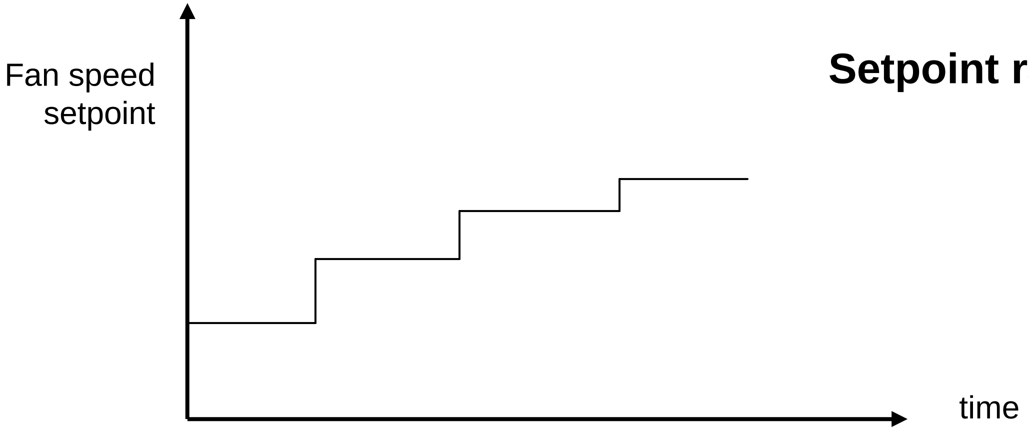
Reduce in-rush current

- In-rush current due to change in fan speed setpoint can cause sudden current surge
- External power supplies may trip due to current surge
- Solutions:
  - Setpoint – current RPM differential limit
  - Setpoint ramping



Motor Speed Control Challenges

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Over-current limit

- Required for large current fans to prevent damage to electronics
- Over-current is caused by physical obstruction of rotor movement
- Can be implemented using current measurement resistor and fast ADC peripheral – available in MC9S08SH4

Motor Speed Control Challenges

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Speed Control Accuracy

- PID speed control steady state error
- Output speed measurement accuracy
- Input PWM duty cycle measurement accuracy

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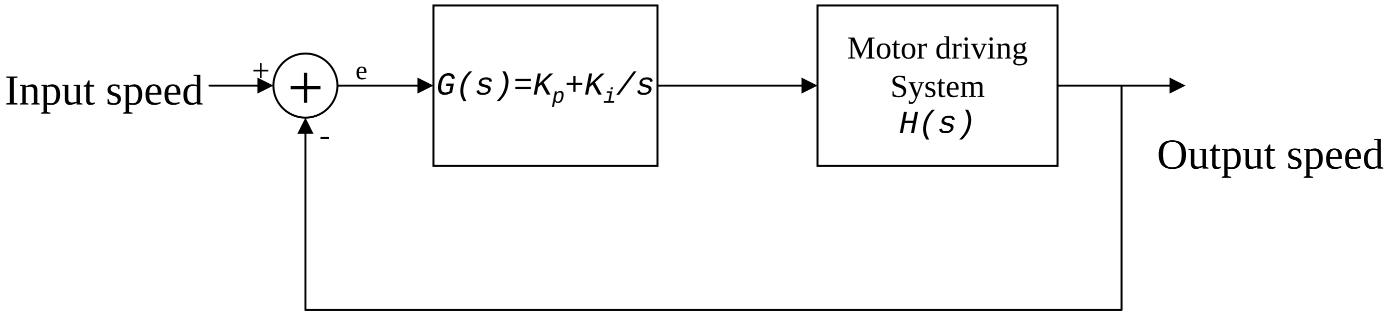
PI Closed-Loop Speed Control Model



Input speed

+

-

e

$G(s)=K_p+K_i/s$

Motor driving
System
$H(s)$

Output speed

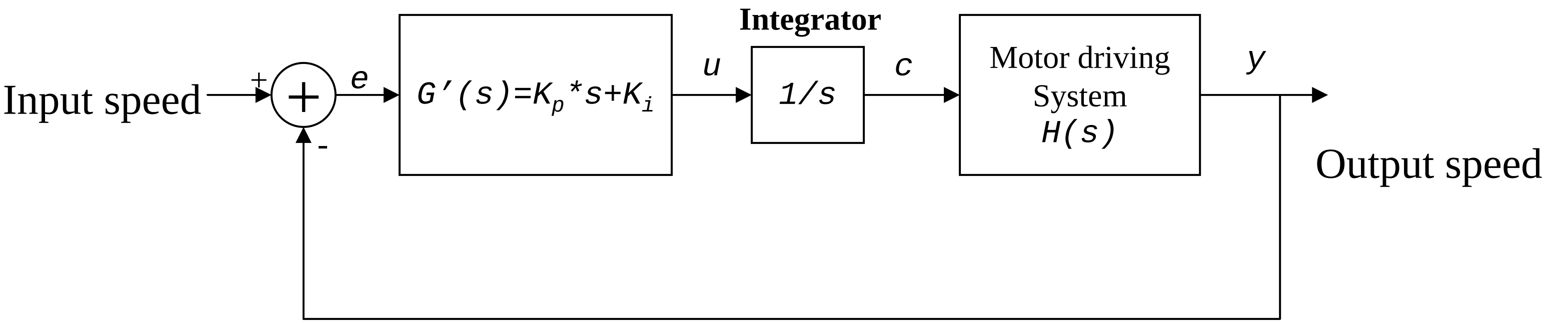
PI Motor Speed Control

PI Closed-Loop Speed Control

- Velocity form of PI, also called “incremental” or “differential” PI is used to control motor speed.
- Derived by differentiation of the standard form.

- The velocity form of PI:
- $G'(s) = K_p * s + K_i$

PI Closed-Loop Speed Control Model (Velocity form)



PI Motor Speed Control (Velocity form)

PI Speed Control Steady State Error

- Steady state error occurs when non-zero *e* results in zero *u* output
- Caused by implementation of PI Control loop in integer arithmetic:
  - `Ki*e < 1 = 0`
  - `=> e < 1/Ki`
- Maximum steady state error = `1/Ki`

Speed Control Accuracy

- PID speed control steady state error
- Output speed measurement accuracy
- Input PWM duty cycle measurement accuracy

Output speed measurement accuracy

- Output speed measurement accuracy depends on MCU clock accuracy
- Crystal can be used to provide accurate clock – but this is expensive solution
- MC9S08SH4 can run on internal oscillator.
    - Factory-trimmed with typical accuracy of 1% over voltage and temperature range

Speed Control Accuracy

- PID speed control steady state error
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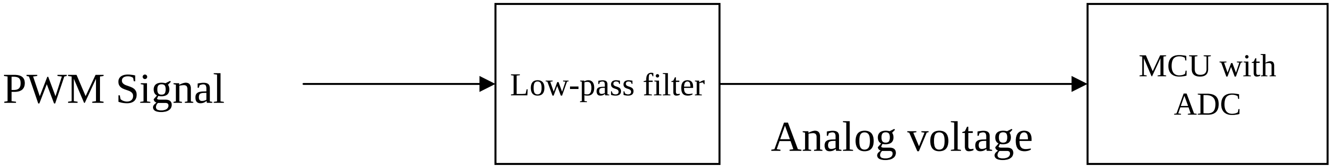
Measuring Input PWM duty cycle

“Standard” Method of measuring PWM duty cycle


PWM Signal

Low-pass filter

Analog voltage

MCU with ADC

Step 1: Low pass filter to convert PWM to analog voltage where analog voltage level is proportional to the PWM duty cycle

Step 2: MCU measures analog voltage level using internal ADC

Step 3: MCU derives duty cycle by dividing measured ADC value by maximum ADC value.

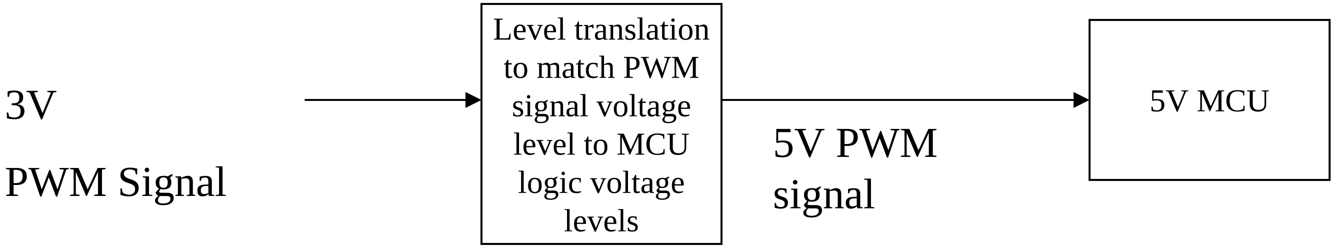
Measuring Input PWM duty cycle

- Problems with ADC method:
  - Accuracy is affected by ground noise when motor is running – especially bad for high-current motor
  - Low pass filter circuit subject to component value variation (e.g. 1% resistors) and temperature variations.
  - ADC performance limitations (output resistance limits of low pass filter circuit, non-linearity errors, zero-scale errors, full-scale errors, quantization errors)

- Conclusion:
  - It is odd to measure a digital signal by conversion to analog signal to derive its digital value!

Measuring Input PWM duty cycle

Random Sampling Method of measuring PWM duty cycle



3V

PWM Signal

Level translation to match PWM signal voltage level to MCU logic voltage levels

5V PWM signal

5V MCU

Step 1: Level translation circuit to convert PWM signal voltage level to MCU logic voltage level

Step 2: MCU samples PWM signal at its GPIO pin at random intervals to derive PWM duty cycle

Duty cycle = (Total number of ‘1’ samples) ÷ (Total number of samples)

Measuring Input PWM duty cycle

- Mathematics behind random sampling:
  - One reading of GPIO will yield either logic ‘1’ or ‘0’
  - Therefore, one sample of PWM signal is a Bernoulli trial; where the probability of reading logic ‘1’ is:
    - P(reading a logic ‘1’) = duty cycle of PWM signal
  - For multiple independent samples, this becomes a binomial distribution

Measuring Input PWM duty cycle

- According to Binomial Distribution:
- The proportion of samples with logic '1' = $np/n = p$
- The standard deviation is $(p(1-p)/n)^{1/2}$

Measuring Input PWM duty cycle

- When n is large, Central Limit Theorem states that the binomial distribution can be approximated by a Normal distribution
- Based on approximation to Normal distribution, the relationship between actual mean (p), observed mean (X), standard deviation (σ)and Z, the standard normal distributed variable is:
- $p = X \pm Z\sigma \approx X \pm Z.(X.(1-X)/n)^{½}$
- Hence, the probability that p is outside of above range is defined by the Z, the standard normal distributed variable:
- $1 - P((X - Z\sigma) < p < (X + Z\sigma)) = 1 - P(-Z < z < Z)$

Speed Control Accuracy - Conclusion

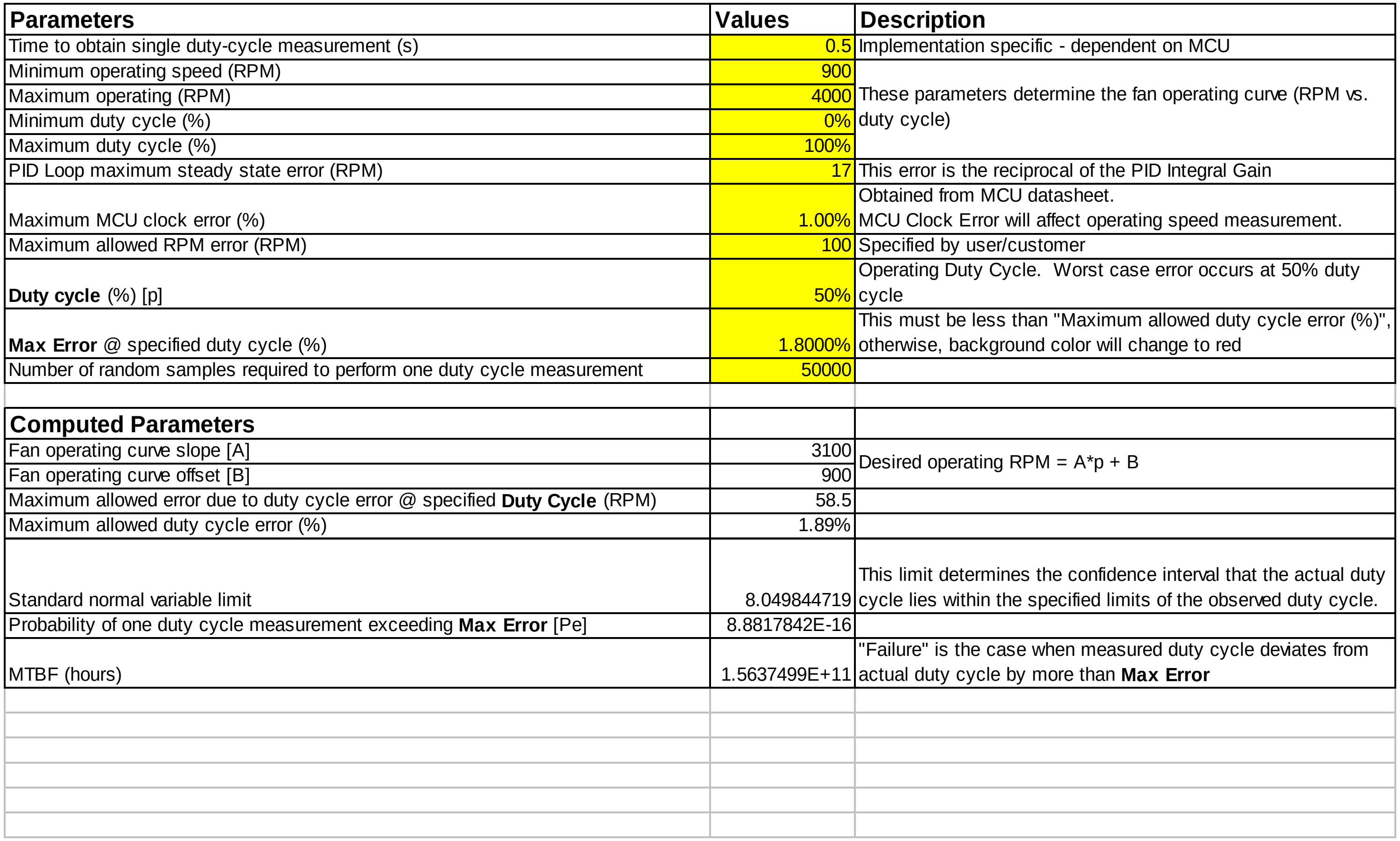
- Error contributions between Input PWM and Output Speed (RPM):
  - Input PWM duty cycle measurement error
  - Output speed measurement error
    - E.g MCU datasheet indicates MCU clock error less than 1% - this will result in up to 1% error in output speed measurement error
  - PID Control Loop steady state error
    - E.g. if the Integral Gain is 0.0722, the maximum steady state error is 1/0.0722 = 13 (rounded down)

Speed Control Accuracy - Conclusion

- Therefore, to achieve a certain output RPM error limit:
  - Duty cycle measurement error + Output speed measurement error + PID steady state error <= Output RPM error limit
  - Duty cycle measurement error <= Output RPM error limit - Output speed measurement error - PID steady state error

Speed Control Accuracy - Conclusion

- We can put all these into a spreadsheet:



Parameters	Values	Description
Time to obtain single duty-cycle measurement (s)	0.5	Implementation specific - dependent on MCU
Minimum operating speed (RPM)	900	These parameters determine the fan operating curve (RPM vs. duty cycle)
Maximum operating (RPM)	4000	
Minimum duty cycle (%)	0%	
Maximum duty cycle (%)	100%	
PID Loop maximum steady state error (RPM)	17	This error is the reciprocal of the PID Integral Gain
Maximum MCU clock error (%)	1.00%	Obtained from MCU datasheet. MCU Clock Error will affect operating speed measurement.
Maximum allowed RPM error (RPM)	100	Specified by user/customer
Duty cycle (%) [p]	50%	Operating Duty Cycle. Worst case error occurs at 50% duty cycle
Max Error @ specified duty cycle (%)	1.8000%	This must be less than "Maximum allowed duty cycle error (%)", otherwise, background color will change to red
Number of random samples required to perform one duty cycle measurement	50000	
Computed Parameters		
Fan operating curve slope [A]	3100	Desired operating RPM = A*p + B
Fan operating curve offset [B]	900	
Maximum allowed error due to duty cycle error @ specified **Duty Cycle** (RPM)	58.5	
Maximum allowed duty cycle error (%)	1.89%	
Standard normal variable limit	8.049844719	This limit determines the confidence interval that the actual duty cycle lies within the specified limits of the observed duty cycle.
Probability of one duty cycle measurement exceeding **Max Error** [Pe]	8.8817842E-16	
MTBF (hours)	1.5637499E+11	"Failure" is the case when measured duty cycle deviates from actual duty cycle by more than **Max Error**

Motor Speed Control Challenges

- Phase commutation efficiency
- Reduce in-rush current
- Over-current limit
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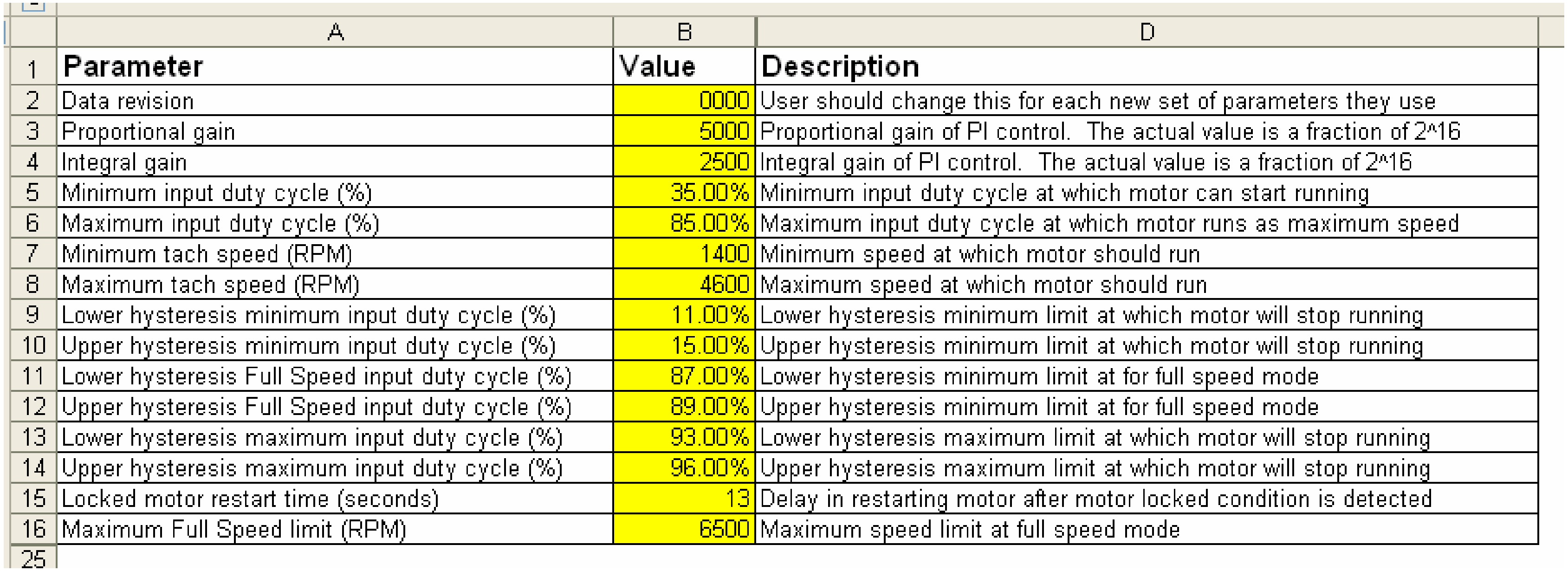
- Tuning motor speed curve

Tuning Motor Speed Curve

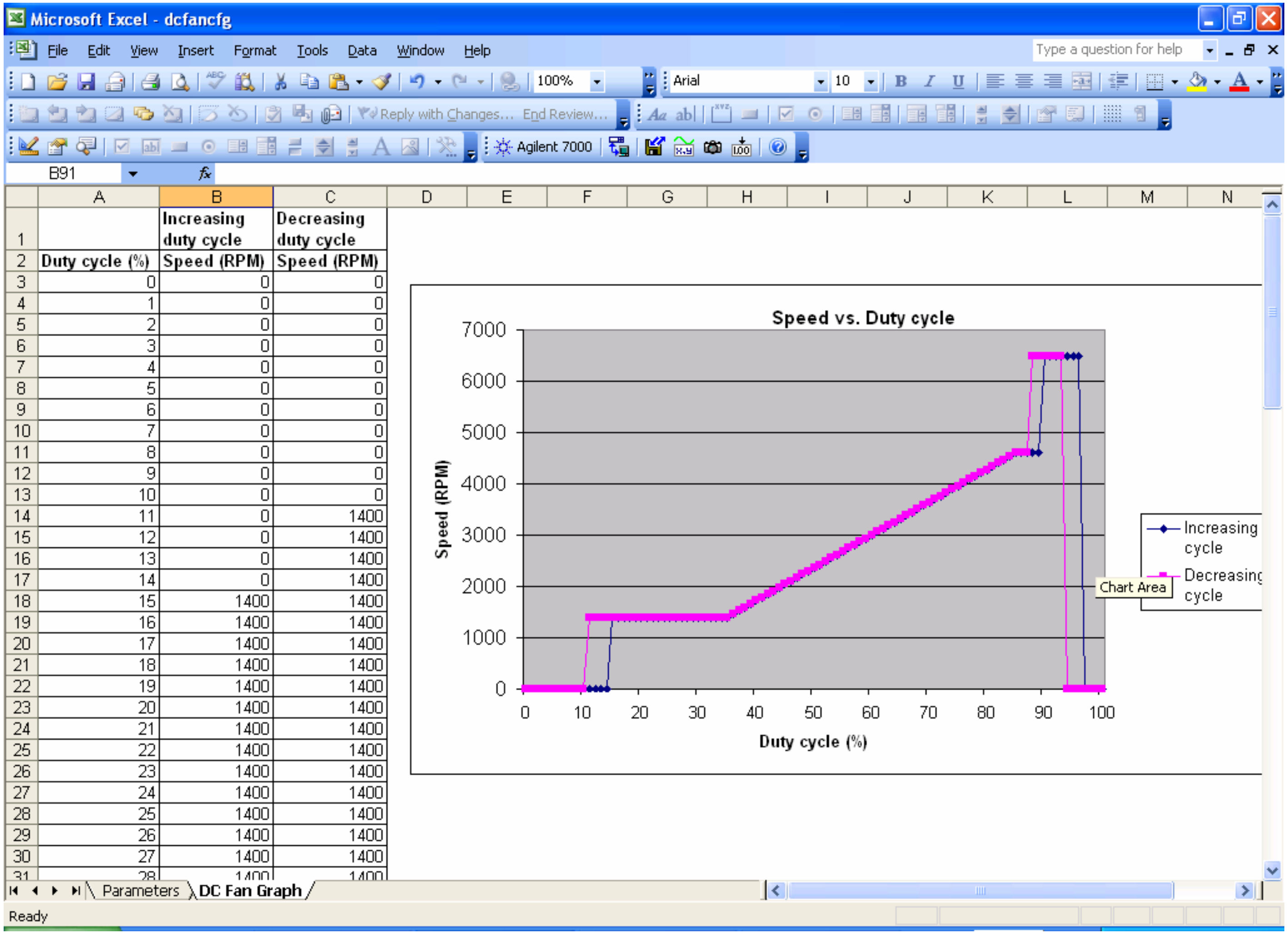
- Must tune quickly to meet customer changing requirements
- Complex motor speed curve requirements
- Avnet’s solution: Configuration by Excel spreadsheet!
  - Easy to use
  - Generates firmware automatically

Tuning Motor Speed Curve



	A	B	D
1	**Parameter**	**Value**	**Description**
2	Data revision	0000	User should change this for each new set of parameters they use
3	Proportional gain	5000	Proportional gain of PI control. The actual value is a fraction of 2^16
4	Integral gain	2500	Integral gain of PI control. The actual value is a fraction of 2^16
5	Minimum input duty cycle (%)	35.00%	Minimum input duty cycle at which motor can start running
6	Maximum input duty cycle (%)	85.00%	Maximum input duty cycle at which motor runs as maximum speed
7	Minimum tach speed (RPM)	1400	Minimum speed at which motor should run
8	Maximum tach speed (RPM)	4600	Maximum speed at which motor should run
9	Lower hysteresis minimum input duty cycle (%)	11.00%	Lower hysteresis minimum limit at which motor will stop running
10	Upper hysteresis minimum input duty cycle (%)	15.00%	Upper hysteresis minimum limit at which motor will stop running
11	Lower hysteresis Full Speed input duty cycle (%)	87.00%	Lower hysteresis minimum limit at for full speed mode
12	Upper hysteresis Full Speed input duty cycle (%)	89.00%	Upper hysteresis minimum limit at for full speed mode
13	Lower hysteresis maximum input duty cycle (%)	93.00%	Lower hysteresis maximum limit at which motor will stop running
14	Upper hysteresis maximum input duty cycle (%)	96.00%	Upper hysteresis maximum limit at which motor will stop running
15	Locked motor restart time (seconds)	13	Delay in restarting motor after motor locked condition is detected
16	Maximum Full Speed limit (RPM)	6500	Maximum speed limit at full speed mode
25			

Tuning Motor Speed Curve



Duty cycle (%)	Increasing duty cycle Speed (RPM)	Decreasing duty cycle Speed (RPM)
0	0	0
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	1400
12	0	1400
13	0	1400
14	0	1400
15	1400	1400
16	1400	1400
17	1400	1400
18	1400	1400
19	1400	1400
20	1400	1400
21	1400	1400
22	1400	1400
23	1400	1400
24	1400	1400
25	1400	1400
26	1400	1400
27	1400	1400
28	1400	1400