DEVCON

Enabling the Smart Society

OCTOBER 22-25, 2012
HYATT REGENCY ORANGE COUNTY

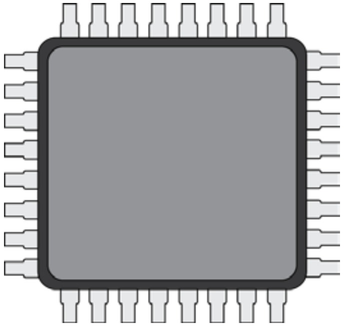
IGBT vs. MOSFET : Which Device to Select?

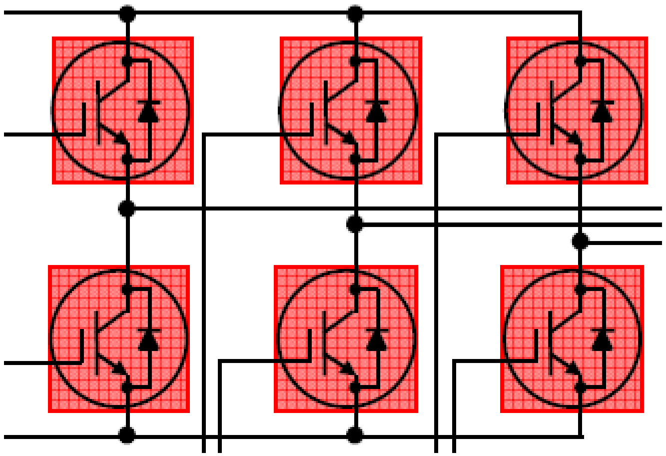
Renesas Electronics America Inc.

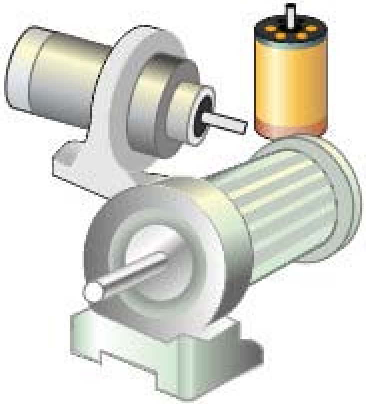
Renesas Technology & Solution Portfolio

‘Enabling The Smart Society’

- Challenge:
  “The challenge of the smart society is to create energy efficient solutions for today’s needs.”







- Solution:

  Our solution is to show you how to select best suited MCU, power devices and sensors for a given application

Discrete and Integrated Power Products

RENESAS MOSFETs

30V-1500V in Application Optimized Processes

- Low voltage family optimized for Qgd x Rds(on)
- Separate family optimized for pure Rds(on) performance
- 600V Super Junction MOSFETs for SMPS

RENESAS Diodes

SiC, Fast Recovery, SBD and Others

- SiC Schottky barrier diodes for very high switching speeds
- 3A to 30A, 600V parts available
- SBD optimized for high switching speeds

RENESAS IGBTs

300V-1350V Discrete Devices

- Class-leading turn-off loss
- High-speed, short-circuit rated, and low Vce(on) optimized using thin wafers
- Multiple package options and bare die option available

RENESAS Power ICs

Optimized for Highest Efficiency & Compactness

- Dr MOS solutions for > 93% peak efficiency, up to 1.5MHz
- PFC ICs for solutions up to 98% peak efficiency
- Smallest CSP packages for POL, Battery Charger and Fuel Gauge Applications

RENESAS TRIACs

Broad Line-up of Packages and Devices

- Current ratings from 0.8A to 30A rms
- Voltage ratings from 600V to 1500V
- Junction temperature to 150° C

Agenda

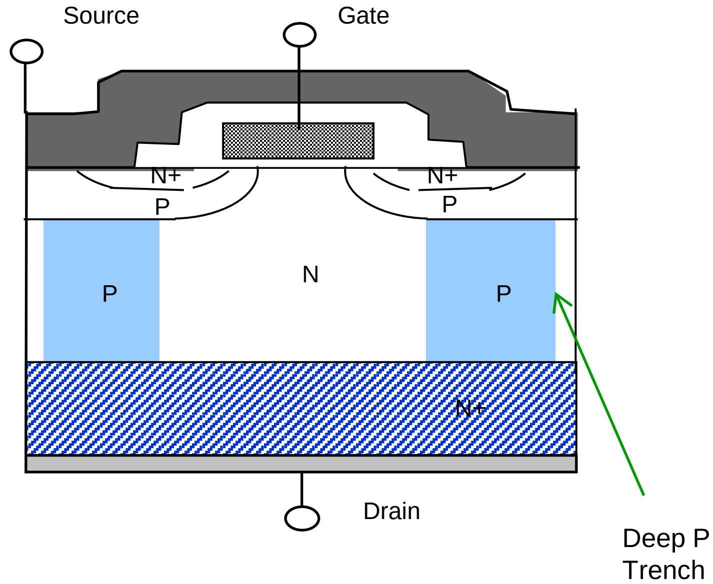
- Section I: Quick Comparison of 600 V MOSFETs and IGBTs
- Section II: The Appliance Motor Inverter
- Section III: Device Selection for a 1 kW Motor Inverter
- Section IV: Conclusion and Q/A

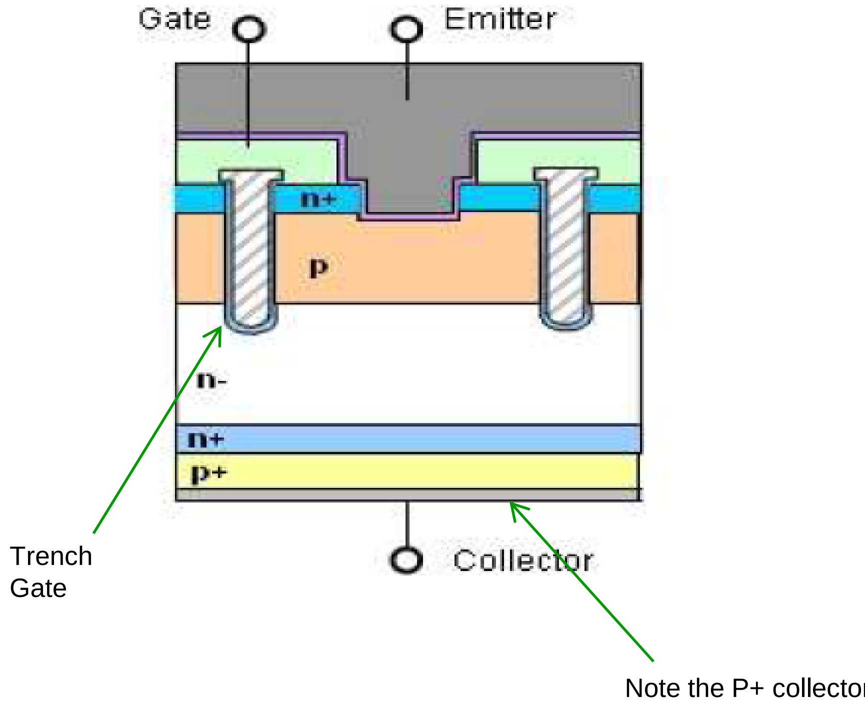
Section I:
Quick Comparison of 600 V MOSFETs & IGBTs

Comparison of 600 V MOSFETs and IGBTs:

- Device Structures
- Key Datasheet Specifications and Significance
- The Underlying Tradeoffs
- Gate Drive Requirements and Considerations
- MOSFET Body Diode Considerations
- When to Use Summary (IGBTs or HV FETs)

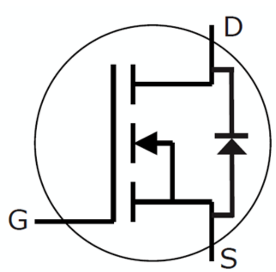
Device Structures



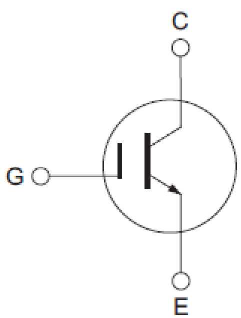


600 V SJ-MOSFET cross section

600 V G6H Trench IGBT cross section



Symbol



Symbol

Source: Renesas

Key Datasheet Specifications: Similarities

Absolute Maximum Ratings

(Ta = 25°C)

Item		Symbol	Ratings	Unit
Drain to source voltage		V_{DSS}	600	V
Gate to source voltage		V_{GSS}	+30, –20	V
Drain current	Ta = 25°C	I_D Note1	55	A
	Ta = 100°C	I_D Note1	34.8	A
Drain peak current		$I_{D\ (pulse)}$ Note1	110	A
Body-drain diode reverse drain current		I_{DR} Note1	55	A
Body-drain diode reverse drain peak current		$I_{DR\ (pulse)}$ Note1	110	A
Channel dissipation		Pch Note2	416.6	W
Channel to case thermal impedance		θch-c	0.3	°C/W
Channel temperature		Tch	150	°C
Storage temperature		Tstg	–55 to +150	°C

Notes: 1. Limited by Tch max.
2. Value at Tc = 25°C

MOSFET (RJK60S8DPK)

Key Datasheet Specifications: Similarities

Absolute Maximum Ratings

(Tc = 25°C)

Item		Symbol	Ratings	Unit
Collector to emitter voltage		V_{CES}	600	V
Gate to emitter voltage		V_{GES}	±30	V
Collector current	Tc = 25°C	I_C	90	A
	Tc = 100°C	I_C	50	A
Collector peak current		ic(peak) [Note1]	180	A
Collector to emitter diode forward peak current		i_{DF}(peak) [Note2]	100	A
Collector dissipation		P_C	328.9	W
Junction to case thermal impedance (IGBT)		θj-c	0.38	°C/W
Junction to case thermal impedance (Diode)		θj-c	2.0	°C/W
Junction temperature		Tj	150	°C
Storage temperature		Tstg	–55 to +150	°C

Notes: 1. Pulse width limited by safe operating area.

2. PW ≤ 5 μs, duty cycle ≤ 1%

IGBT (RJH60F7DPK)

Key Datasheet Specifications: Differences

Electrical Characteristics

(Ta = 25°C)

Item	Symbol	Min	Typ	Max	Unit	Test conditions
Static drain to source on state resistance	$R_{DS(on)}$	—	0.045	0.056	Ω	I_D = 27.5 A, V_{GS} = 10 V Note4
	$R_{DS(on)}$	—	0.117	—	Ω	Ta = 150°C I_D = 27.5 A, V_{GS} = 10 V Note4

MOSFET (RJK60S8DPK)

On state **Resistance**

Collector to emitter saturation voltage	$V_{CE(sat)}$	—	1.35	1.75	V	I_C = 50 A, V_{GE} = 15V Note3
	$V_{CE(sat)}$	—	1.6	—	V	I_C = 90 A, V_{GE} = 15V Note3

IGBT (RJH60F7DPK)

On state **Forward Voltage drop**

Body-drain diode forward voltage	V_{DF}	—	1.0	1.6	V	I_F = 55 A, V_{GS} = 0 Note4
Body-drain diode reverse recovery time	t_{rr}	—	540	—	ns	I_F = 55 A V_{GS} = 0 di_F/dt = 100 A/µs
Body-drain diode reverse recovery current	I_{rr}	—	28	—	A	
Body-drain diode reverse recovery charge	Q_{rr}	—	9.3	—	µC	

MOSFET (RJK60S8DPK)

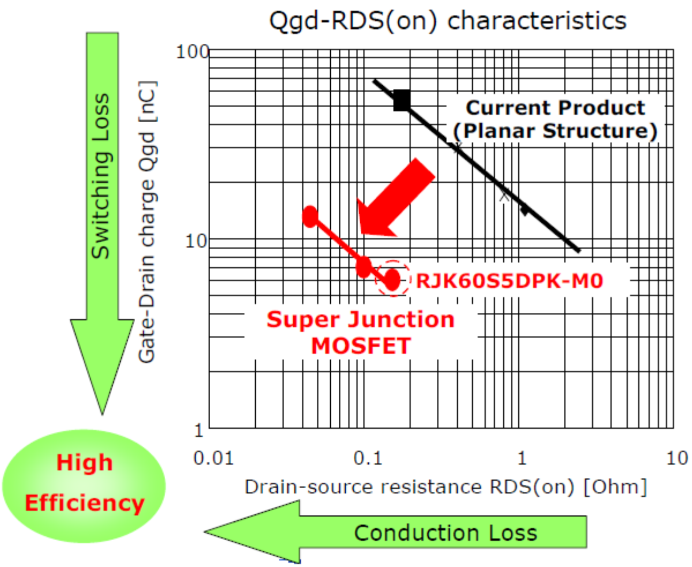
Body Diode Characteristics

C-E diode forward voltage	V_{ECF1}	—	1.6	2.1	V	I_F = 20 A Note3
C-E diode reverse recovery time	t_{rr}	—	140	—	ns	I_F = 20 A di_F/dt = 100 A/µs

IGBT (RJH60F7DPK)

Discrete FRD Characteristics

The Key Underlying Tradeoffs



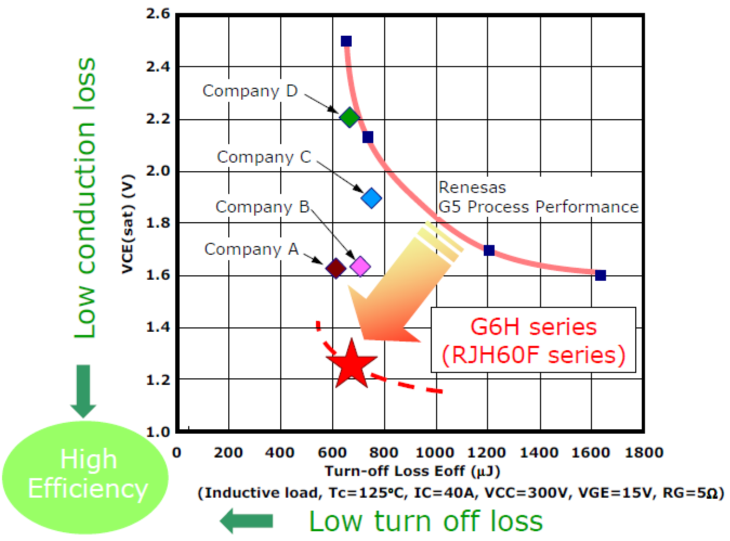
MOSFET Optimization

A key MOSFET design goal is to minimize Rds(on) * Qgd

=> Minimum conduction + Switching Loss

A key IGBT design goal is to minimize Vce(sat) * Eoff

=> Minimum conduction + Switching Loss



IGBT Optimization

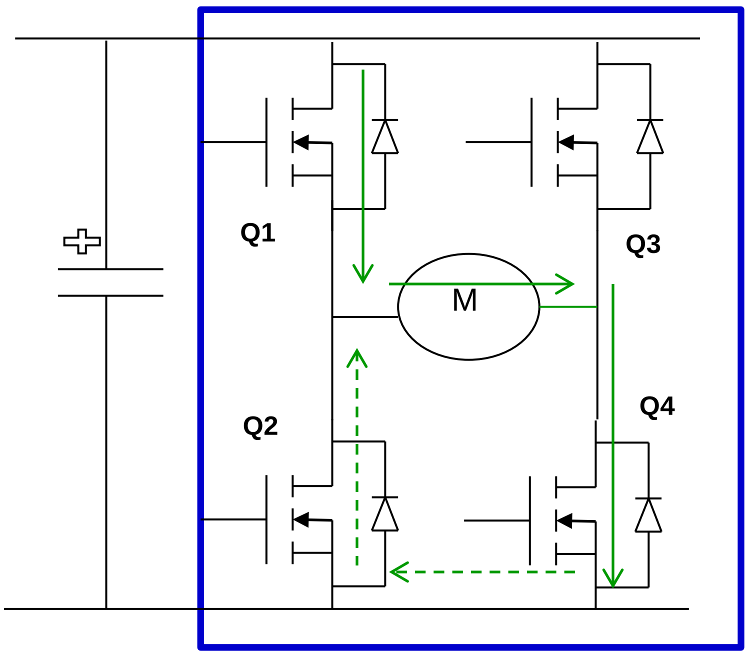
Gate Drive Requirements and Considerations

- Total Gate Charge (Qg)
  - Generally higher for HV MOSFETs (larger die compared to IGBT, for same current rating)
- Turn on gate resistors
  - Generally higher values used for IGBT (lower input capacitance compared to HV MOSFETs)
- Gate Drive Voltage
  - Higher (15 V) preferred for IGBT, 10 V is ok for HV MOSFETs
- Negative Gate Drive Voltage
  - Generally not needed for HV MOSFETs, sometimes used for older process IGBTs

MOSFET Body Diode dv/dt Considerations

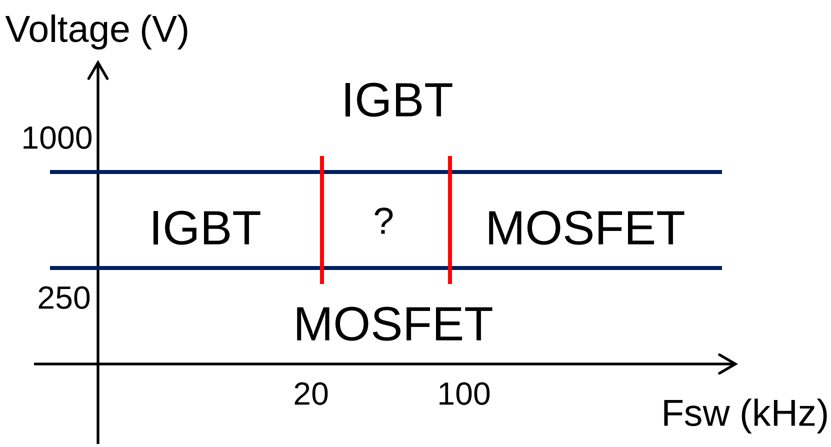
Use of the MOSFET body diode:

- Initially Q1 and Q4 are conducting
- Q1 is turned off, body diode of Q2 starts to conduct
- Q1 is switched on again at the next pulse, Q2 body diode has to recover
- This adds to the switching loss in the devices (Q1 and Q2), and causes ringing on the current and voltage waveforms
- Also, the rate at which Q1 turns on has to be controlled or limited (to be within the specified diode recovery dv/dt)



Typical H bridge Motor Drive Circuit

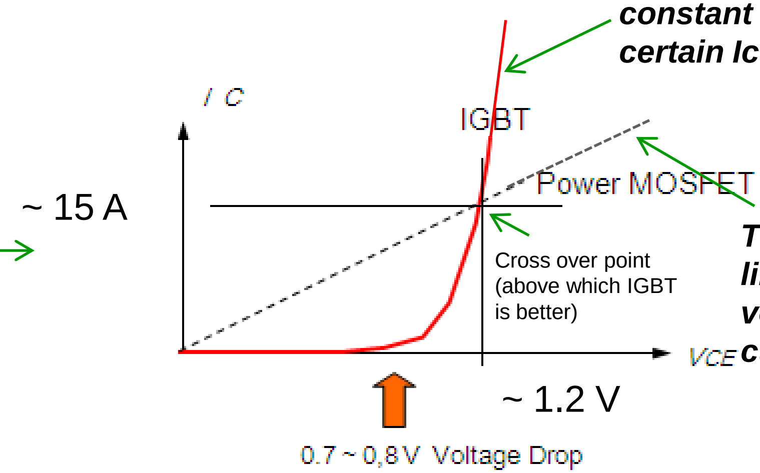
When to Use Summary: Device Perspective



Switching Frequency and Voltage Level Considerations

The IGBT saturates with an almost constant forward drop above a certain Ic

Forward Drop (Conduction Loss) Considerations



The MOSFET essentially has a linear increase of on state voltage with drain current

When to Use Summary: Conditions Based

- Low Switching Frequency (<20kHz)
- High Power levels (above say 3 kW)
- High dv/dt needed to be handled by the diode
- High full load Efficiency is needed

IGBT Preferred..!

- High Switching Frequency (>100kHz)
- Wide line and load conditions
- dv/dt on the diode is limited
- High light load efficiency is needed

MOSFET Preferred..!

When to Use Summary: Applications Based

- Motor Drives (>250W)
- UPS and Welding H Bridge inverters
- High power PFCs (>3kW)
- High Power Solar/Wind Inverters (>5kW)

IGBT Preferred..!

- Motor Drives (<250W)
- Universal input AC-DC flyback and forward converter power supplies
- Low to Mid power PFCs (75W to 3 kW)
- Solar Micro Inverters

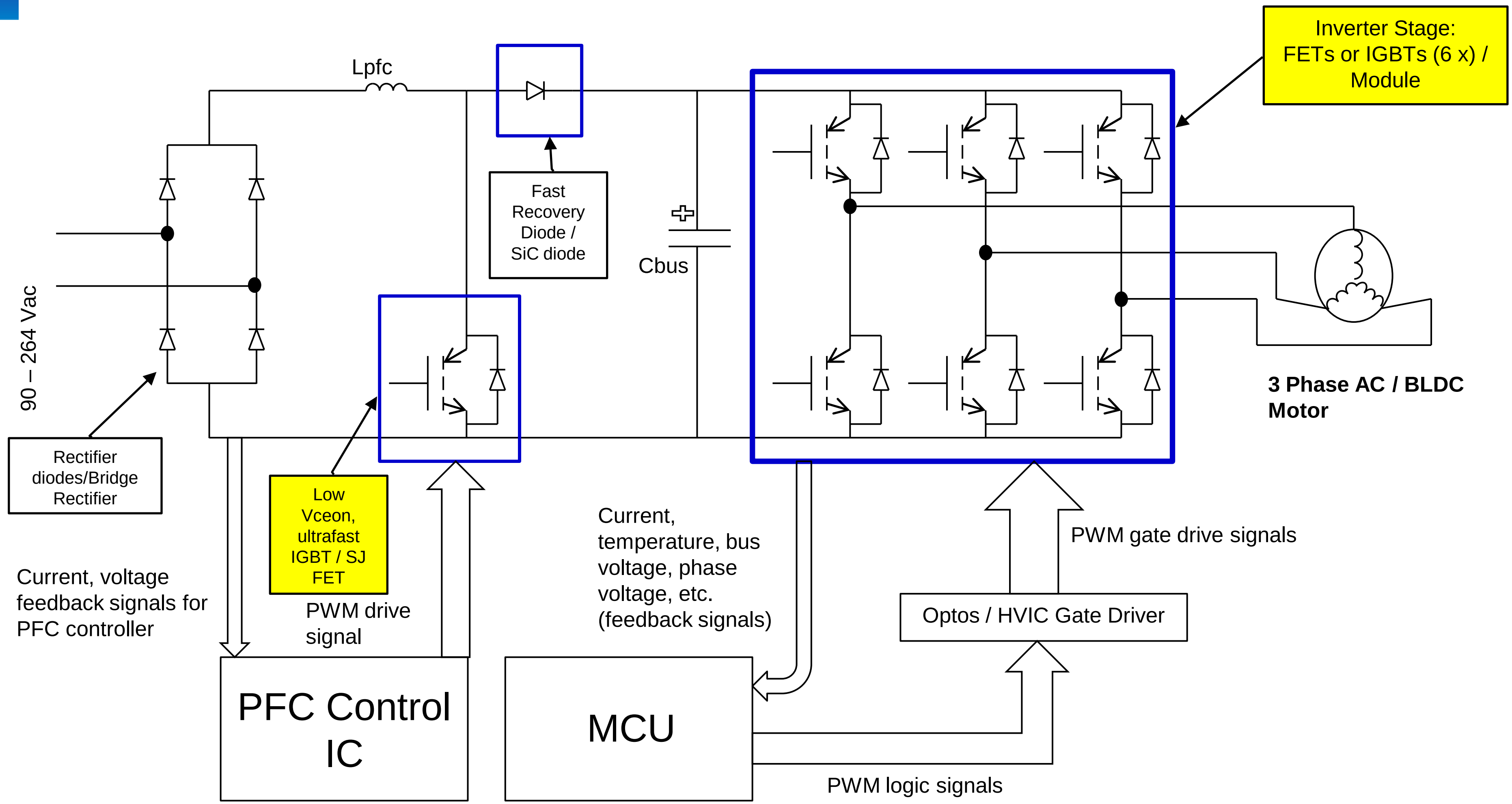
MOSFET Preferred..!

Section II: The Appliance Motor Inverter

The Appliance Motor Inverter:

- Typical Motor Inverter Block Diagram
- The PFC stage:
  - Types of PFC Designs: CCM and CRM; Single and Interleaved
  - IGBT or MOSFET Selection for the PFC Stage
- The Inverter Power Stage:
  - Key Power Components
  - IPM (Intelligent Power Module vs. Discrete Approach)
  - The Fast Body Diode MOSFET
  - IGBT vs. MOSFET for the Inverter Stage
  - Some General Comments

Typical Appliance Motor Inverter Block Diagram



The PFC Stage: IGBT or SJ-MOSFET

Some Key Application Conditions and Device Requirements

CCM (Continuous Conduction Mode) Topology

Application Conditions	Device Requirements
Typical Power Range is 1 kW to 4 kW	High average currents, large die / package devices
Typical Switching Frequency : 25 kHz to 150 kHz	At lower levels IGBTs, at higher levels MOSFETs preferred
Typically Devices are Hard switched	Fast switching capabilities essential
Typically lower inductor current ripple	Less stressful for the device

CRM (Critical Conduction Mode) Topology

Application Conditions	Device Requirements
Typical Power Range is 100 W to 1 kW	Relatively smaller die / package devices could be considered
Typical Switching Frequency range is wide (50 kHz to 300 kHz)	Almost always MOSFETs are used
Typically Devices are Soft switched at turn on and hard switched turn off	Low Rdson is as important as gate charge
Typically higher inductor current ripple	More stressful for the device

The Inverter Stage: IGBT or FET

Some Key Application Conditions and Device Requirements

Application Conditions/Requirements		IGBT (with FRD) or HV FET
Power Level	75 W to 200W	Fast Body Diode FET preferred
	500 W to 5 kW	IGBT is preferred
	200 W to 500 W	Could be either, based on cost, target efficiency, etc.
PWM Frequency	Few kHz to say 25 kHz	IGBT is generally preferred
	Above say 25 kHz	Also depends on power level, but a Fast body diode FET may be preferred

The Inverter Stage: IGBT or FET

Some Key Application Conditions and Device Requirements

Application Conditions/Requirements	IGBT (with FRD) or HV FET
Diode Recovery Loss Important	IGBT (with fast recovery diode co-packaged) preferred
High Light load efficiency requirement	Fast Body Diode FET preferred
Lowest device cost	IGBT (with FRD) typically preferred

Section III: A 1 kW Appliance Motor Inverter

A 1 kW Appliance Motor Inverter:

- Defining The Design Requirements:
  - The PFC Stage
  - The Inverter Stage
- Device Selection for the PFC stage:
  - Understanding the Design Requirements
  - A loss Analysis Exercise
  - Selecting a suitable device
- Device Selection for the Inverter Power Stage:
  - Understanding the Design Requirements
  - A loss Analysis Exercise
  - Selecting a suitable device

Defining the Design Requirements: PFC Stage

PFC Application Details			
Parameter/Specification	**Value**	**Units**	**Comments**
Vin_min	85	Vrms	minimum ac input voltage
Vin_max	265	Vrms	maximum ac input voltage
P_out	1000	W	Rated Output Power
V_dc	400	Vdc	DC Bus Voltage
Fsw	100	kHz	PWM switching frequency
Circuit Topology Preference	Single		One phase OR dual phase interleaved
Circuit Mode (CCM, CRM)	CCM		CCM = Continuos Conduction Mode, CRM = Critical Conduction Mode)
Package Preference for IGBT/FET and Diode	TO247		TO220, TO247, D2pak, etc.
Worst case ambient temperature	45	deg C	
Worst case heat sink temperature	100	deg C	
Target Efficiency at 20% load	90	%	
Target Efficiency at 50% load	> 90	%	
Target Efficiency at 100% load	> 90	%	
Any Special Requirements..?	--		Tight Board layout, yes/no air flow, inrush current withstanding needed, …

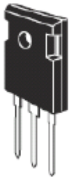
User Inputs

Device Selection for the PFC Stage

- Understanding the Design Requirements and First Pass Selection:
  - The Topology is CCM => Hard switching, High Speed capability needed
  - The switching Frequency is 100kHz => High for an IGBT, better suited for MOSFET
  - The Power Level is 1kW => Better suited for MOSFET
  - The DC bus voltage is 400V (nominal) =>600V rated device would be advisable

Looking at the Product Matrix of 600V, SJ-MOSFETs in TO247 package, we select the RJK60S5DPQ, and RJK60S7DPQ:

PKG	P/N	VDSS [V]	ID [A]	RDS(on) [Ω] Typ./Max	Qg typ. [nC]
TO-247	RJK60S5DPQ-E0	600	20	0.15/0.178	27
	RJK60S7DPQ-E0	600	30	0.10/0.125	39



TO-247
(RJK60S5**DPQ**-E0)

Device Selection for the PFC Stage

Datasheet Comparison:

BVdss	P/N	Rdson,max	Qg,typ	Qgd,typ	Rthjc,max	FOM1	FOM2
(V)		(mOhm)	(nC)	(nC)	(C/W)	Rds*Qg	Rds*Qgd
600	RJK60S5DPQ	178	27	8.5	0.65	**4806**	**1513**
600	RJK60S7DPQ	125	39	11	0.55	**4875**	**1375**

Notes:

1. FOM1,2 = Figures of Merit 1 => this reflects the impact of the on resistance and gate charge on the total losses (Rdson -> conduction loss; Qg, Qgd -> switching loss)
2. The lower the FOM, the lower the total loss, and potentially the better the device performance (in terms of overall system efficiency and device operating temperature)

Device Selection for the PFC Stage

Estimated Device Loss and Operating Tj Summary:

RJK60S7DPQ		
Pout	Loss (W)	Tj (deg C)
1000	39.8	121.9
750	26.2	114.4
500	15.1	108.3
250	6.32	103.5

RJK60S5DPQ		
Pout	Loss (W)	Tj (deg C)
1000	39.8	125.9
750	25.1	116.3
500	13.5	108.8
250	5.14	103.3

Summary:

1. The S7 is a larger die, with lower Rdson, and benefits by way of its lower thermal impedance in terms of lower operating Tj.
2. The losses are about the same at full load but actually lower for the S5 device at lighter loads; this is due to lower gate charge => lower switching loss.
3. If lowest operating Tj is the key design goal (for longest operating life expectancy), then the S7 is a better option.
4. In terms of loss and for a lower cost target, the S5 is a better option to consider.

Defining the Design Requirements: Inverter Stage

Motor Inverter Application Details			
Parameter/Specification	**Value**	**Units**	**Comments**
Motor Type	3 ph, ACIM		AC Induction, BLDC, PMSM
Rated Power	1 kW	kW/hp	1 hp = 0.75 kW
Rated rms current/phase	2.6	Arms	
Rated rms voltage/phase	127	Vrms	
PWM switching frequency	20	kHz	
Maximum DC bus voltage	400	Vdc	
Maximum Ambient Temperature	45	deg C	
Maximum Heat Sink*/PCB Copper Temperature	105	deg C	*In case devices are heat sinked
Package preference for the IGBT/FET	D2pak		TO220, TO247, D2pak, Dpak, etc.
Gate Driver sourcing/sinking current rating	1	A	This is usually specified on the gate driver's datasheet
Maximum or Blocked Rotor current	10	Arms	
Maximum or Blocked Rotor current duration	1	s	
Any Special Requirements, Considerations	5	us	No/Yes Air flow available, 10 us short circuit rating needed, etc.
Notes:			
BLDC = Brushless DC			
PMSM = Permanent Magnet Synchronous Motor			

User Inputs

Device Selection for the Inverter Stage

- Understanding the Design Requirements and First Pass Selection:
  - Power level is 1kW => IGBT preferred
  - Fsw is 20kHz => Better suited for IGBT
  - DC bus voltage is 400V (nominal) => 600V rated device is advisable
  - Diode recovery loss important => IGBT (with FRD) preferred
  - A 5 us short circuit capability is desired => A SC rated IGBT (or MOSFET)
  - Lower Device Cost is needed => IGBT is preferred

Looking at the Product Matrix of 600V, G6H Trench, 5 us rated IGBTs in D2pak (LDPAK-S) package, we select the RJH60D2DPE, and RJH60D2DPE:

P/N	VCES (V)	Ic (A)		IGBT					Diode			Package
				$V_{CE(sat)}$ (V)		tf(ns)		tsc(μs)	IF(A)	V_F(V)	trr (ns)	
		25℃	100℃	typ.	Ic(A)	typ.	Ic(A)	typ.	25℃	typ.	typ.	
RJH60D2DPE	600	25	12	1.7	12	80	12	5	12	1.2	100	LDPAK-S
RJH60D3DPE	600	35	17	1.6	17	80	17	5	17	1.3	100	LDPAK-S

Device Selection for the Inverter Stage

Estimated Device Loss and Operating Tj Summary:

RJH60D2DPE		
Pout	Loss (W)	Tj (deg C)
1000	2.5	109.9
750	1.6	108.2
500	0.96	106.9
250	0.46	105.9

RJH60D3DPE		
Pout	Loss (W)	Tj (deg C)
1000	2.2	107.4
750	1.5	106.7
500	1.0	106.1
250	0.6	105.7

Summary:

1. The D3 is a larger device and benefits by way of its lower thermal impedance in terms of lower operating Tj.
2. The losses are about the same at half load but lower for the S5 device at lighter loads; this is due to lower switching loss component compared to conduction loss.
3. Given the similar loss and operating Tj at > 50% load and lower loss at lighter loads with similar operating Tj, the D2 is a better option to consider, particularly if cost is a key factor as well.

Section IV: Conclusion and Q/A

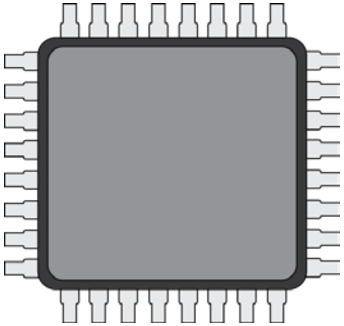
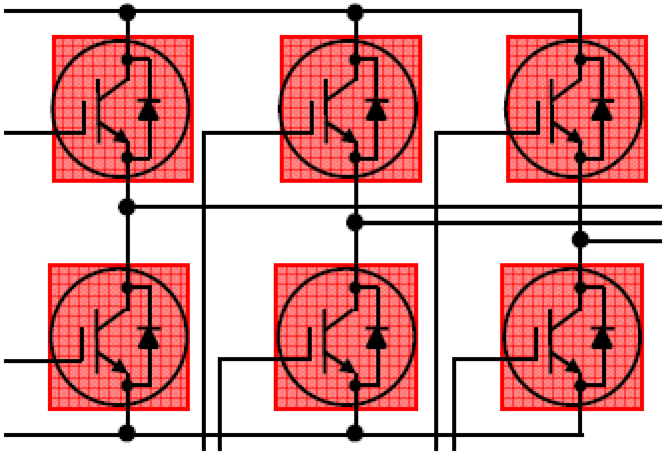
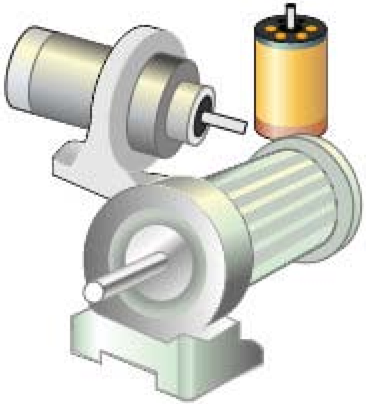
Conclusion:

- IGBTs and HV MOSFETs are similar in many ways but differ from a performance and application perspective
- A one size fits all approach does not work
- The best device is the one that best meets the application needs in terms of size, efficiency and Amps/$ capability..!

Questions?

‘Enabling The Smart Society’

- Challenge:
  “The key challenge is to enable a smart and energy efficient solution for a given application using the best suited MCU, Power Devices and sensors.”

- Conclusion:

  This class showed you how to select best suited Power Device for a typical 1 kW appliance inverter application

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Appendix Slides:

1. Loss Analysis Tool for PFC switch selection

2. Loss Analysis Tool for Inverter Switch selection

Device Selection for the PFC Stage

PFC switch Loss Calculator for RJK60S7DPQ			
Parameter	Value	Units	Comments
Vin(min)	85	Vac	Minimum ac rms line voltage
Vin(max)	265	Vac	Maximum ac rms line voltage
Vdc(nominal)	400	Vdc	DC Bus voltage
Theatsink/pcb	100	deg C	Maximum heat sink or PCB copper temperature
Fsw	100	kHz	PWM Switching Frequency
Pout	1000	W	Rated Output Power
Target η	95	%	Target Efficiency at rated load
Pin	1052.631579	W	Calculated input power (maximum)
Iac_rms_max	12.38390093	Arms	Maximum input ac rms current
Isw_rms	10.68606696	Arms	MOSFET maximum rms current
Isw_peak	15.11009869	Adc	MOSFET maximum peak current
Isw_peak_ave	5.036699562	Apeak	MOSFET equivalent peak current (for switching loss calcution)
Rds_hot	170	mOhm	MOSFET On resistance at 150 C
Qg_typ	39	nC	Typical Gate Charge From Datasheet
Qg_max	50.7	nC	Estimated Maximum Gate Charge (30% guard banding assumed)
Ig_min_src	1.5	A	From IC or gate driver datasheet
Ig_min_sink	1.5	A	From IC or gate driver datasheet
Trise	33.8	ns	Calculated Rise Time
Tfall	33.8	ns	Calculated Fall Time
Pcond	19.41264461	W	Calculated Conduction loss in MOSFET
Psw	20.42885342	W	Calculated Switching Loss in MOSFET
Ptot	**39.84149804**	W	Total Loss in MOSFET (Pcond+Psw)
Rthjc	0.55	deg C/W	From MOSFET datasheet
Tj_calc	**121.9128239**	deg C	Calculated Junction Temperature
Tj_max	150	deg C	Allowed Maximum junction Temperature
Check	**YES**	Yes/No	Device temperature within allowed maximum?

Notes:

1) Reference for Equations: Table 18.3, Fundamentals of Power Electronics, 2nd Ed, Robert W. Erickson

2) Color Code:

User Inputs

From Datasheet

Calculation/Result

3) For purposes of the switching loss calculation, I estimated an average switch current value of 1/3 of the peak switch current

Loss Estimator Tool (example snapshot of S7DPQ at 100% load)

Device Selection for the Inverter Stage

RJH60D2DPE

Appliance Motor Inverter IGBT Selector and Loss Estimator Tool			
Prated	1000	W	
Vbus	400	V	
Vrms_phase	127	Vrms	
Irms_max_phase		Arms	If provided
PF	0.9		
Irms_calc_phase	2.916302129	Arms	Estimated
Ipeak_calc_phase	4.12365121	Apeak	Estimated
Fsw	20	kHz	
V_test	300	V	
MI	0.8		Modulation Index
Iswitch_ave	1.027342996	A	
Iswitch_rms_square	14.94831525	A^2	
Idc_for_loss_calc	1.312428775	A	
Vcezero	1	V	
Vcesat_hot	2.2	V	
Icsat_hot	25	A	
Rceon	0.088	Ohms	
Eon_25C_DS_Iswpeak	2	uJ	
Eoff_25C_DS_Iswpeak	18	uJ	
Eon_hot_est_Vscaled	3	uJ	
Eoff_hot_est_Vscaled	2.8125	uJ	
Psw	0.11625	W	
Pcond	2.342794738	W	
Ptot	**2.459044738**	W	
Tcase	105	C	
Rthjc	1.98	C/W	
Tj	**109.8689086**	C	

A Loss Analysis Tool