OLLSCOIL NA hÉIREANN, CORCAIGH
THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2011

B.E. DEGREE (ELECTRICAL)

POWER ELECTRONICS, DRIVES AND ENERGY CONVERSION
EE4001

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Time allowed: *3 hours*

Answer *four* out of five questions.
All questions carry an equal weighting of 20 marks.

The use of departmental-approved non-programmable calculators is permitted.

1. Induction Motor Characterization

(a) The specification table for Westinghouse induction motors is provided as an attachment. Consider the **450** kW, **four**-pole machine with 400 V (line-line), 50 Hz applied in the delta configuration.
(i) Estimate the per-phase equivalent circuit parameters: R_R', P_{CFW}, L_{LS}, L_{LR}', and L_M.
(ii) Based on the calculated parameters, estimate the real power that would be measured during the no-load test at rated voltage and frequnecy. (This part of the question is worth 2 marks)
Assume $R_S = 10\ \text{m}\Omega$ and L_{LS} equals L_{LR}' for this class of machine.

[10 *marks*]

(b) A four-pole star-connected induction motor used in an electric vehicle application has the following per-phase equivalent circuit parameters:
R_S = 11.8 mΩ, L_{LS} = 0.0972 mH, L_M = 2.0 mH, L_{LR}' = 0.0772 mH, R_R' = 12.9 mΩ, P_{CFW} = 2.3 kW
At the rated condition, the motor acts as a **generator** with an applied torque to the rotor shaft of -40 Nm at 6055 rpm, when supplied by a current-controlled inverter at 200 Hz.
Determine the input per-phase voltage and current, power factor, and efficiency at this operating point.

[10 *marks*]

2. Induction Motor Speed Control

(a) Sketch the wiring diagram for the star-delta starter for inrush control of the induction machine.

[4 *marks*]

(b) Consider the Westinghouse 75 kW, 6-pole machine delta-wired to 400 V (line-line), 50 Hz.

(i) What are the initial starting line current and torque for a direct-on-line start?

A volts/hertz controller with voltage boost is integrated into the delta-wired drive. The series resistance is estimated to be 80 mΩ.

(ii) Determine approximate values for the starting frequency, line voltage and current in order to supply the specified starting torque.

(iii) Determine approximate values for the line voltage and current and power factor required to ensure constant-power operation of the machine at twice the rated speed.

(iv) Determine approximate values for the line voltage and current and power factor required to ensure constant-power operation of the machine at twice the rated speed when operating as a **generator**.

(v) Determine the dc link voltage required to operate at the rated conditions under sinusoidal PWM.

Use the formula $slope = \dfrac{V_{ph,rated} - R_S \cdot I_{R,rated}'}{f_{rated}}$ for low-voltage boost.

[16 *marks*]

3. AC Machines Space Vectors and Vector Control of the Induction Motor

(a) The specification sheet for the TK 164-250-09 12-pole permanent magnet motor is attached.
(i) Estimate the no-load core, friction and windage losses and determine the per-phase no-load current.
(ii) Under full-load determine the applied per-phase current and voltage, power factor for the full power condition under water cooling: 13.92 kW output power at 173.99 rad/s. Note that the specified winding parameters are twice the per-phase parameters.
(iii) Determine the flux linkage of the stator d-winding due to the flux produced by the rotor magnets, λ_{fd}. Assume that the d-axis is aligned with the rotor magnetic axis.
Apply the following formulae:

$$T_{EM} = 3 \cdot k \cdot I_{ph(rms)} = \frac{P}{2}\lambda_{fd} i_{sq} \text{ and } E_{ph(rms)} = k \cdot \omega$$

(b) A four-pole star-connected induction motor used in a servo application has the following per-phase equivalent circuit parameters:
R_S = 20 mΩ, L_{LS} = 0.2 mH, L_M = 7.2 mH, L_{LR}' = 0.3 mH, and R_R' = 35 mΩ.
At the rated condition of 400 V line-line, 50 Hz, the machine is acting as a **generator** and outputs 225 A at a power factor of -0.841. At time t = 0, the machine is in steady state.
(i) Taking the per-phase input voltage as the reference, calculate the per-phase rotor current phasor and the per-phase rotor flux-linkage phasor.
(ii) Align the d-axis with the rotating rotor flux linkage state vector and calculate the rotor and stator current space vectors.
(iii) Calculate the input currents i_{sd} and i_{sq} and the electromagnetic torque.

$$\vec{i}_s = \frac{3}{2}\sqrt{2} I_s \angle\theta_{Is} = \sqrt{\frac{3}{2}}\left(i_{sd} + j i_{sq}\right); \quad \vec{\lambda}_r(t) = -L_r \vec{i}_r(t) + L_m \vec{i}_s(t); \quad T_{em} = \frac{P}{2}\lambda_{rd} i_{rq}$$

[20 *marks*]

4. Power Electronics Converters

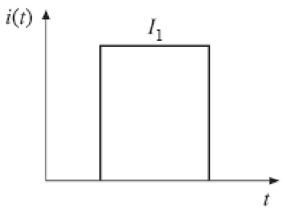
(a) A 40 kHz forward converter, is supplied by $V_d = 380$ V, and outputs 5 V at 100 A. Maintain the maximum duty cycle at no greater than 0.45, and allow for a 0.4 drop across the output diode.
(i) Sketch the circuit.
(ii) Calculate the transformer turns ratio, output inductance, and rms inductor current, if the output inductor has a 10 % peak-to-peak current ripple.
(ii) Calculate the average and rms currents in the primary if the magnetizing current is 1 A peak. Reference the information below on rms values.

[10 *marks*]

(b) The Gen II Toyota Prius uses a 20 kW bidirectional converter to generate a 500 V dc link voltage, V_D, from the 200 V NiMH battery pack, V_{BP}. The bidirectional converter has an inductance of 435 uH and switches at 10 kHz.
The vehicle is operating in generating mode and the bi-directional converter is required to act as a buck at full power.
At 2 kW, or 10 % of rated load, determine the average and rms currents in the inductor, switch and diode, and output capacitor. Reference the information below on rms values.

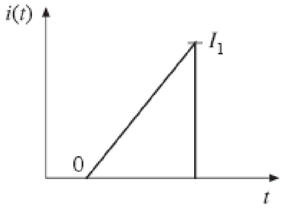
The duty cycle during DCM is given by $D = \sqrt{\frac{V_{BP}}{V_D\left(V_D - V_{BP}\right)} 2\, f\, L\, I_{BP}}$

[10 *marks*]



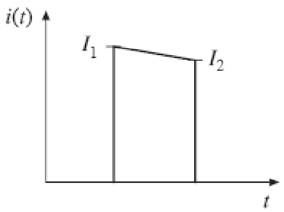
Constant segment

$$u_k = I_1^2$$



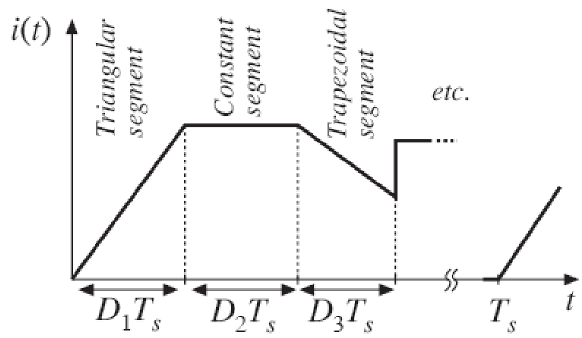
Triangular segment

$$u_k = \frac{1}{3} I_1^2$$



Trapezoidal segment

$$u_k = \frac{1}{3}\left(I_1^2 + I_1 I_2 + I_2^2\right)$$



$$rms = \sqrt{\sum_{k=1}^{n} D_k u_k}$$

5. **Power Semiconductors**

(a) A new power MOSFET and SiC diode package (from manufacturer *IXYS*) operates in a boost converter switching at 20 kHz, with a dc link voltage V_d = 380 V, and load current I_o = 12 A.

The device characteristics are as follows: threshold voltage $V_{GS(th)}$ = 3 V, drain current I_D = 12 A at gate voltage V_{GS} = 4.2 V, gate-source capacitance C_{gs} = 2000 pF, gate-drain capacitance C_{gd} = 40 pF, and on-state resistance $R_{DS(on)}$ = 0.3 Ω. The MOSFET is driven by an ideal voltage-source square wave v_{GG}, of amplitude 0 V to 10 V, in series with an external gate resistance R_G = 10 Ω. Assume a 1.5 V diode forward drop and no reverse recovery.

(a) Sketch $v_{GG}(t)$, $v_{GS}(t)$, $v_{DS}(t)$, $i_D(t)$ during turn-on of the MOSFET.

(b) Calculate the following (i) turn-on delay time $t_{d(on)}$, (ii) current rise time t_{ir}, (iii) voltage fall time t_{fv}. Sketch the basic switching circuit under analysis in each case.

(c) Calculate the turn-on energy loss.

(d) If the converter is switching at 200 kHz, what is the temperature rise of the MOSFET due to turn-on switching losses alone if the MOSFET has a thermal resistance from junction to heatsink of 1.35 °C/W.

Useful formulae: RC charge time $t = -RC\ln\left[1 - \frac{v_c - V_{ci}}{V_{GG} - V_{ci}}\right]$ RC discharge time $t = -RC\ln\left[\frac{v_c - (-V_{GG})}{V_{ci} - (-V_{GG})}\right]$

[10 *marks*]

(b) The 2005 Lexus RX400h hybrid vehicle uses a bidirectional converter to generate a 650 V dc link voltage from the 288 V NiMH battery. The bidirectional converter has an inductance of 245 µH and switches at 10 kHz.

The rms of a triangular wave is $\Delta I_{P-P} \div \sqrt{12}$.

(i) Determine the output current and power at the boundary between CCM and DCM when the vehicle is operating in braking\generating\buck mode.

(ii) Calculate the maximum, minimum, rms, and average currents in the IGBT and diode for the boundary condition.

(i) Determine the typical power loss at 125 C due to conduction and switching in the IGBT for the boundary condition when using the SEMiX252GB126HDs as the half-bridge module.

[10 *marks*]

75kW-450kW TEFC, CLASS F, S1 (MCR) DUTY

kW	Full Speed (RPM)	Frame No.	Rated Torque (Nm)	Current (amp) at volts			Efficiency (%) at load			Power Factor at load			D.O.L. Starting current (%FLC)	D.O.L. Starting Torque (%FLT)	Pull out Torque (%FLT)	Rotor inertia mr² (kg.m²)	Max load inertia mr² (kg.m²)	Sound pressure (dB(A)) (avg no-load@1m)
				380	400	415	100%	75%	50%	100%	75%	50%						
75	2960	D250M	242	131	125	120	95.5	95.5	95.0	0.91	0.88	0.85	685	140	250	0.5	10	81
75	1480	D250M	484	137	130	126	95.5	95.5	95.0	0.87	0.84	0.77	650	220	240	1.1	44	73
75	984	D280M	728	139	132	127	95.3	94.8	94.3	0.86	0.83	0.76	688	140	230	2.8	127	75
90	2960	D280S	290	161	153	147	95.4	94.8	94.0	0.89	0.88	0.82	712	110	230	0.7	16	80
90	1480	D280S	581	164	156	151	95.6	95.0	94.2	0.87	0.84	0.78	694	140	230	2	56	78
90	985	D315S	872	167	159	153	95.3	94.9	94.8	0.86	0.83	0.76	689	155	230	4.3	150	79
110	2960	D280M	355	195	186	179	95.4	95.0	94.8	0.90	0.88	0.82	715	105	230	0.9	18	80
110	1482	D280S	709	198	188	182	95.8	95.2	94.4	0.88	0.85	0.79	703	140	230	2.4	68	78
110	985	D315M	1066	202	192	185	95.8	95.3	94.9	0.86	0.84	0.77	689	140	220	5	105	75
110	737	D315A	1425	217	206	198	94.8	94.5	93.0	0.81	0.76	0.65	643	120	220	7.5	320	75
132	2976	D315S	424	233	221	213	95.8	95.2	94.3	0.90	0.88	0.83	723	100	220	1.3	20	80
132	1482	D315S	850	236	224	215	96.2	95.6	94.8	0.89	0.85	0.80	741	140	220	3.1	75	78
132	986	D315M	1278	243	231	222	95.8	95.4	95.3	0.86	0.85	0.78	694	150	220	5.7	228	79
132	737	D315A	1710	259	246	237	95	94.5	93.1	0.82	0.77	0.66	638	110	220	6.3	365	75
150	2976	D315M	481	263	250	241	96	95.4	95.4	0.90	0.89	0.84	724	95	220	1.5	23	83
150	1485	D315M	964	268	254	245	96.2	95.6	94.8	0.89	0.85	0.80	709	140	220	3.6	91	78
150	985	D315A	1454	276	262	252	95.3	94.8	93.5	0.87	0.85	0.78	697	110	220	7.3	260	79
150	737	D315A	1943	292	277	267	95.5	94.8	93.2	0.82	0.78	0.69	655	100	220	9.1	400	75
185	2982	D315M	592	323	307	296	96.1	94.7	93.5	0.91	0.89	0.86	677	105	215	2	30	83
185	1486	D315M	1189	324	308	294	96	95.4	94.5	0.90	0.89	0.84	715	140	220	3.7	78	78
185	985	D315A	1793	338	321	310	95.5	95	93.5	0.87	0.85	0.79	673	120	220	8.9	270	79
185	737	D315C	2397	359	341	329	95.5	94.8	93.5	0.82	0.79	0.69	634	110	220	11.7	450	77
220	2970	D315A	707	350	332	320	96	96	95.5	0.91	0.90	0.86	722	90	240	2.2	30	83
220	1475	D315A	1424	358	340	328	95.8	95.2	94.0	0.89	0.87	0.83	726	100	240	5.9	130	81
220	987	D315C	2128	360	342	329	95.5	95.4	94.6	0.89	0.87	0.80	699	100	230	11.5	350	81
220	738	D315D	2846	388	369	355	95.5	95	93.5	0.82	0.78	0.69	663	100	220	13.6	520	78
260	2970	D315C	836	437	415	400	96	95.5	94.0	0.91	0.90	0.86	720	85	240	2.85	40	85
260	1480	D315C	1677	447	424	409	96	95.5	94.0	0.89	0.87	0.83	700	100	240	6.9	150	82
260	985	D315D	2520	452	430	414	96	95.6	94.5	0.88	0.86	0.79	695	90	220	12.9	400	82
260	738	D315A	3364	483	459	442	95.9	95.3	94.0	0.82	0.78	0.69	650	110	210	20.3	750	79
300	2975	D315D	963	484	460	444	96.3	95.8	94.5	0.91	0.90	0.87	735	85	240	3.35	45	85
300	1480	D315C	1935	499	474	457	96.3	95.8	94.5	0.89	0.87	0.83	720	110	240	7.6	150	83
300	985	D355A	2908	506	481	464	96.0	95.6	94.5	0.88	0.86	0.80	710	90	220	19.2	550	82
300	740	D355C	3871	540	514	495	96.0	95.5	94.5	0.82	0.78	0.69	665	100	210	22.4	800	80
335	2975	D315D	1075	544	517	498	96.4	96	94.5	0.91	0.90	0.87	745	85	240	3.9	52	85
335	1480	D315D	2161	561	533	514	96.4	95.8	94.5	0.89	0.87	0.84	710	100	240	8.6	165	85
335	987	D355C	3241	566	538	519	96.0	95.6	94.5	0.88	0.86	0.80	705	90	210	21.0	550	83
335	740	D400A	4322	616	585	564	96.0	95.5	94.5	0.81	0.76	0.66	650	100	210	29.3	950	80
375	2975	D355A	1204	612	581	560	96.4	96.0	94.8	0.92	0.90	0.89	730	85	240	4.725	60	85
375	1480	D355A	2419	632	600	578	96.5	96.0	94.8	0.89	0.87	0.84	710	100	230	12.1	195	85
375	987	D400A	3628	640	608	586	96.3	95.8	94.8	0.88	0.86	0.80	700	82	200	22.7	550	83
375	740	D400C	4839	693	658	635	96.1	95.6	94.5	0.81	0.77	0.68	645	95	210	30.5	960	80
450	2978	D400C	1443	688	654	630	96.5	96.1	94.8	0.92	0.90	0.88	735	80	240	7.7	85	85
450	1485	D355C	2893	711	675	650	96.6	96.0	94.8	0.89	0.87	0.84	715	95	230	13.5	210	85
450	987	D400A	4353	721	685	660	96.3	95.8	94.8	0.88	0.88	0.80	705	80	210	25	580	83
450	740	D450A	5806	771	733	706	96.1	95.6	94.6	0.82	0.80	0.70	660	95	210	50	1300	83

Technical Data Summary TK 164

High power medium speed spindle motors
Applications:
Direct drive lathes
Swiss type lathes
Speed up to 5000 rpm, 40-200 Nm
Short duty constant power

	Symbol	TK 164-60-04	TK 164-110-03	TK 164-250-09	Units
Reference data (winding independent)					
Nominal torque, S1,0 speed, conduction+convection cooled IC 418 1)	Tnc	19	40	106	*Nmrms*
Nominal torque, S1, 0 speed, water cooled 2)	Tnw	37	80	209	*Nmrms*
Peak torque, S6 10% 1)	Tpk	54	114	302	*Nmrms*
Maximum torque 3)	Tul	93	171	389	*Nm*
Maximum structural speed	Pn	500	500	500	*rad/sec*
Critical flux control torque 4)	Pf	86	157	366	*Nm*
Motor constant	Tw	2,33	3,63	6,31	*Nm/sqrt(W)*
Pole number	PN	12	12	12	
Connection		Y	Y	Y	
Physical data (winding independent)					
Rotor inertia	Jm	4,30	7,30	16	*mkgm2*
Acceleration at maximum torque	apk	12576	15595	18855	*rad/s2*
Outer diameter	Dout	164	164	164	*mm*
Rotor hole diameter	Din	96	96	96	*mm*
Overall stator length	Stkout	102	152	292	*mm*
Stack length	Stk	60	110	250	*mm*
Stator mass	Msta	4,8	8	17	*kg*
Rotor mass	Mrot	1,3	2,4	5,5	*kg*
Insulation		Class H - F	Class H - F	Class H - F	
Protection		IP 00	IP 00	IP 00	
Thermal data (winding independent)					
Thermal imp. assumed for cond. Cooling 1)	Rthc	0,390	0,214	0,093	*K/W*
Thermal impedance, motor to cooling frame 2)	Rthw	0,092	0,050	0,021	*K/W*
Thermal capacity	Cth	2.016	3.360	7.140	*J/K*
Thermal time constant cond cooling 1)	Tc	786	719	664	*sec*
Thermal time constant, water cooled 2)	Tw	185	168	150	*sec*
Loss at Tnc	L0c	267	491	1.120	*W*
Loss at Tnw	L0w	1.030	1.880	4.380	*W*
Coolant flow, 5 C temp rise, 35 C inlet	Cfl	3,0	5,4	12,6	*lit/min*
Treshold of built-in PTC	PTCt	130	130	130	*oC*
Electrical data (winding dependent)					
Nominal speed (knee speed) 5)	wn	173,29	173,99	52,40	*rad/sec*
Nominal power, water cooling, knee speed 6)	Pnw	6,41	13,92	10,95	*kW*
Back E.M.F. between phases	Ke	1,80	1,76	5,13	*Vs*
Torque constant	Kt	3,13	3,05	8,89	*Nm/Arms*
Temp.coeff. of E.M.F. and Kt	dKe/dT	-0,09	-0,09	-0,09	*%/oC*
Winding resistance, 20oC	Rw	2,69	1,06	2,98	*Ohm*
Winding inductance	Lw	12,63	6,58	24,00	*mH*
Nominal current, zero speed 1)	In0	6,08	13,12	11,92	*Arms*
Nominal current, zero speed, 2)	In	12,46	27,62	24,74	*Arms*
Maximum current 3)	Ipk	37,19	70,12	54,69	*Arms*
Frequency	fn	166	166	50	*Hz*
Efficiency at rated power 6)	n	0,86	0,88	0,71	

Definitions:
1) Motor assembled in light alloy case with outer surface = 500% of
2) Water cooled motor, water inlet temperature = 35 C, copper temp, 120
3) Torque at which magnetic saturation prevents further overloading
4) Knee torque corresponding to unlimited constant power operation
5) Limit of constant torque operation with 400 Vac supply

SEMiX 252GB126HDs

SEMiX®2s

Trench IGBT Modules

SEMiX 252GB126HDs

Preliminary Data

Features

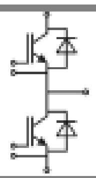
- Homogeneous Si
- Trench = Trenchgate technology
- $V_{CE(sat)}$ with positive temperature coefficient
- High short circuit capability

Typical Applications

- AC inverter drives
- UPS
- Electronic Welding

Remarks

- Case temperatur limited to T_C=125°C max.



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Absolute Maximum Ratings		T_{case} = 25°C, unless otherwise specified		
Symbol	**Conditions**		**Values**	**Units**
IGBT				
V_{CES}	T_j = 25 °C		1200	V
I_C	T_j = 150 °C	T_c = 25 °C	270	A
		T_c = 80 °C	200	A
I_{CRM}	I_{CRM}=2xI_{Cnom}		400	A
V_{GES}			± 20	V
t_{psc}	V_{CC} = 600 V; V_{GE} ≤ 20 V; VCES < 1200 V	T_j = 125 °C	10	µs
Inverse Diode				
I_F	T_j = 150 °C	T_c = 25 °C	210	A
		T_c = 80 °C	160	A
I_{FRM}	I_{FRM} = 2xI_{Fnom}		400	A
I_{FSM}	t_p = 10 ms; sin.	T_j = 25 °C	1000	A
Freewheeling Diode				
I_F	T_j = °C	T_{case} = °C	10	A
I_{FRM}	I_{FRM} = 2xI_{Fnom}, t_p = ms			A
Module				
$I_{t(RMS)}$			600	A
T_{vj}			- 40 ... + 150	°C
T_{stg}			- 40 ... + 125	°C
V_{isol}	AC, 1 min.		4000	V

Characteristics		T_{case} = 25°C, unless otherwise specified				
Symbol	**Conditions**		**min.**	**typ.**	**max.**	**Units**
IGBT						
$V_{GE(th)}$	V_{GE} = V_{CE}, I_C = 6,4 mA		5	5,8	6,5	V
I_{CES}	V_{GE} = 0 V, V_{CE} = V_{CES}	T_j = 25 °C			1	mA
V_{CE0}		T_j = 25 °C		1	1,2	V
		T_j = 125 °C		0,9	1,1	V
r_{CE}	V_{GE} = 15 V	T_j = 25°C		4,7	6,3	mΩ
		T_j = 125°C		7,3	9	mΩ
$V_{CE(sat)}$	I_{Cnom} = 150 A, V_{GE} = 15 V	T_j = 25°$C_{chiplev.}$		1,7	2,15	V
		T_j = 125°$C_{chiplev.}$		2	2,45	V
C_{ies}				10,7		nF
C_{oes}	V_{CE} = 25, V_{GE} = 0 V	f = 1 MHz		0,6		nF
C_{res}				0,5		nF
Q_G	V_{GE} = -8 ... +15V			1050		nC
$t_{d(on)}$				300		ns
t_r	R_{Gon} = 3 Ω	V_{CC} = 600V		45		ns
E_{on}		I_{Cnom}= 150A		20		mJ
$t_{d(off)}$	R_{Goff} = 3 Ω	T_j = 125 °C		570		ns
t_f				110		ns
E_{off}				21		mJ
$R_{th(j-c)}$	per IGBT				0,15	K/W

SEMiX 252GB126HDs

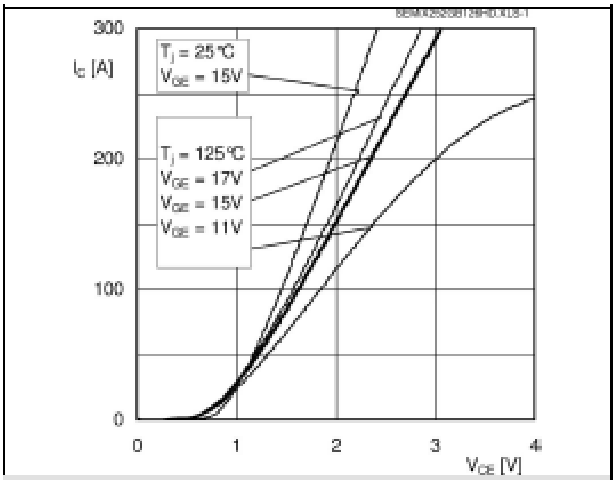

Fig. 1 Typ. output characteristic, inclusive $R_{CC'+ EE'}$

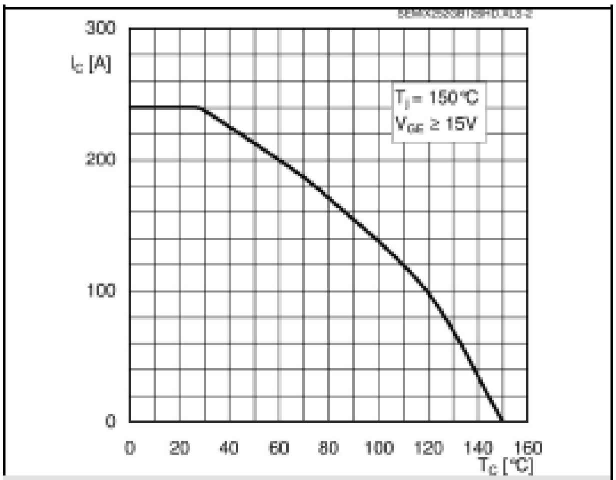

Fig. 2 Rated current vs. temperature $I_C = f(T_C)$

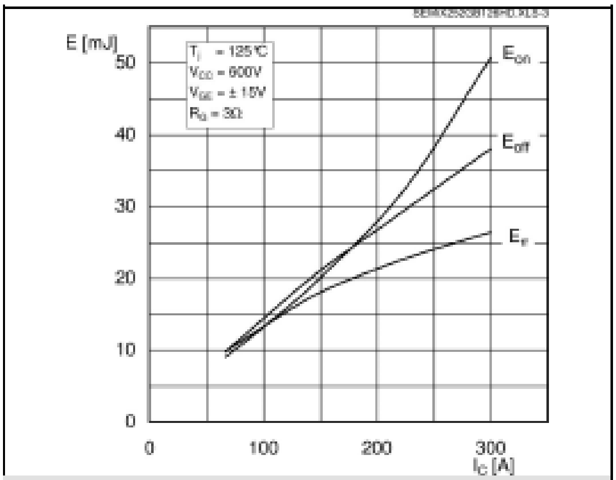

Fig. 3 Typ. turn-on /-off energy = f (I_C)

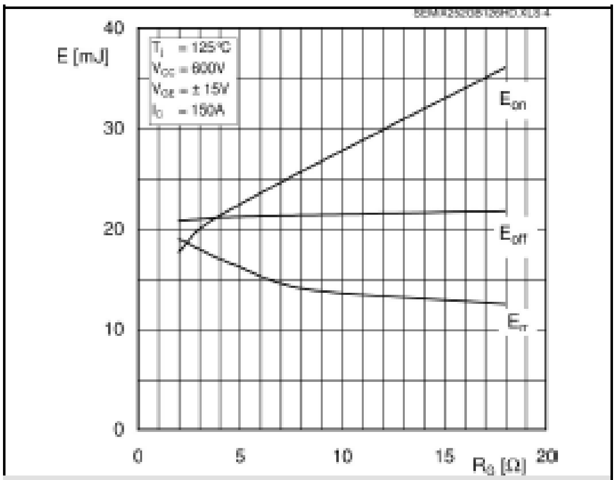

Fig. 4 Typ. turn-on /-off energy = f (R_G)

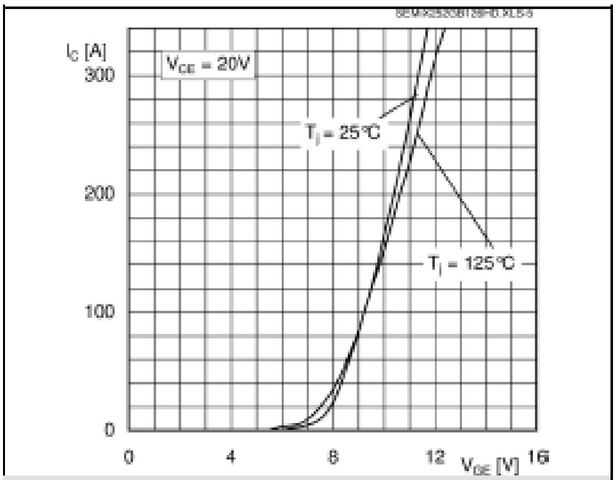

Fig. 5 Typ. transfer characteristic

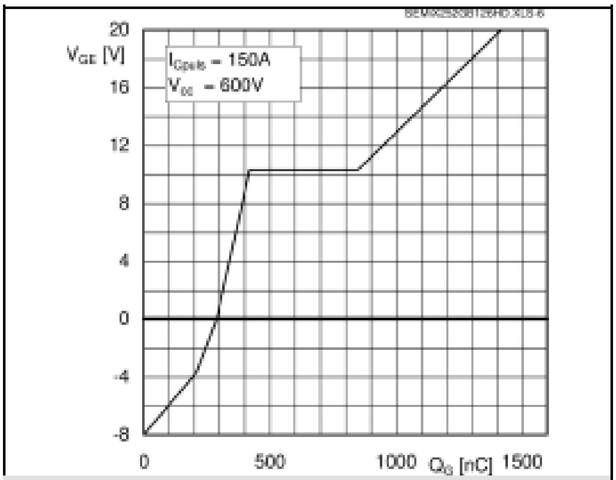

Fig. 6 Typ. gate charge characteristic