MIDDLE EAST TECHNICAL UNIVERSITY
Department of Electrical and Electronics Engineering

EE463 – Power Electronics Hardware Project

Design and Thermal Analysis of a DC-DC Buck Converter

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"Buck ve Ötesi"

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1 Component Selection and Revised Thermal Analysis

1.1 Deviation from Initial Design (Component Substitution)

The initial design specifications called for the **IXGH24N60C4D1** IGBT. However, due to a supply chain substitution, the **IXFH80N65X2** (Ultra-Junction X2-Class Power MOSFET) was received and implemented.

A comparative analysis confirmed that the substituted MOSFET offers superior characteristics for this application ($V_{DSS} = 650V$, $I_{D25} = 80A$, $R_{thJC} = 0.14°C/W$). Consequently, the thermal calculations were revised to account for the resistive nature of the MOSFET.

1.2 Power Loss Calculation (IXFH80N65X2)

Unlike IGBTs, which are modeled with a relatively constant voltage drop (V_{CE}), the conduction loss of a MOSFET depends on its On-State Resistance ($R_{DS(on)}$).

It is crucial to note that $R_{DS(on)}$ **is not a constant value**; it varies significantly with the junction temperature (T_J). MOSFETs exhibit a *Positive Temperature Coefficient*, meaning their resistance increases as they heat up. Relying solely on the datasheet's nominal resistance at $25°C$ would lead to a severe underestimation of power losses and potentially dangerous thermal runaway.

1.2.1 Conduction Losses (P_{cond}) and Effective Resistance

To ensure a realistic and safe thermal design, an **"Effective Hot Resistance"** (R_{hot}) was calculated. This value represents the device's resistance at the target operating temperature, rather than its cold state.

- **Nominal Resistance (R_{cold}):** The datasheet specifies a maximum $R_{DS(on)}$ of **38 mΩ** at $T_J = 25°C$.
- **Thermal Adjustment Factor:** According to *Fig. 4: $R_{DS(on)}$ Normalized vs. Junction Temperature* in the datasheet, the resistance increases by a factor of approximately **2.2** when the junction temperature approaches the design limit of $125°C$.

Using this normalization factor, the effective resistance used for the power calculation is:

$$R_{hot} = R_{DS(on),25°C} \times 2.2 = 38m\Omega \times 2.2 \approx 83.6m\Omega \ (0.0836\ \Omega) \tag{1}$$

Consequently, the conduction power loss at the load current of 12A is:

$$P_{cond} = I_{load}^2 \times R_{hot} = 12^2 \times 0.0836 = 144 \times 0.0836 \approx \mathbf{12.04\ W} \tag{2}$$

1.2.2 Switching Losses (P_{sw})

The switching losses are determined by the transition times provided in the datasheet ($t_{on} \approx 56ns$, $t_{off} \approx 81ns$) and the switching frequency ($2kHz$).

$$P_{sw} \approx \frac{1}{2} V_{bus} I_{load} (t_{total}) f_{sw} \tag{3}$$

$$P_{sw} \approx 0.5 \times 400 \times 12 \times (137 \times 10^{-9}) \times 2000 \approx \mathbf{0.66\ W} \tag{4}$$

1.2.3 Total Power Dissipation

$$P_{total} = P_{cond} + P_{sw} = 12.04\ W + 0.66\ W \approx \mathbf{12.7\ W} \tag{5}$$

1.3 Heatsink Selection and Cooling Strategy

To maintain the junction temperature below the safety limit of $110°C$, the thermal resistance requirement was calculated using the derived total power loss.

Thermal Parameters:

- $R_{\theta JC}$ **(Junction-to-Case): 0.14 °C/W** (Directly from datasheet).
- $R_{\theta CS}$ **(Case-to-Sink): 1.0 °C/W** (Conservative estimate for the isolation pad).

Calculation:

$$R_{\theta SA} \leq \frac{T_{J,max} - T_{amb}}{P_{total}} - (R_{\theta JC} + R_{\theta CS}) \tag{6}$$

$$R_{\theta SA} \leq \frac{110 - 30}{12.7} - (0.14 + 1.0) \tag{7}$$

$$R_{\theta SA} \leq \frac{80}{12.7} - 1.14 \approx 6.30 - 1.14 = \mathbf{5.16\ °C/W} \tag{8}$$

1.4 Conclusion on Main Switching Cooling

The calculation dictates that a heatsink with a thermal resistance of **5.16 °C/W** or lower is required.

Since the standard passive aluminum heatsinks in the laboratory inventory typically provide **10–15 °C/W** (which is insufficient for this load), the **Active Cooling Solution (Heatsink + Fan)** remains mandatory to ensure the MOSFET operates within its Safe Operating Area (SOA).

1.5 Auxiliary Thermal Protection: Freewheeling Diode

In addition to the main switching element, the thermal stability of the freewheeling diode was evaluated as a critical factor for the system's long-term reliability.

Although the theoretical power dissipation analysis suggested that the diode operates within its Safe Operating Area (SOA), practical considerations regarding ambient temperature fluctuations and continuous high-load operation necessitated a conservative approach.

To eliminate any risk of *thermal runaway* and to minimize the thermal stress on the junction, a dedicated **passive aluminum heatsink** was integrated onto the diode package. This preventive measure serves two key purposes:

1. **Derating:** It keeps the operational junction temperature (T_J) significantly below the maximum rating, extending the component's lifespan.
2. **Transient Stability:** It provides a larger thermal mass to absorb transient heat spikes during rapid load changes.

Consequently, this auxiliary cooling solution ensures that the freewheeling diode remains thermally stable, safeguarding the overall integrity of the Buck Converter circuit.

A Appendix A: Component Datasheet

The technical specifications for the substituted component, **IXFH80N65X2**, are attached below for reference.

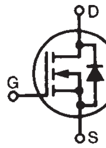
IXYS

X2-Class HiPerFET™ Power MOSFET

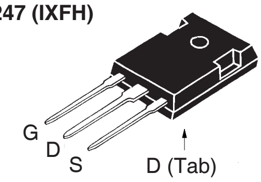
IXFH80N65X2
IXFK80N65X2

V_{DSS} = 650V
I_{D25} = 80A
$R_{DS(on)} \leq$ 38mΩ

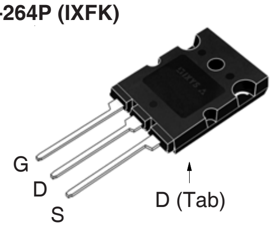
N-Channel Enhancement Mode
Avalanche Rated
Fast Intrinsic Diode



TO-247 (IXFH)



TO-264P (IXFK)



G = Gate   D = Drain
S = Source   Tab = Drain

Symbol	Test Conditions	Maximum Ratings	
V_{DSS}	T_J = 25°C to 150°C	650	V
V_{DGR}	T_J = 25°C to 150°C, R_{GS} = 1MΩ	650	V
V_{GSS}	Continuous	±30	V
V_{GSM}	Transient	±40	V
I_{D25}	T_C = 25°C	80	A
I_{DM}	T_C = 25°C, Pulse Width Limited by T_{JM}	160	A
I_A	T_C = 25°C	20	A
E_{AS}	T_C = 25°C	3	J
dv/dt	$I_S \leq I_{DM}$, $V_{DD} \leq V_{DSS}$, $T_J \leq$ 150°C	50	V/ns
P_D	T_C = 25°C	890	W
T_J		-55 ... +150	°C
T_{JM}		150	°C
T_{stg}		-55 ... +150	°C
T_L	Maximum Lead Temperature for Soldering	300	°C
T_{SOLD}	1.6 mm (0.062in.) from Case for 10s	260	°C
M_d	Mounting Torque	1.13 / 10	Nm/lb.in
Weight	TO-247	6	g
	TO-264P	10	g

Features

- International Standard Packages
- Low $R_{DS(ON)}$ and Q_G
- Avalanche Rated
- Low Package Inductance

Advantages

- High Power Density
- Easy to Mount
- Space Savings

Applications

- Switch-Mode and Resonant-Mode Power Supplies
- DC-DC Converters
- PFC Circuits
- AC and DC Motor Drives
- Robotics and Servo Controls

Symbol	Test Conditions (T_J = 25°C, Unless Otherwise Specified)	Characteristic Values Min.	Typ.	Max.	
BV_{DSS}	V_{GS} = 0V, I_D = 1mA	650			V
$V_{GS(th)}$	V_{DS} = V_{GS}, I_D = 4mA	3.5		5.0	V
I_{GSS}	V_{GS} = ±30V, V_{DS} = 0V			±100	nA
I_{DSS}	V_{DS} = V_{DSS}, V_{GS} = 0V			50	µA
	T_J = 125°C			3	mA
$R_{DS(on)}$	V_{GS} = 10V, I_D = 0.5 • I_{D25}, Note 1			38	mΩ

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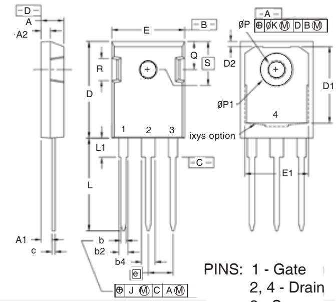
Symbol	Test Conditions (T_J = 25°C, Unless Otherwise Specified)	Characteristic Values Min.	Typ.	Max	
g_{fs}	V_{DS} = 10V, $I_D = 0.5 \bullet I_{D25}$, Note 1	33	55		S
R_{Gi}	Gate Input Resistance		0.6		Ω
C_{iss}	V_{GS} = 0V, V_{DS} = 25V, f = 1MHz		8300		pF
C_{oss}			5010		pF
C_{rss}			1.6		pF
	Effective Output Capacitance				
$C_{o(er)}$	Energy related; V_{GS} = 0V, $V_{DS} = 0.8 \bullet V_{DSS}$		280		pF
$C_{o(tr)}$	Time related		1160		pF
$t_{d(on)}$	**Resistive Switching Times** V_{GS} = 10V, $V_{DS} = 0.5 \bullet V_{DSS}$, $I_D = 0.5 \bullet I_{D25}$, R_G = 3Ω (External)		32		ns
t_r			24		ns
$t_{d(off)}$			70		ns
t_f			11		ns
$Q_{g(on)}$	V_{GS} = 10V, $V_{DS} = 0.5 \bullet V_{DSS}$, $I_D = 0.5 \bullet I_{D25}$		140		nC
Q_{gs}			50		nC
Q_{gd}			40		nC
R_{thJC}				0.14	°C/W
R_{thCS}			0.21		°C/W
R_{thCS}			0.15		°C/W

Source-Drain Diode

Symbol	Test Conditions (T_J = 25°C, Unless Otherwise Specified)	Characteristic Values Min.	Typ.	Max	
I_S	V_{GS} = 0V			80	A
I_{SM}	Repetitive, pulse Width Limited by T_{JM}			320	A
V_{SD}	$I_F = I_S$, V_{GS} = 0V, Note 1			1.4	V
t_{rr}	I_F = 40A, -di/dt = 100A/μs, V_R = 100V		200		ns
Q_{RM}			1.7		μC
I_{RM}			16.7		A

Note 1. Pulse test, t ≤ 300μs, duty cycle, d ≤ 2%.

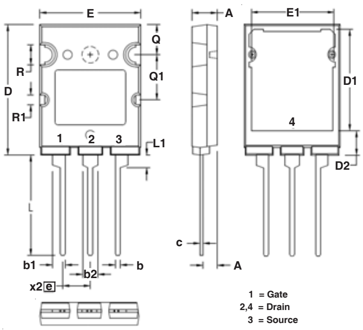
TO-247 Outline



PINS: 1 - Gate
2, 4 - Drain
3 - Source

SYM	INCHES MIN	INCHES MAX	MILLIMETERS MIN	MILLIMETERS MAX
A	.190	.205	4.83	5.21
A1	.090	.100	2.29	2.54
A2	.075	.085	1.91	2.16
b	.045	.055	1.14	1.40
b2	.075	.087	1.91	2.20
b4	.115	.126	2.92	3.20
C	.024	.031	0.61	0.80
D	.819	.840	20.80	21.34
D1	.650	.690	16.51	17.53
D2	.035	.050	0.89	1.27
E	.620	.635	15.75	16.13
E1	.545	.565	13.84	14.35
e	.215 BSC		5.45 BSC	
J	--	.010	--	0.25
K	--	.025	--	0.64
L	.780	.810	19.81	20.57
L1	.150	.170	3.81	4.32
øP	.140	.144	3.55	3.65
øP1	.275	.290	6.99	7.37
Q	.220	.244	5.59	6.20
R	.170	.190	4.32	4.83
S	.242 BSC		6.15 BSC	

TO-264P Outline



SYM	INCHES MIN	INCHES MAX	MILLIMETERS MIN	MILLIMETERS MAX
A	.185	.209	4.70	5.30
A1	.102	.118	2.60	3.00
b	.035	.049	0.90	1.25
b1	.091	.106	2.30	2.70
b2	.110	.126	2.80	3.20
c	.020	.033	0.50	0.85
D	1.012	1.035	25.70	26.30
D1	.783	.799	19.90	20.30
D2	.185	.205	4.70	5.20
E	.776	.799	19.70	20.30
E1	.661	.677	16.80	17.20
e	.215 BSC		5.46 BSC	
L	.768	.807	19.50	20.50
L1	.091	.106	2.30	2.70
Q	.228	.244	5.80	6.20
Q1	.346	.362	8.80	9.20
øR	.150	.165	3.80	4.20
øR1	.071	.087	1.80	2.20

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IXYS MOSFETs and IGBTs are covered by one or more of the following U.S. patents: 4,835,592 4,931,844 5,049,961 5,237,481 6,162,665 6,404,065B1 6,683,344 6,727,585 7,005,734B2 7,157,338B2 4,860,072 5,017,508 5,063,307 5,381,025 6,259,123B1 6,534,343 6,710,405B2 6,759,692 7,063,975B2 4,881,106 5,034,796 5,187,117 5,486,715 6,306,728B1 6,583,505 6,710,463 6,771,478B2 7,071,537

Fig. 1. Output Characteristics @ T_J = 25ºC

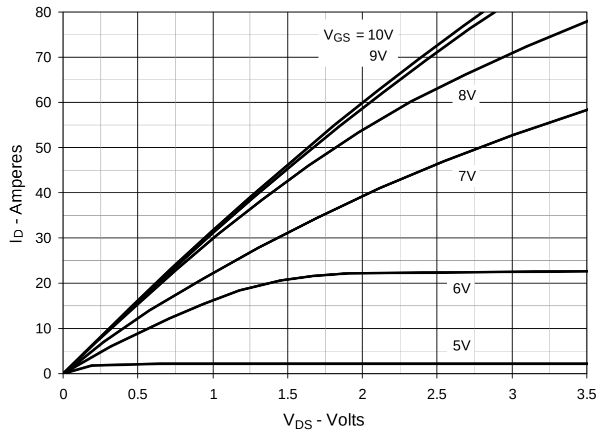


Fig. 2. Extended Output Characteristics @ T_J = 25ºC

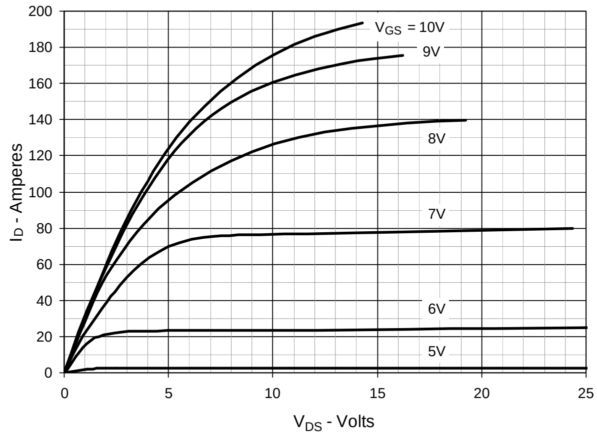


Fig. 3. Output Characteristics @ T_J = 125ºC

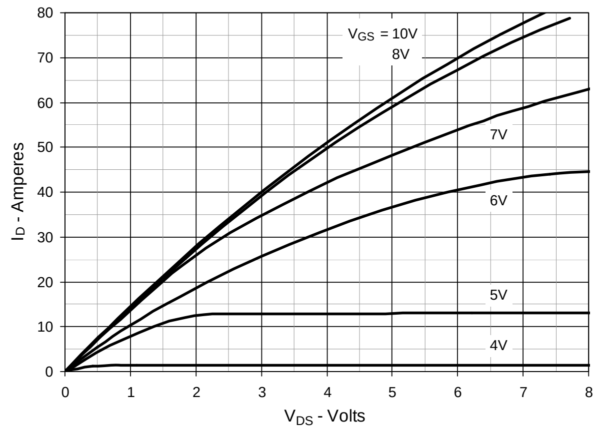


Fig. 4. $R_{DS(on)}$ Normalized to I_D = 40A Value vs. Junction Temperature

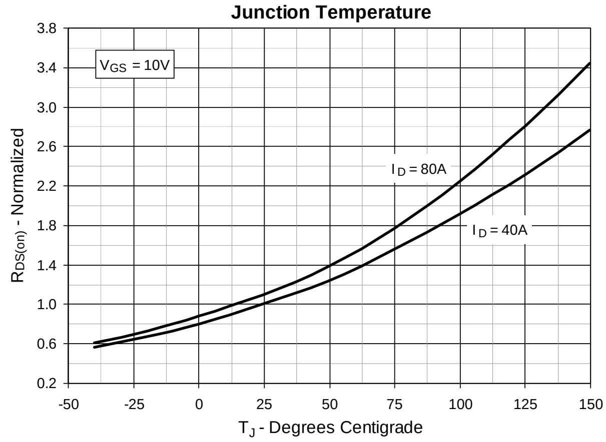


Fig. 5. $R_{DS(on)}$ Normalized to I_D = 40A Value vs. Drain Current

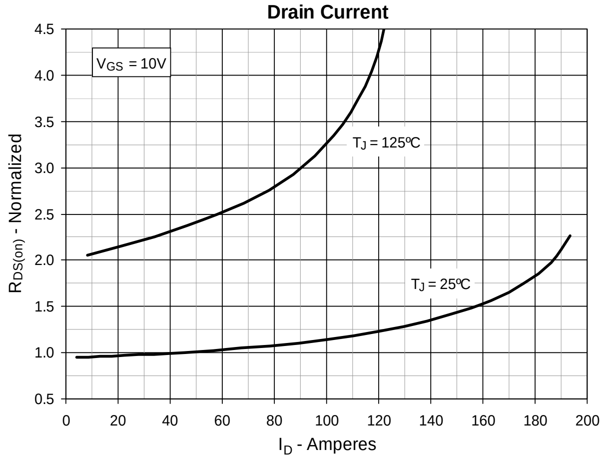
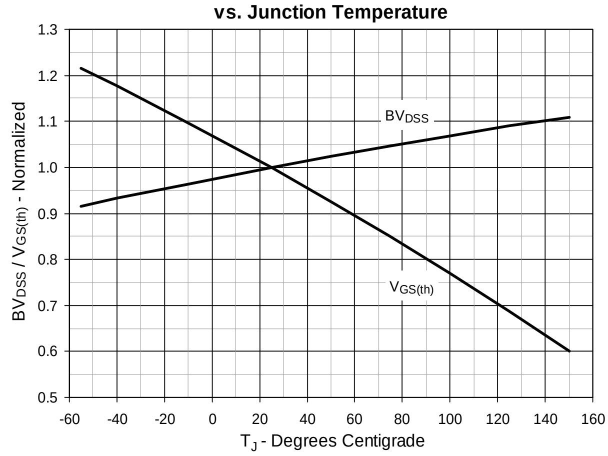


Fig. 6. Normalized Breakdown & Threshold Voltages vs. Junction Temperature



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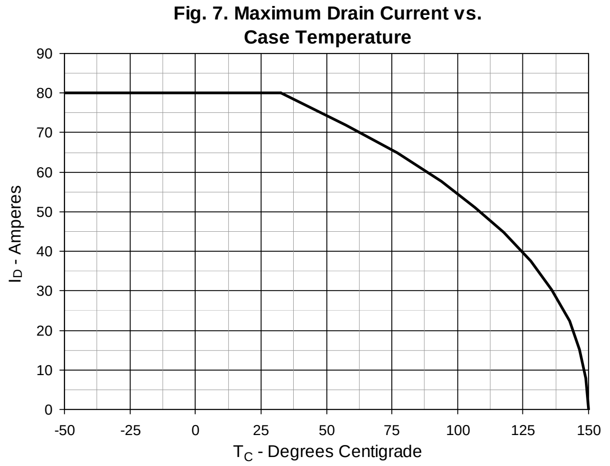

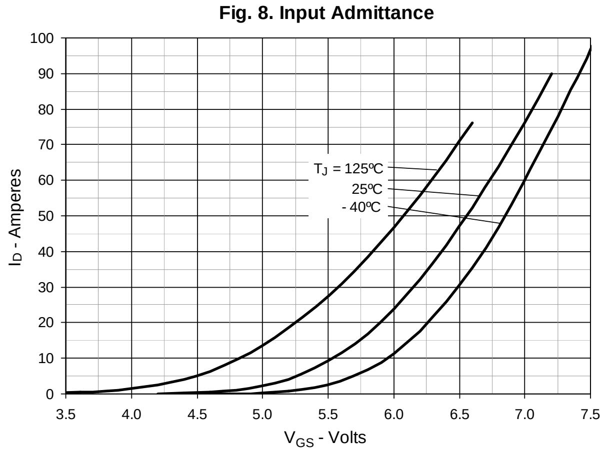

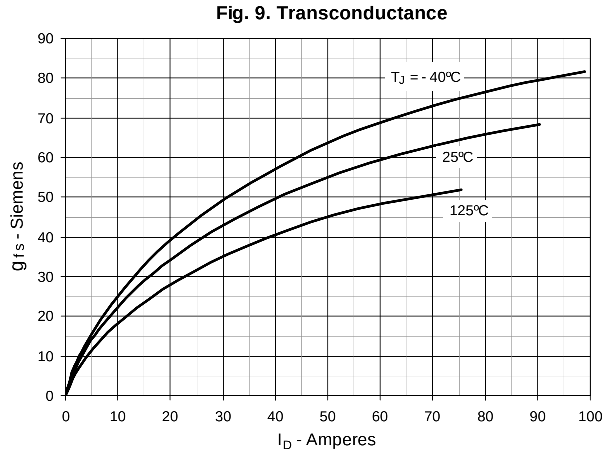

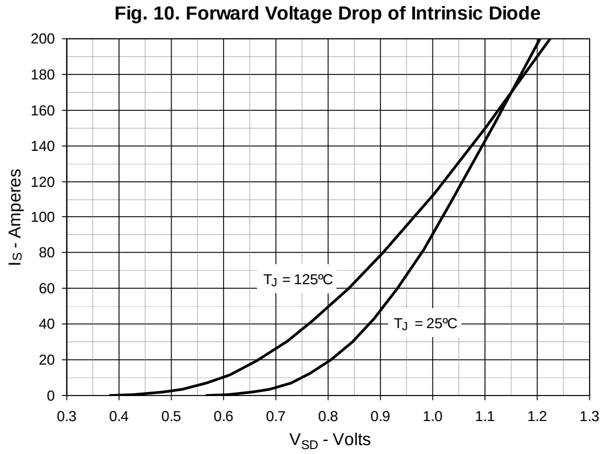

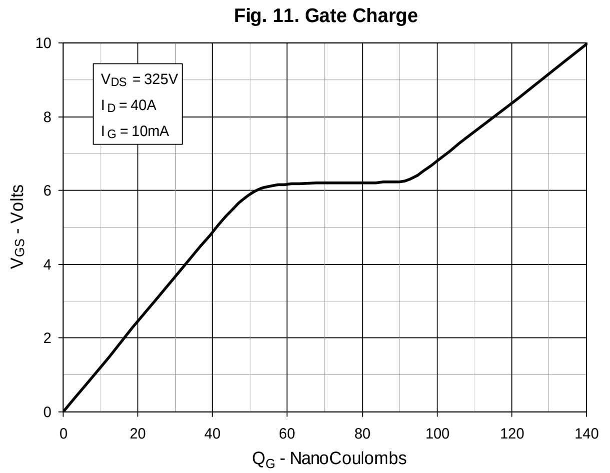

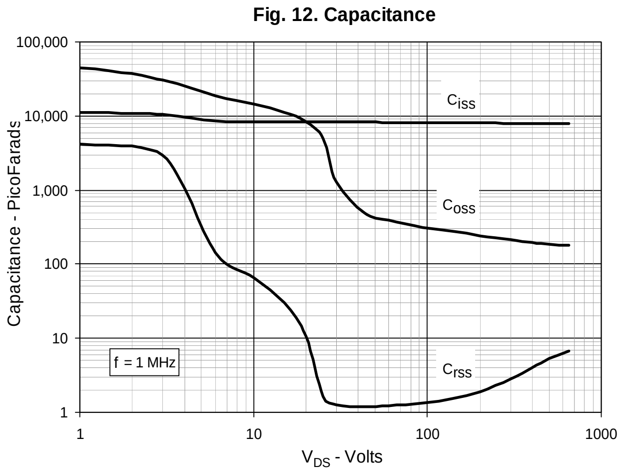

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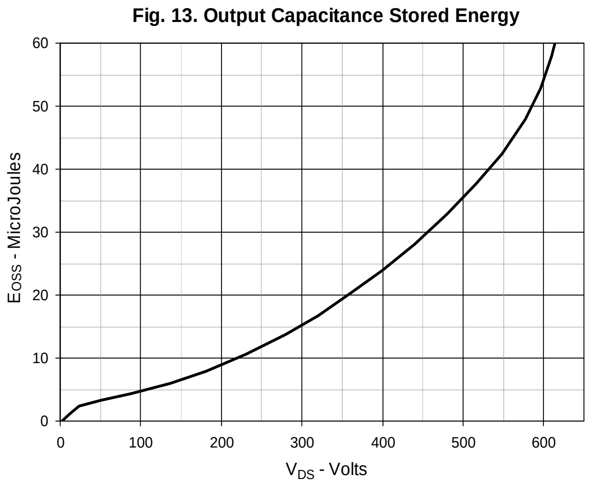

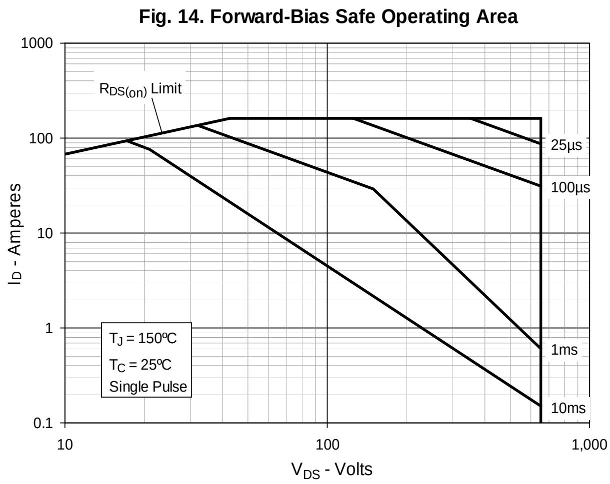

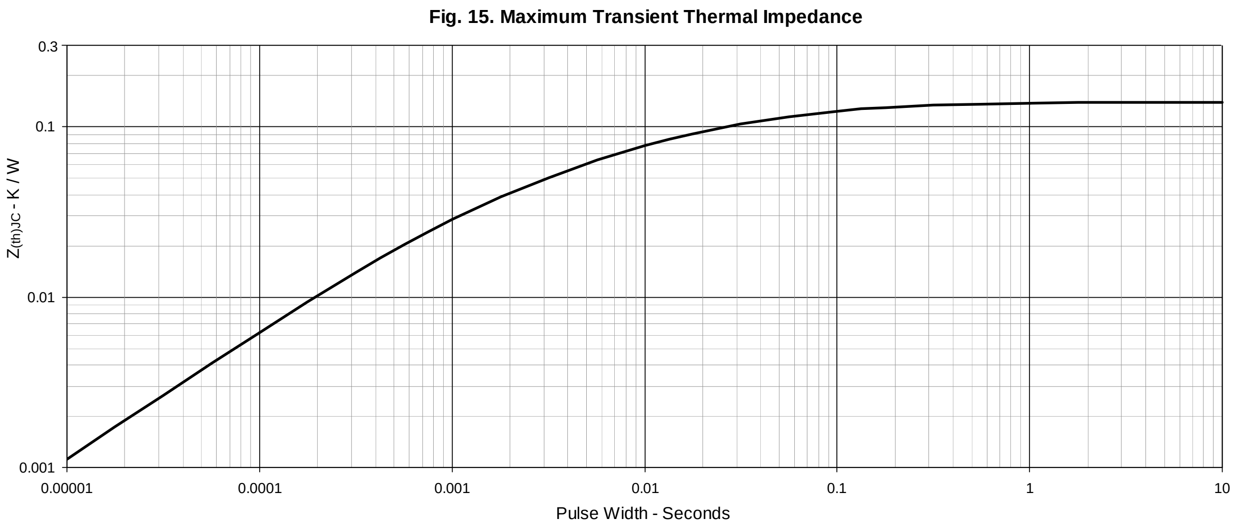

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