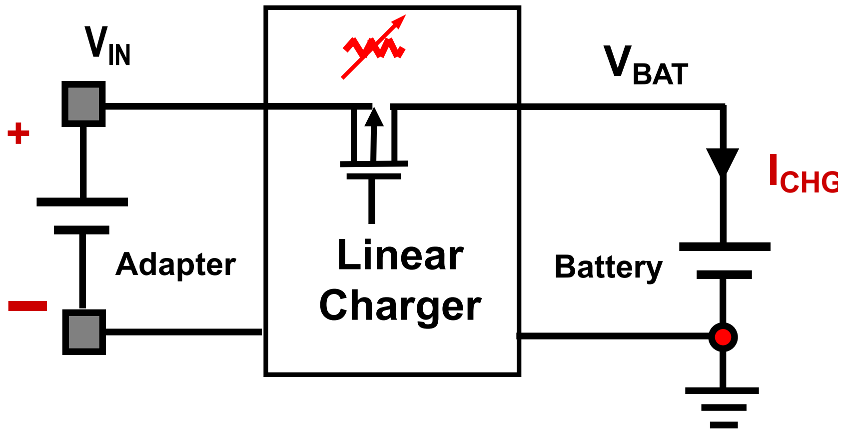
Optimizing Efficiency of Switching Mode Chargers

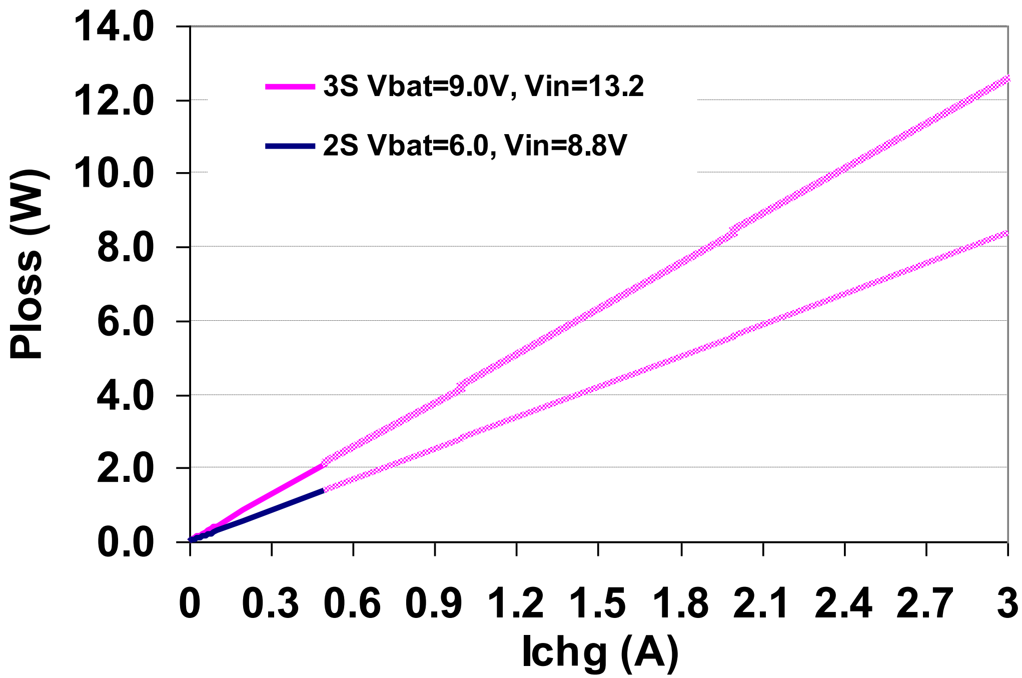
Multi-Cell Battery Charge Management (MBCM)

Outline and Purpose

- Understand the key parameters of a MOSFET and the relationship to power loss of a switching charger
  1. Conduction loss
  2. Switching loss
  3. Gate drive
- Inductor selection and its impact to the loss
- Current sensing resistance vs. the loss
- Go through the loss analysis with an existing charger EVM design

Linear Chargers

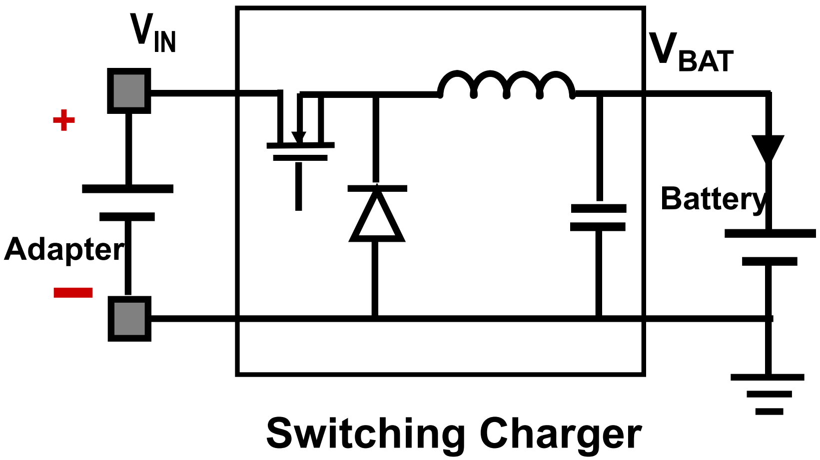


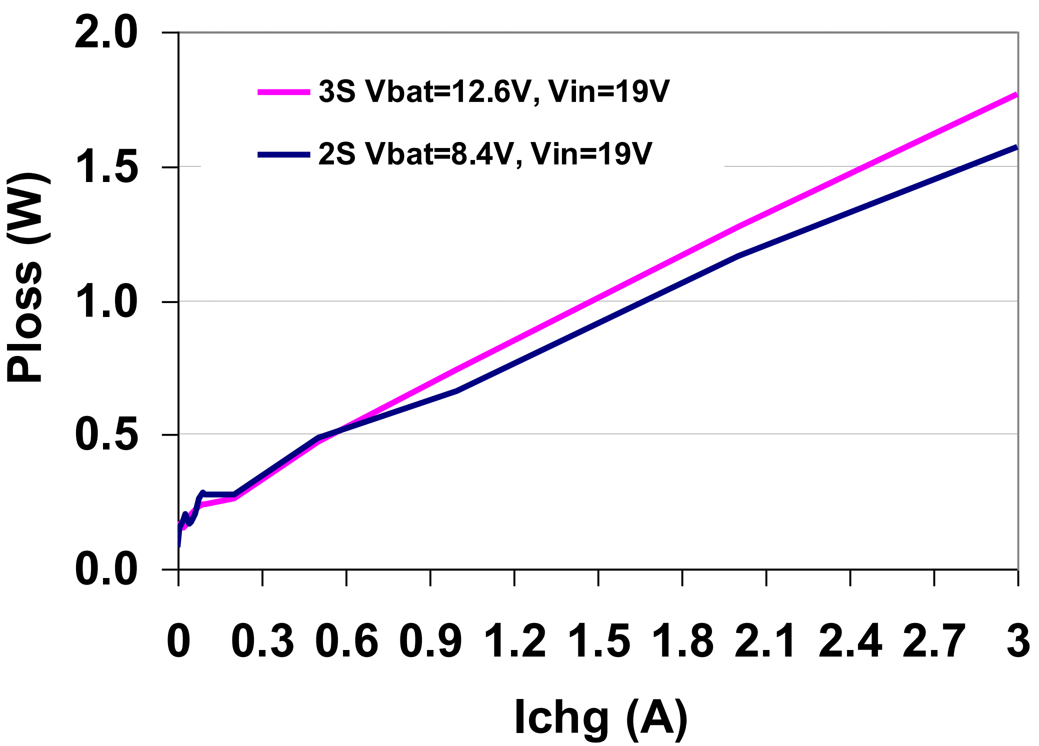


$$P_{LOSS} = \left(V_{IN} - V_{BAT}\right) \cdot I_{chg}$$

- Simple and low cost
- High loss
  - Difference of the adaptor and battery voltage
- Only for small current
  - The charging current is limited due to the high loss

Advantage of Switching Chargers

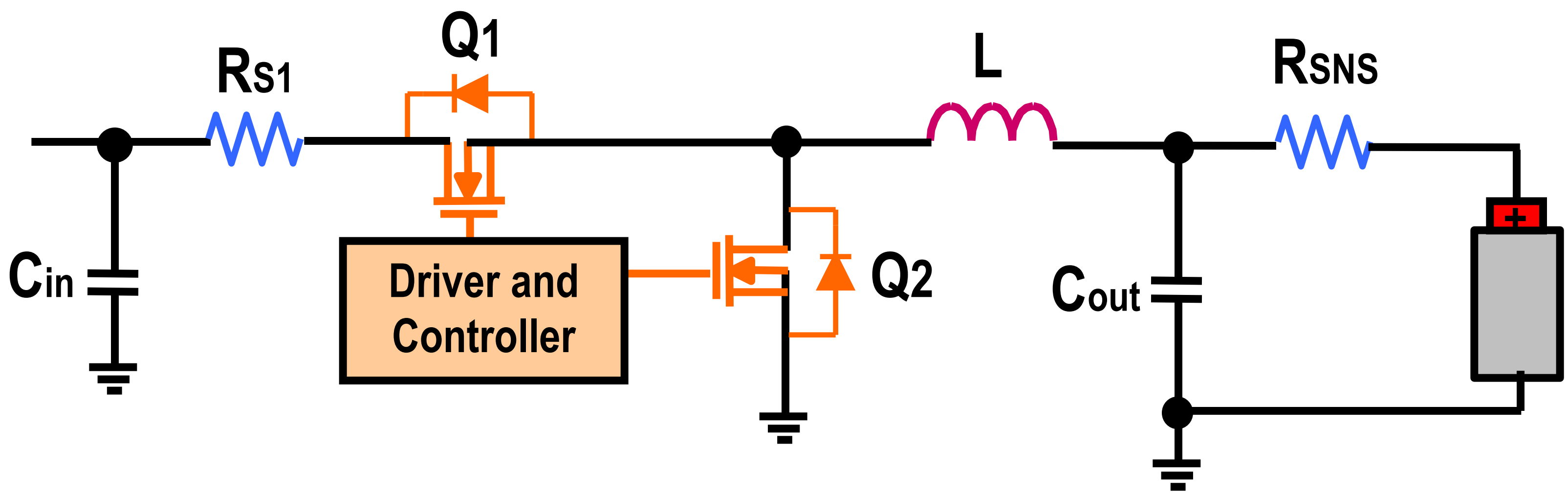




- High efficiency
  - Wide range input voltage
  - High output current
- High output current

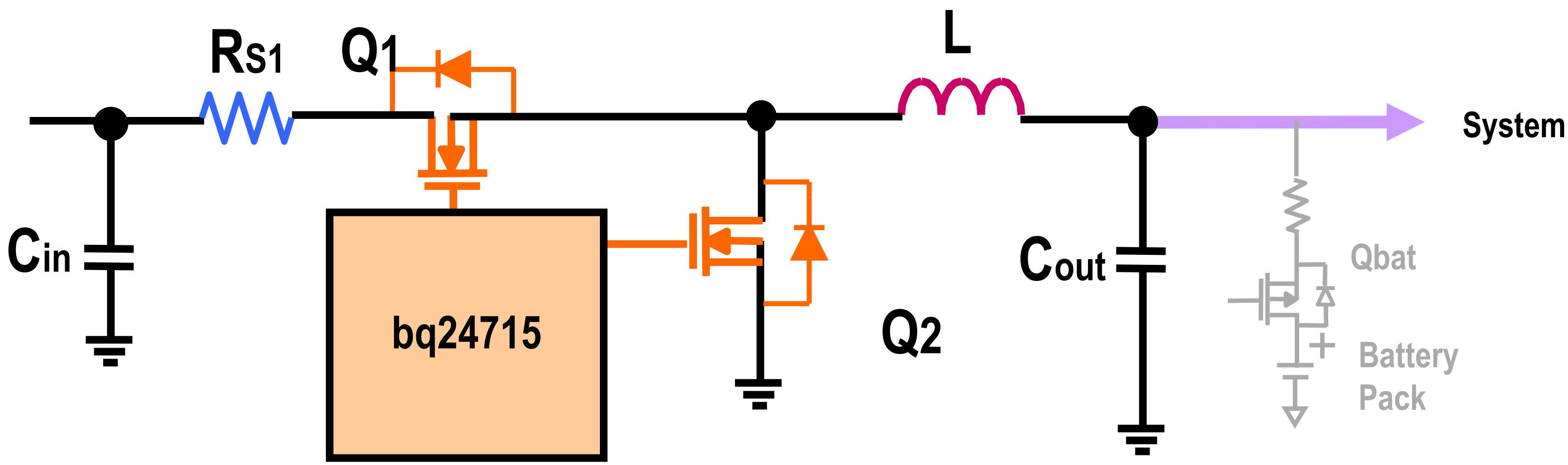
Need to understand the loss and optimize the efficiency

A Switching Charger and the Loss Components



	Conduction (IR)	Switching	Gate Driver	Other
Q1	√	√	√	Qrr Loss
Q2	√		√	Dead time Loss
Inductor	√			Core Loss
Rs1, Rs2	√			
IC				Gate Driver
PCB	√			

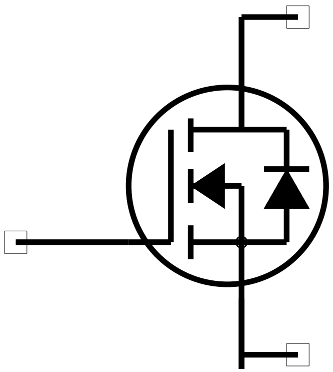
Circuit under Study --- bq24715 NVDC-1 Charger



- Key features
  - NVDC-1 Charger
  - Extreme low quiescent current to meet Energy Star Requirement
  - Ultra fast transient 100us to supplement mode to prevent adaptor crash during turbo boost operation
- Operation Condition
  - Vin=19V, Vo=8.4V, Io=6A
  - Fs=800KHz

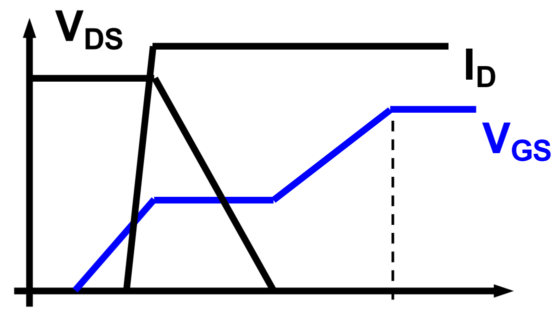
How to Select MOSFET

MOSFET Losses

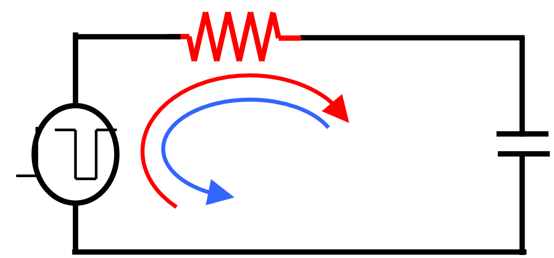


Conduction Loss

Switching Loss



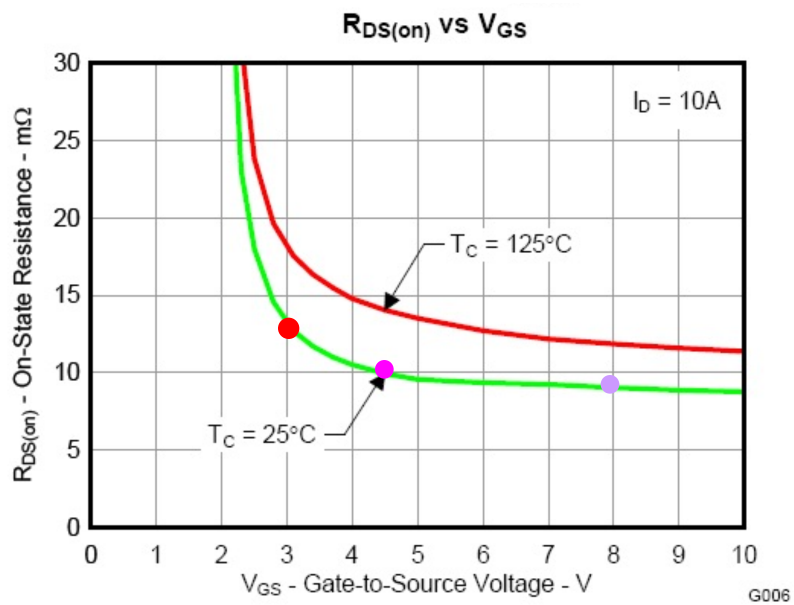
Gate driver Loss

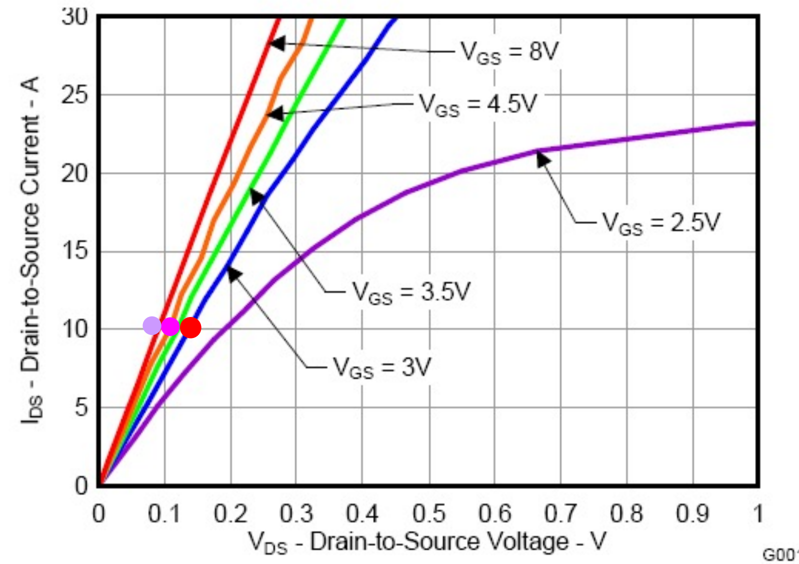


- MOSFET is equivalent to a R when it is fully on
- Loss is with I-V overlapping during the On-off transition
- Capacitor charge and discharge

How to find the information on the DS

Rdson Dependency on the Gate Drive Voltage





CSD17308Q3

Figure 2. Saturation Characteristics

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
$R_{DS(on)}$	Drain to Source On Resistance	V_{GS} = 3V, I_D = 10A		12.5	16.5	mΩ
		V_{GS} = 4.5V, I_D = 10A		9.4	11.8	mΩ
		V_{GS} = 8V, I_D = 10A		8.2	10.3	mΩ

- When the switch is on, it is equivalent to a resistor R_{DS_on}. Which determines the conduction loss
- R_{DS_on} is a function of the driver voltage

Rdson Dependency on the Temp

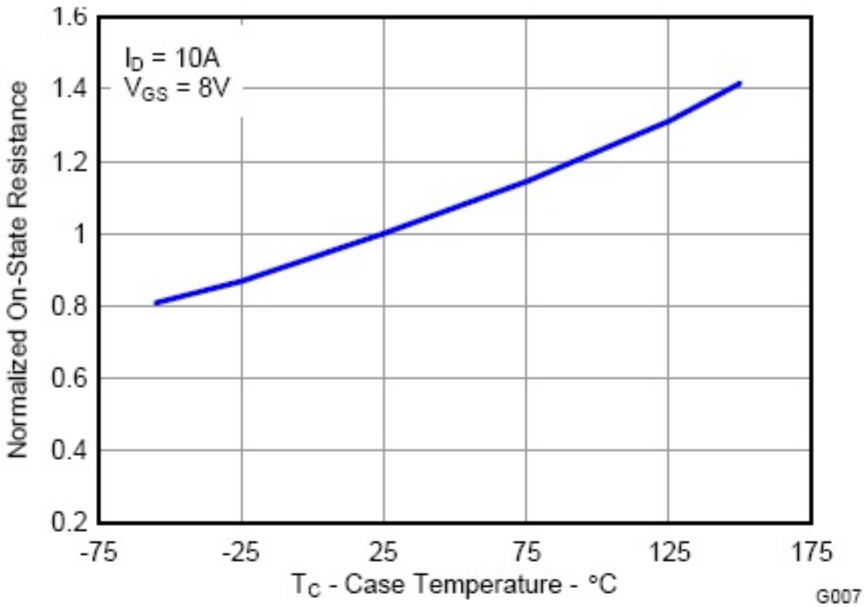
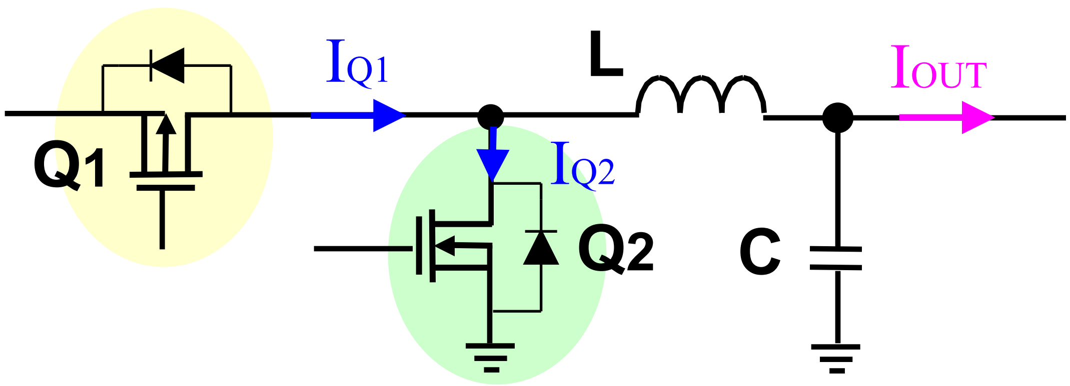


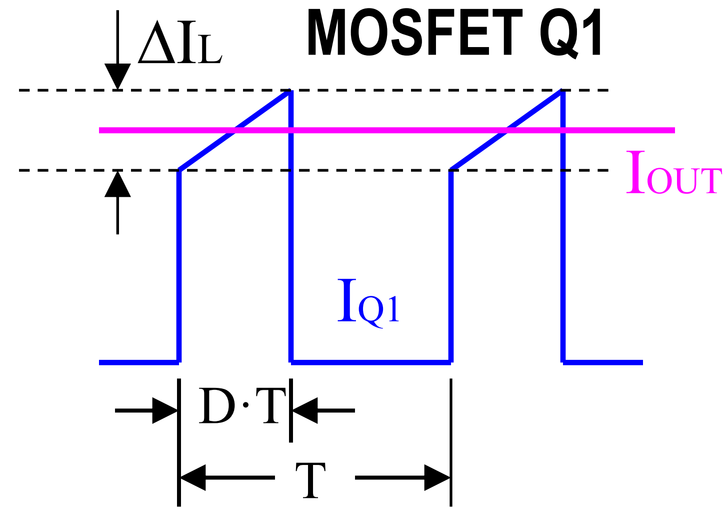
Figure 8. Normalized On-State Resistance vs. Temperature

- **R_{DS_on} is a strong function of temperature. At 150°C junction temperature, the temp coefficient is around 1.4 to 1.5**

- **The conduction loss calculation must take the temperature coefficient into consideration**

Calculation the Conduction Loss





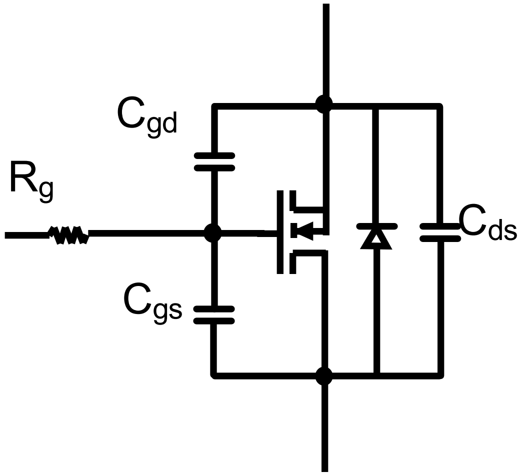
$$P_{cond} = I_{rms}^2 \cdot R_{DS\_on} \cdot Co_{temp}$$

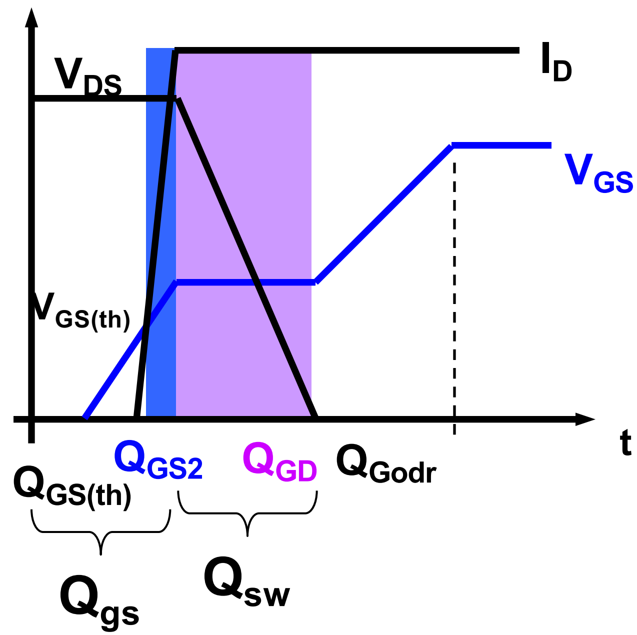
$$I_{rms} = \sqrt{\frac{1}{T}\int_0^{DT} I_o{}^2 dt} = \sqrt{D\left(I_{OUT}^2 + \frac{1}{12}\Delta I_L^2\right)}$$

- **The conduction loss for Q1 and Q2 can be calculated**
- **It starts with a assumed temperature and iteration**

Gate Charge and Switching loss

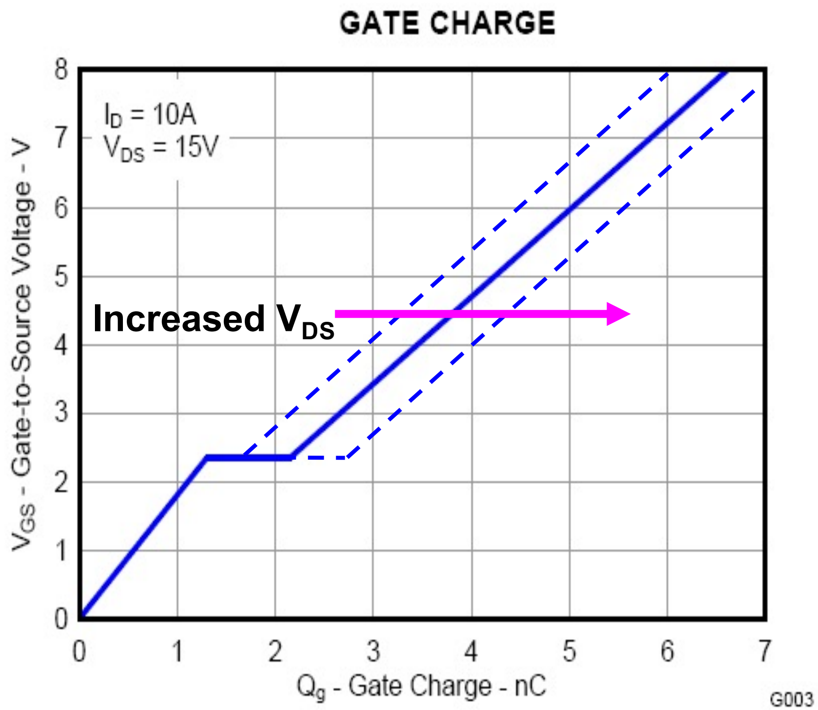
PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
Q_g	Gate Charge Total (4.5V)	V_{DS} = 15V, I_D = 10A		3.9	5.1	nC
Q_{gd}	Gate Charge Gate to Drain			0.8		nC
Q_{gs}	Gate Charge Gate to Source			1.3		nC
Qg(th)	Gate Charge at Vth			0.7		nC





- ❑ Q_{sw} determines the switching loss
- ❑ FOM = R_{DS_on} x Q_{sw}
- ❑ The test condition is important

Q_{GD} is a Function of V_{DS}



- Qgd is a function of V_{DS} and Q_g is a function of V_{GS}
- The comparison of the Qgd should be under the same Vds conditions
- Some MOSFET venders specify Qgd at low Vds, resulting in *better data sheets*, but not better performance

Q_{GD} a Function of V_{DS}

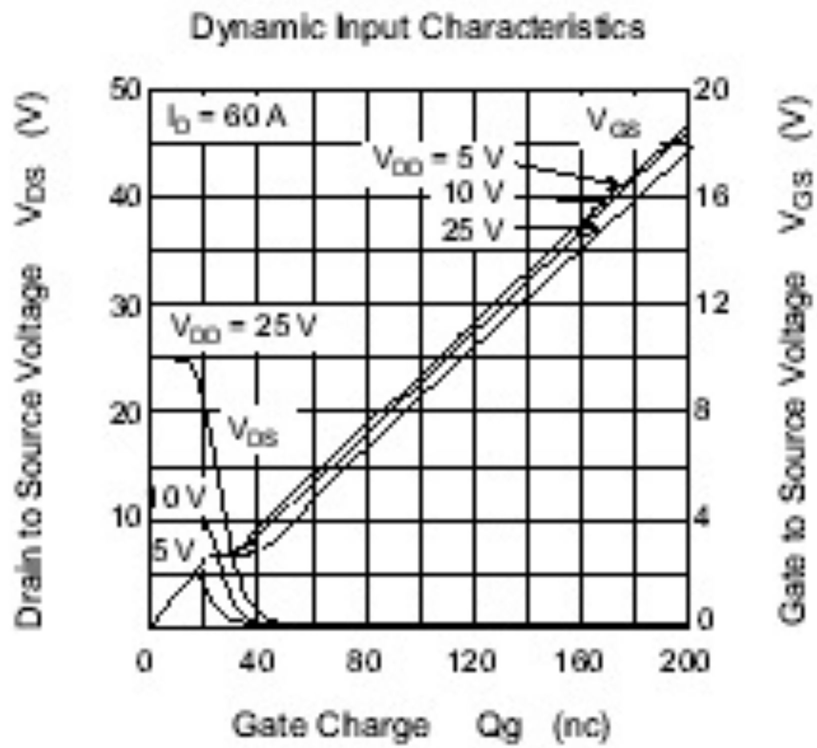
Item	Symbol	Min	Typ	Max	Unit	Test Conditions
Static drain to source on state resistance	$R_{DS(on)}$	—	2.5	3.1	mΩ	I_D = 30 A, V_{GS} = 10 V Note4 ?
	$R_{DS(on)}$	—	3.0	4.4	mΩ	I_D = 30 A, V_{GS} = 4.5 V Note4
Total gate charge	Qg	—	50	—	nC	V_{DD} = 10 V V_{GS} = 4.5 V, I_D = 60 A
Gate to source charge	Qgs	—	22	—	nC	
Gate to drain charge	Qgd	—	10	—	nC	

	Parameter	Min.	Typ.	Max.	Units	Conditions
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	–––	2.5	3.3	mΩ	V_{GS} = 10V, I_D = 24A ⑦
		–––	3.4	4.4		V_{GS} = 4.5V, I_D = 19A ⑦
Q_g	Total Gate Charge	–––	30	45	nC	
Q_{gs1}	Pre-Vth Gate-to-Source Charge	–––	8.5	–––		V_{DS} = 15V
Q_{gs2}	Post-Vth Gate-to-Source Charge	–––	2.9	–––		V_{GS} = 4.5V
Q_{gd}	Gate-to-Drain Charge	–––	10	–––		I_D = 19A
Q_{godr}	Gate Charge Overdrive	–––	8.6	–––		See Fig. 14
Q_{sw}	Switch Charge (Q_{gs2} + Q_{gd})	–––	13	–––		

- The R_{dson} and Q_{gd} are similar
- The test conditions are different

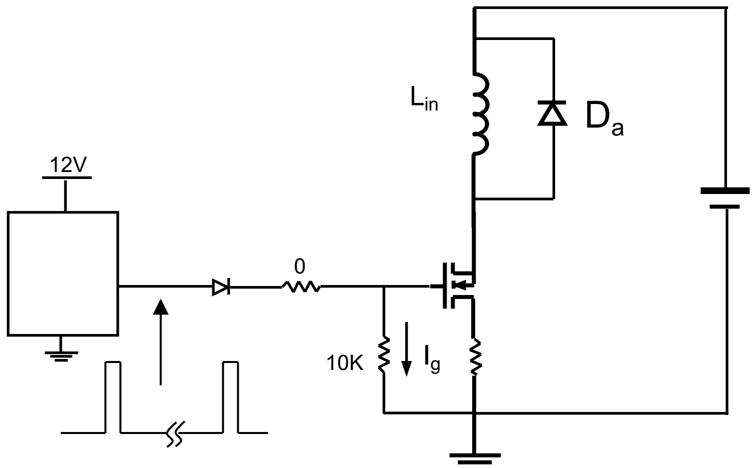
Find the Correct Q_{GD}

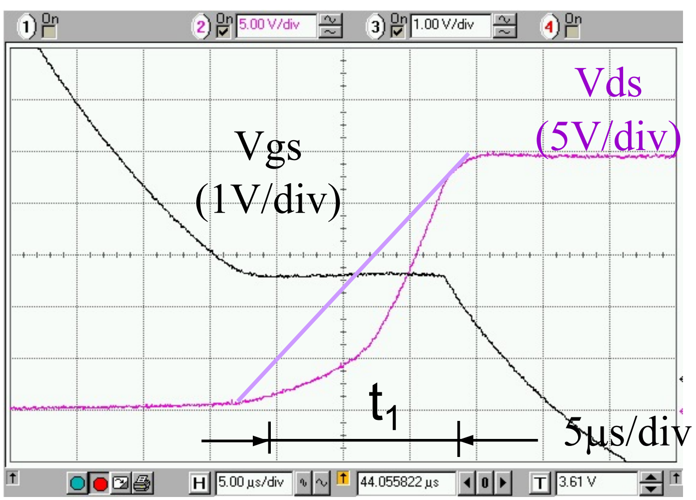
- Need to use the charge graph to determine the charge under certain conditions
- The charge under the same test condition is shown below (30% higher Qgd)



Item	Symbol	Min	Typ	Max	Unit	Test Conditions
Total gate charge	Qg	—	**53**	—	nC	V_{DD} = **15V** V_{GS} = 4.5 V, I_D = 60 A
Gate to source charge	Qgs	—	22	—	nC	
Gate to drain charge	Qgd	—	**13**	—	nC	

Switching Loss Accurate Formula





- Switching loss calculation assumes linear transition

$$P_{sw\_Qgd} = \frac{1}{2} \cdot I_D \cdot V_{DS} \cdot t_1 \cdot F_s$$

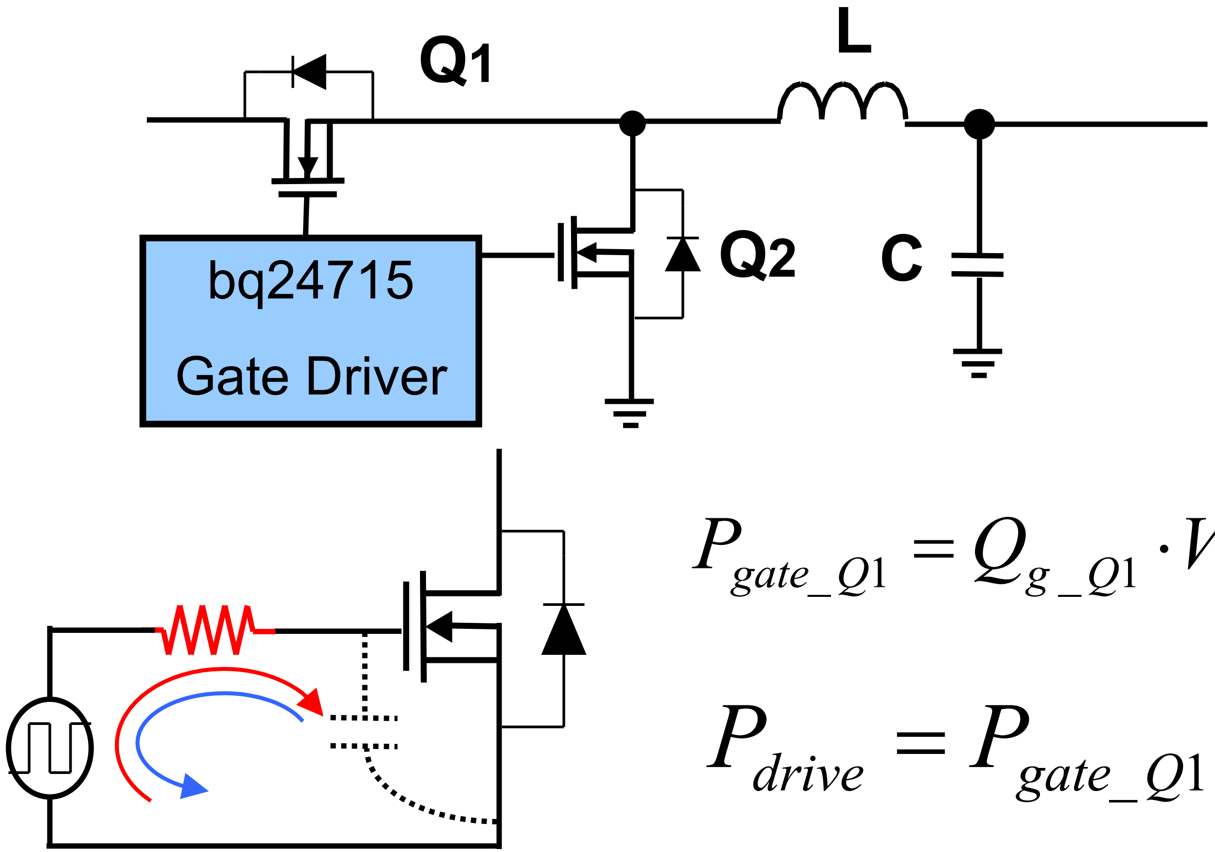
- The voltage transitions are nonlinear, which can be included in K_v:

$$K_v = \frac{\int_0^T V_d(t)dt}{T \cdot V_{in}} < 0.5$$

- K_v is about from 0.27 to 0.35 for most of the devices

$$P_{sw\_Qgd} = K_v \cdot I_o \cdot V_{in} \cdot t_1 \cdot F_s$$

Gate Drive Loss

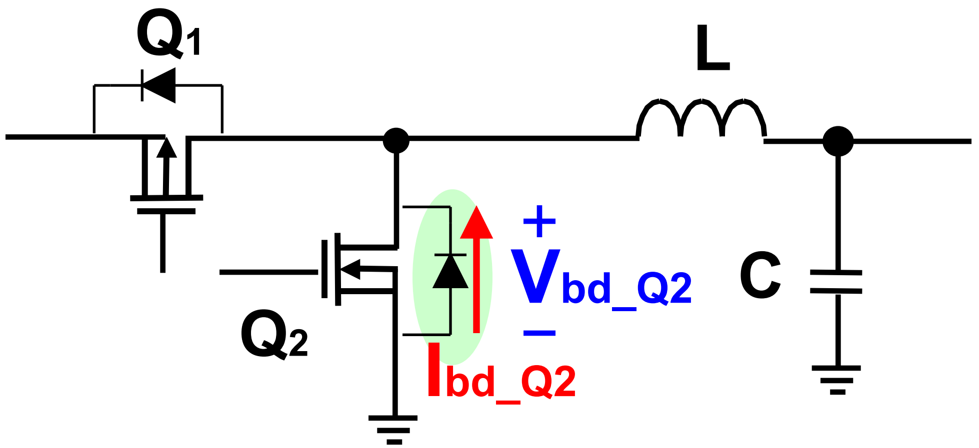


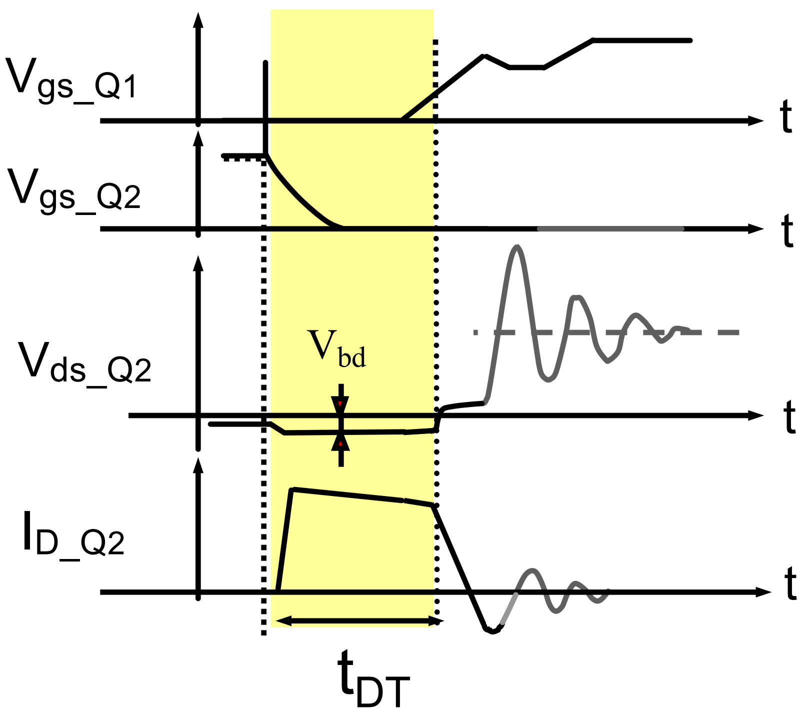
$$P_{gate\_Q1} = Q_{g\_Q1} \cdot V_{DRV\_Q1} \cdot f_{SW}$$

$$P_{drive} = P_{gate\_Q1} + P_{gate\_Q2}$$

- Gate driver loss is the energy of the gate charge dissipated on the resistance of the driver loop
- Gate driver loss is proportional to the gate charge and switching frequency

Body Diode Conduction Loss





$$P_{BD\_Q2} = V_{BD} \cdot I_{OUT} \cdot (t_{DT1} + t_{DT2}) \cdot f_{SW}$$

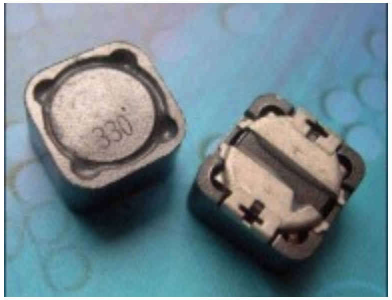
- The typical dead time is 20-40ns
- The dead time loss impact becomes significant at high switching frequency

MOSFET Selection vs. Loss

	Conduction (IR)	Switching	Gate Driver	Other
Q1	0.21	0.49	0.06	0.14 (Qrr)
Q2	0.24		0.06	0.13 (DT)
Inductor	√			Core Loss
Rs1	√			
IC				Gate Driver
PCB	√			

- The table above shows the loss breakdown
- The selection is a tradeoff of cost and performance
- The optimized design is to minimize the loss for given MOSFETS

How to Select Inductor



Inductance Selection

- 30% to 40% peak-to-peak current at the worst scenario

$$L = \frac{V_{IN} - V_{BAT}}{\Delta I_{ripple}} \frac{V_{BAT}}{V_{IN}} \frac{1}{f_s}, \ \Delta I_{ripple} = 30\% \, I_{CHG}$$

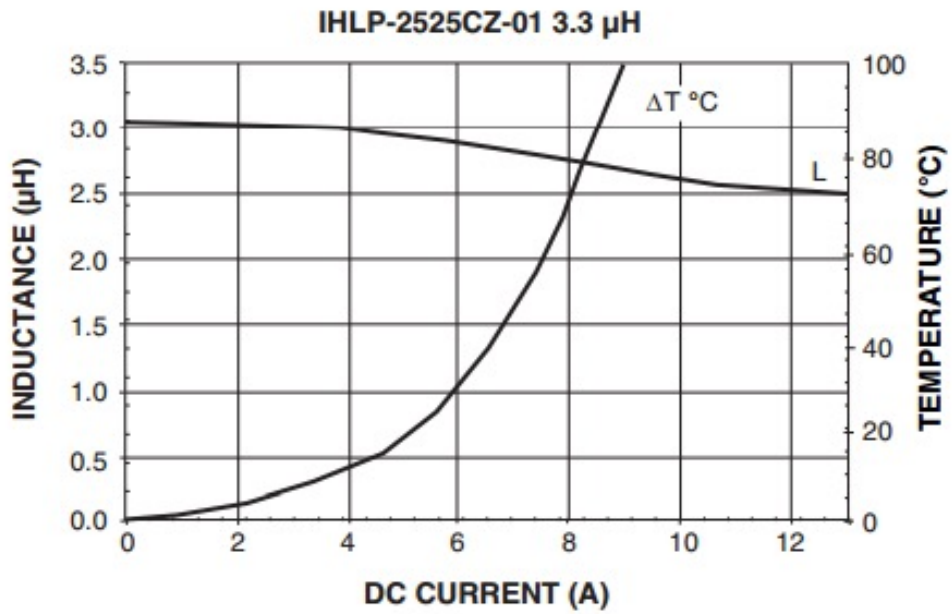
- Selection Consideration
  - Ipeak < Inductor Isat
  - Low DCR
  - Size such as low profile

- Use table in Datasheet to select

Inductor and the Loss

STANDARD ELECTRICAL SPECIFICATIONS				
L_0 INDUCTANCE ± 20 % AT 100 kHz, 0.25 V, 0 A (µH)	DCR TYP. 25 °C (mΩ)	DCR MAX. 25 °C (mΩ)	HEAT RATING CURRENT DC TYP. (A) (3)	SATURATION CURRENT DC TYP. (A) (4)
2.2	18	20	8	14
3.3	28	30	6	13.5
4.7	37	40	5.5	10

2525CZ 3.3uH (6.9mm x 6.5mm x 3mm)



- **Manufacturers provide calculation tools**

Core loss calculation: http://www.vishay.com/docs/34252/ihlpse.pdf

	Copper loss	Switching	Gate Driver	Other
Inductor	**1.11**			**0.15 (core)**

Sensing Resistors and IC Loss

Sensing Resistor

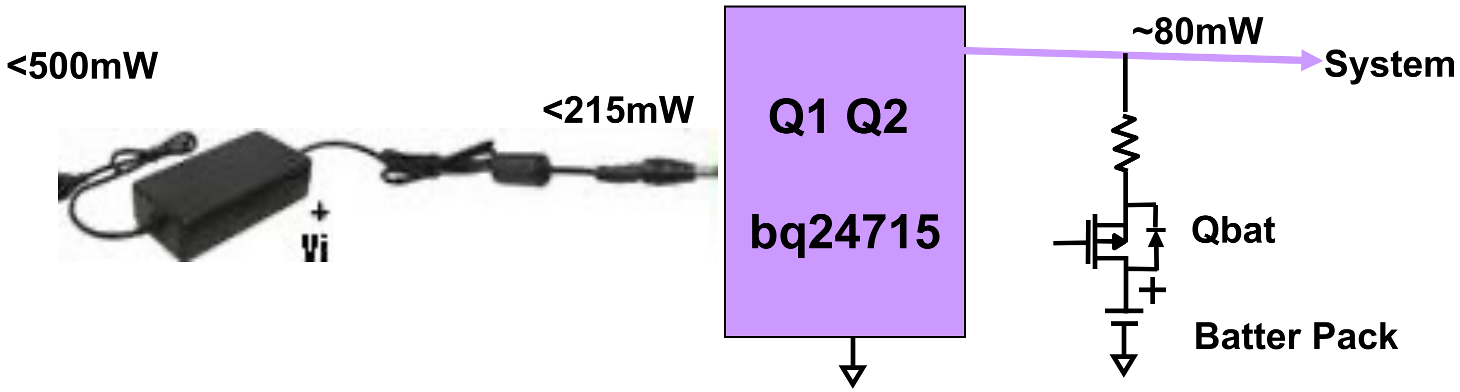
- **Selection Consideration**
  - **Accuracy : requiring high value of sensing resistance**
  - **The main source of the error is the offset of the comparator**

bq24715 PARAMETER	TEST CONDITION	MIN	TYP	MAX	UNIT
INPUT CURRENT REGULATION (0-125C)	10mΩ current sensing resistor	3937	4096	4219	V
		-3		3	%

  - **Competition needs 20mΩ sensing resistor to achieve the same accuracy**
  - **Power dissipation: requiring low value of sensing resistance**

$$P_{Rsens} = I_{IN}^{2} \cdot R_{SENSE\_IN} + I_{CHG}^{2} \cdot R_{SENSE\_CHG}$$

bq24715 Quiescent Current Efficiency

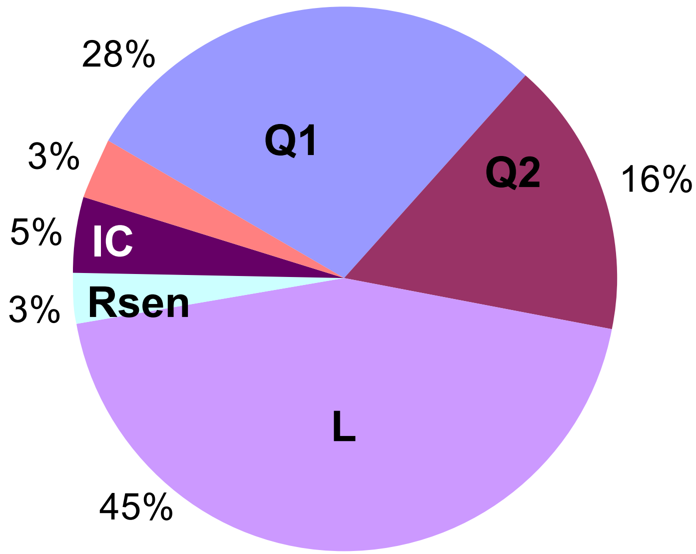


bq24715 PARAMETER	TEST CONDITION	MIN	TYP	MAX	UNIT
Standby Quiescent Current	Vin=20V, Vbat=12.6V TJ = -20 to 85°C. No switching			0.7	mA

- **Standby current**
  - **Crucial to the light load efficiency and meet the Energy Star requirement**
  - **Competition has a maximum 5mA**

Loss Breakdown

	Conduction (IR)	Switching	Gate Driver	Other
Q1	0.21	0.46	0.06	0.14 (Qrr)
Q2	0.24		0.06	0.23 (DT)
Rs1	0.09			
Inductor	1.11			0.15 (Core)
IC			0.12	0.013 (Bias)
PCB	0.1			



- The loss has a good match
  - The calculated loss is 2.86W
  - The measured loss is about 2.98W
  - Can be verified at different operation points

Summary

- MOSFET selection is based on the loss optimization and cost trade off. The loss modeling of a MOSFET is analyzed:
  1. Conduction loss
  2. Switching loss
  3. Dead time loss
  4. Gate drive
- The selection of a Inductor and the tradeoff is discussed
- Other loss in a charger circuit breakdown and the impact are addressed
- The EVM loss breakdown is conducted