Application note

STPM066S external components sizing

Introduction

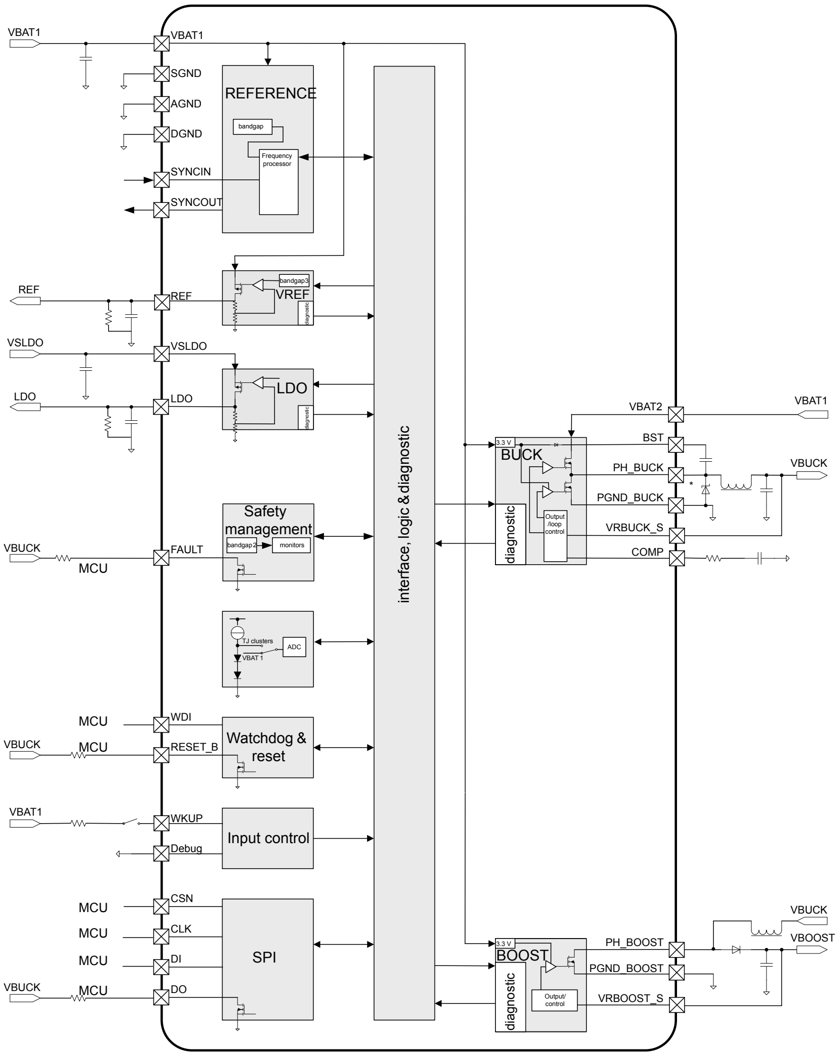
This document is intended to integrate the information provided in the STPM066S product datasheet, in order to facilitate the correct BUCK and BOOST external components sizing into the different applicative conditions. A specific focus is reserved to external components like inductor, output capacitor and compensation network.

1 STPM066S features

One of the main advantages in using a multi-regulator solution is the integration and scalability compared with a discrete solution. Figure 1 shows the STPM066S functional block diagram to have the complete view of the device.

In the next chapters the relationships to define the external components will be described. Generally, the expressions define a minimum value for those components. To avoid poor dynamic behavior, it is recommended not to exceed too much (1.5 - 2 typically) the minimum value calculated if not specifically indicated.

Figure 1. Functional block diagram

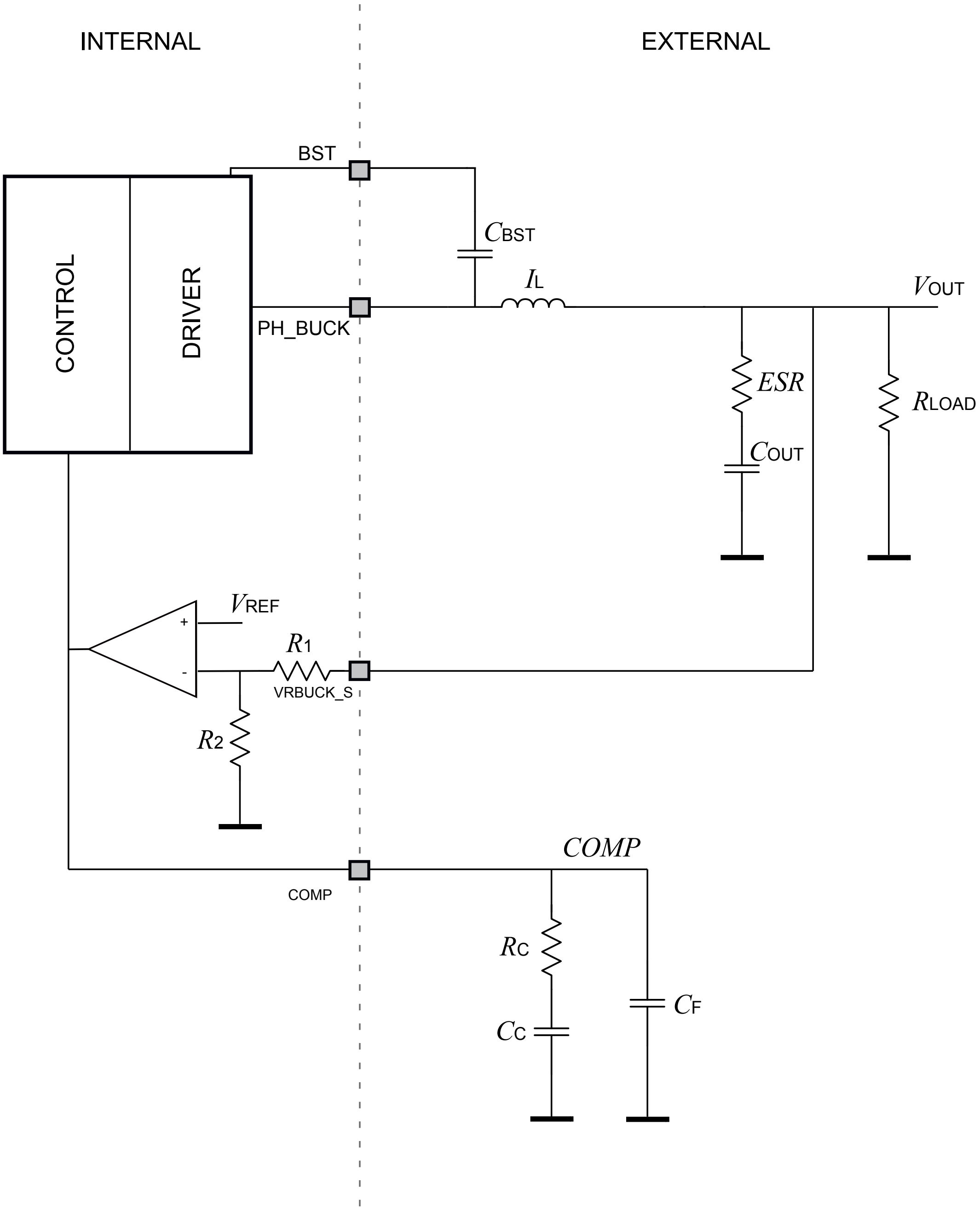


* A Schottky diode is needed. A 100 V, min 2 A forward current diode, is strongly suggested.

2 BUCK components

BUCK is a converter. It is therefore necessary to provide the inductor, the output capacitor and the compensation network externally (see Figure 2). The controller implements a peak current mode strategy.

Figure 2. Buck functional block diagram



Note: An unproper external components choice, could activate the overcurrent flag at power-up. A read and clear of the register resets the flag.

2.1 Output inductor

The value of the output inductor is usually calculated to satisfy the peak-to-peak ripple current requirement. To achieve the best compromise of cost, size and performance, it is suggested to keep the inductor current ripple between 20% and 40% of maximum load current.

As an example, the current ripple can be evaluated with the usage of Eq. (1):

$$I_{Ripple} = \Delta I_L = 0.3\, I_{OUT(MAX)} \tag{1}$$

Where $I_{OUT(MAX)}$ is the maximum output current.

Then, the inductor value can be estimated by the equation:

$$L = \frac{1}{F_{SW}\,\Delta I_L}\, V_{OUT}\left(1 - \frac{V_{OUT}}{V_{IN(MAX)}}\right) \tag{2}$$

Where F_{SW} is the switching frequency and $V_{IN(MAX)}$ is the maximum input voltage.

The peak current flowing through the inductor is:

$$I_{L(PEAK)} = I_{OUT(MAX)} + \frac{\Delta I_L}{2} \tag{3}$$

If the inductor value decreases, the peak current increases. The peak current needs to be lower than the current limit of the device.

The inductor should have a saturation current higher than the device current limit.

In order to meet slope compensation, L needs to meet the following equation:

$$L > \frac{V_{OUT}}{2\, I_{slope}} \tag{4}$$

The I_{slope} for BUCK is evaluated the with equation:

$$I_{slope} = N\, 45\, \mu A\ f_{SW} \tag{5}$$

With $N = 5{*}4000$ coefficient coming for internal components and depending on the current mirror ratio.

2.2 Output capacitor

Output capacitors are selected to support load transients and output ripple current, as well as loop stability. The voltage ripple is related to the ripple current flowing into the inductor, an adequate output capacitor sizing can reduce the impact of current ripple.

$$\Delta V_{OUT(RIPPLE)} = \Delta I_L\left(ESR + \frac{1}{8\, f_{SW}\, C_{OUT}}\right) \tag{6}$$

Considering that the goal is to define the minimum output current to satisfy the desired max output ripple the equation becomes:

$$C_{OUT(MIN)} = \frac{\Delta I_L}{8\, f_{SW}\,\left(\Delta V_{OUT(RIPPLE)} - \Delta I_L\, ESR\right)} \tag{7}$$

If the capacitor is appropriately chosen, the ESR value will be quite low then the related term can be neglected with a simplification of the above equation.

The output capacitor is also important to sustain the output voltage during a load transient. In general, minimizing the ESR value and increasing the output capacitance results in a better transient response. The ESR can be minimized by simply adding more capacitors in parallel, or by using higher quality capacitors.

$$C_{OUT(MIN)} = \frac{L}{2}\, \frac{\left(I_{OUT(MAX)} - I_{OUT(MIN)}\right)^2}{MIN\left(V_{IN} - V_{OUT}\, ,\, V_{OUT}\right)\Delta V_{OUT(MAX)}} \tag{8}$$

$\Delta V_{OUT(MAX)}$ max allowed transient output variation.

2.3 Bootstrap capacitor

A bootstrap capacitor must be connected between the BST and PH pins to provide a floating gate drive to the high-side MOSFET. For most applications 47 nF is sufficient. This should be a ceramic capacitor with a voltage rating of at least 6 V.

2.4 Compensation network

The compensation network components selection is crucial to ensure stability and good dynamic performance to the regulator. The loop control strategy as already stated is based on the peak current mode control, compatible with external RC compensation network. The error amplifier is a trans-conductance amplifier with large bandwidth, which is larger than the closed-loop one.

The basic regulator loop is modeled as a power modulator, an output feedback divider and an error amplifier. The loop transfer function is:

$$L(s) = \frac{V_{REF}}{V_{OUT}} G_{MOD}(s)\, G_{EA}(s) \tag{9}$$

Where:

V_{REF} is the internal reference voltage equal to 1 V as defined in the specific implementation.

V_{OUT} is the converter output voltage.

$G_{MOD}(s)$ is the transfer function of the error amplifier, it forms a pole and zero, as expressed in the Eq. (10):

$$G_{MOD}(s) = \frac{g_{mMOD}\, R_{LOAD}\,(1 + sESR\, C_{OUT})}{(1 + sR_{LOAD}\, C_{OUT})} \tag{10}$$

g_{mMOD} for the BUCK is 2.2 s.

R_{LOAD} is obtained for the specific output voltage and current selection as:

$$R_{LOAD} = \frac{V_{OUT}}{I_{OUT(MAX)}} \tag{11}$$

The dominant pole is:

$$f_{pMOD} = \frac{1}{2\pi\, C_{OUT}\,(R_{LOAD} + ESR)} \tag{12}$$

The zero is:

$$f_{zMOD} = \frac{1}{2\pi\, C_{OUT}\, ESR} \tag{13}$$

$G_{EA}(s)$ is the transfer function of the buck converter from control to output. As reported in the equation it forms two poles and a zero.

$$G_{EA}(s) \backsimeq \frac{g_{mEA}\, r_o\,(1 + sR_C\, C_C)}{(1 + sr_o\, C_C)(1 + sR_C\, C_F)} \tag{14}$$

g_{mEA} is the trans-conductance of the error amplifier, 1 ms.

r_o is the output resistance of the error amplifier.

The zero is:

$$f_{zEA} = \frac{1}{2\pi\, C_C\, R_C} \tag{15}$$

The first pole can be considered in the origin because r_o is very big, the second pole is:

$$f_{pEA} = \frac{1}{2\pi\, C_F\, R_C} \tag{16}$$

The choice to select the compensation values is to cancel the f_{pMOD} with f_{zEA} and the f_{zMOD} with f_{pEA}. The second cancellation is necessary only if the f_{zMOD} is near to the crossover frequency f_c (see Figure 3).

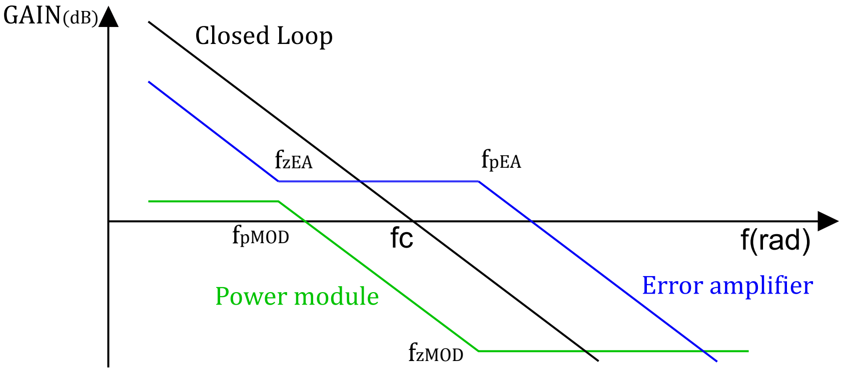


Figure 3. **BUCK simplified gain plot**

The power modulator has a DC gain reported in the Eq. (17):

$$GAIN_{MOD(DC)} = g_{mMOD}\ R_{LOAD} \tag{17}$$

The total loop gain as the product of the modulator gain, the feedback voltage-divider gain, and the error-amplifier gain at f_c should be equal to 1.

Then:

$$\frac{V_{REF}}{V_{OUT}} GAIN_{MOD}\left(f_c\right) G_{EA}\left(f_c\right) = 1 \tag{18}$$

Where:

$$GAIN_{MOD}\left(f_c\right) = GAIN_{MOD(DC)} \frac{f_{pMOD}}{f_c} \tag{19}$$

$$G_{EA}\left(f_c\right) = g_{mEA}\ R_C \tag{20}$$

Finally:

$$R_C = \frac{V_{OUT}}{g_{mEA} V_{REF}\ GAIN_{MOD}\left(f_c\right)} \tag{21}$$

The procedure to follow step by step to define the external network components is:

1. Choose a suitable value for f_c, usually between $\frac{f_{SW}}{5}$ and $\frac{f_{SW}}{10}$.
2. Choose the V_{OUT} value within the selectable options.
3. Calculate the value of R_C:

$$R_C = \frac{V_{OUT}}{g_{mEA} V_{REF}\ GAIN_{MOD}\left(f_c\right)} \tag{22}$$

4. Calculate the C_C value by forcing $f_{pMOD} = f_{zEA}$:

$$C_C = \frac{1}{2\pi\, f_{pMOD}\, R_C} \tag{23}$$

5. If f_{zMOD} is less than 5 f_c, add a second capacitor, C_F, by forcing $f_{zMOD} = f_{pEA}$:

$$C_F = \frac{1}{2\pi\, f_{zMOD}\, R_C} \tag{24}$$

2.5 PH diode

It is necessary to insert a Schottky diode between the BUCK phase and GND as close as possible to the device pins. The diode must ensure almost 2 A forward current and minimum 100 V for reverse voltage.

2.6 Specific sizing example

2.6.1 Example 1

The use of the BUCK as pre-regulator has been considered. This leads to an assumption of $V_{IN} = 12\,V$ and $V_{OUT} = 5\,V$, $I_{OUT(MAX)} = 2\,A$ and $f_{SW} = 400\,kHz$.

$$\Delta I_L = 0.3\,I_{OUT(MAX)} = 0.6\,A \tag{25}$$

$$L = \frac{1}{F_{SW}\,\Delta I_L}\,V_{OUT}\left(1 - \frac{V_{OUT}}{V_{IN(MAX)}}\right) = 15\,\mu H \tag{26}$$

This value needs to be checked with respect to the absolute minimum due to I_{slope}.

$$I_{slope} = N\,45\,\mu A\,f_{SW} = 0.36\,A/\mu s \tag{27}$$

$$L_{MIN} > \frac{V_{OUT}}{2\,I_{slope}} = 7.0\,\mu H \tag{28}$$

From this check it is confirmed the value of L previously calculated.
With a choice of 2.5% max variation for the output $\Delta V_{OUT(RIPPLE)} = 0.125\,V$.

$$C_{OUT(MIN)} = \frac{\Delta I_L}{8\,f_{SW}\,\left(\Delta V_{OUT(RIPPLE)} - \Delta I_L\,ESR\right)} = 1.5\,\mu F \tag{29}$$

A reasonable choice can be $C_{OUT} = 1.8\,\mu F$.

To complete the C_{OUT} evaluation it is necessary to take into account also the dynamic load current variation (see Eq. (1)). The example does not include this contribution for sake of clarity.

After choosing the inductor and capacitor values it is possible to define the compensation network, starting from the evaluation of f_{pMOD} and f_{zMOD}.

With $R_{LOAD} = \frac{V_{OUT}}{I_{OUT(MAX)}} = 2.5\,\Omega$ and $ESR = 0.01\,\Omega$

$$f_{pMOD} = \frac{1}{2\pi\,C_{OUT}\,(R_{LOAD} + ESR)} = 35\text{ KHz} \tag{30}$$

$$f_{zMOD} = \frac{1}{2\pi\,C_{OUT}\,ESR} = 8.8\,MHz \tag{31}$$

With this previous info and defined the $f_c = 80\,KHz$ and $GAIN_{MOD(DC)} = 5.5$, the $GAIN_{MOD(f_c)}$ is:

$$GAIN_{MOD(f_c)} = GAIN_{MOD(DC)}\,\frac{f_{pMOD}}{f_c} = 2.4 \tag{32}$$

Last step is to evaluate the compensation values R_C, C_C:

$$R_C = \frac{V_{OUT}}{g_{mEA}\,V_{REF}\,GAIN_{MOD(f_c)}} = 2.1\,K\Omega \tag{33}$$

$$C_C = \frac{1}{2\pi\,f_{pMOD}\,R_C} = 2.16\,nF \tag{34}$$

Finally, the optional extra capacitor C_F:

$$C_F = \frac{1}{2\pi\,f_{zMOD}\,R_C} = 8.61\,pF \tag{35}$$

2.6.2 Example 2

In this example it is considered to use the BUCK as post-regulator. This leads to an assumption of $V_{IN} = 5\ V$ and $V_{OUT} = 1.5\ V$, $I_{OUT(MAX)} = 2\ A$ and $f_{SW} = 2.4\ MHz$.

$$\Delta I_L = 0.3\ I_{OUT(MAX)} = 0.6\ A \tag{36}$$

$$L = \frac{1}{F_{SW}\,\Delta I_L}\ V_{OUT}\left(1 - \frac{V_{OUT}}{V_{IN(MAX)}}\right) = 0.66\ \mu H \tag{37}$$

This value needs to be checked with respect to the absolute minimum due to I_{slope}.

$$I_{slope} = N\ 45\ \mu A\ f_{SW} = 2.16\ A/\mu s \tag{38}$$

$$L_{MIN} > \frac{V_{OUT}}{2\ I_{slope}} = 0.35\ \mu H \tag{39}$$

From this check it is chosen the value $L = 1.2\ \mu H$.

With a choice of 2.5% max variation for the output $\Delta V_{OUT(RIPPLE)} = 0.0375\ V$.

$$C_{OUT(MIN)} = \frac{\Delta I_L}{8\ f_{SW}\ \left(\Delta V_{OUT(RIPPLE)} - \Delta I_L\ ESR\right)} = 1\ \mu F \tag{40}$$

A reasonable choice can be $C_{OUT} = 1.8\ \mu F$.

To complete the C_{OUT} evaluation it is necessary to take into account also the dynamic load current variation (see Eq. (1)). The example does not include this contribution for sake of clarity.

After choosing the inductor and capacitor values it is possible to define the compensation network, starting from the evaluation of f_{pMOD} and f_{zMOD}.

With $R_{LOAD} = \frac{V_{OUT}}{I_{OUT(MAX)}} = 0.75\ \Omega$ and $ESR = 0.01\ \Omega$

$$f_{pMOD} = \frac{1}{2\pi\ C_{OUT}\ (R_{LOAD} + ESR)} = 116\ \text{KHz} \tag{41}$$

$$f_{zMOD} = \frac{1}{2\pi\ C_{OUT}\ ESR} = 8.8\ MHz \tag{42}$$

With this previous info and defined the $f_c = 480\ KHz$ and $GAIN_{MOD(DC)} = 1.65$, the $GAIN_{MOD(f_c)}$ is:

$$GAIN_{MOD(f_c)} = GAIN_{MOD(DC)}\ \frac{f_{pMOD}}{f_c} = 0.4 \tag{43}$$

Last step is to evaluate the compensation values R_C, C_C:

$$R_C = \frac{V_{OUT}}{g_{mEA}\ V_{REF}\ GAIN_{MOD(f_c)}} = 3.75\ K\Omega \tag{44}$$

$$C_C = \frac{1}{2\pi\ f_{pMOD}\ R_C} = 0.37\ nF \tag{45}$$

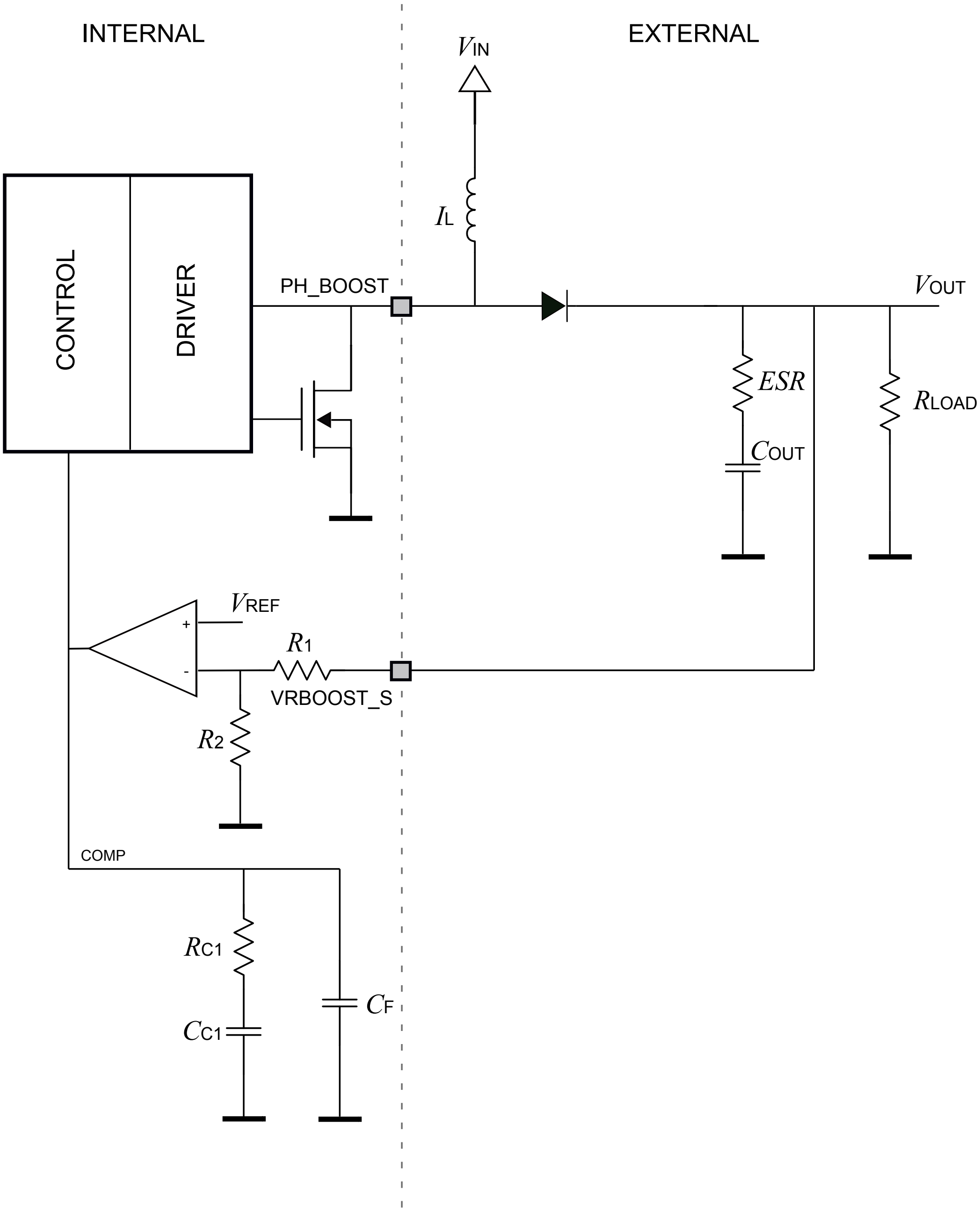
Finally, the optional extra capacitor C_F:

$$C_F = \frac{1}{2\pi\ f_{zMOD}\ R_C} = 4.82\ pF \tag{46}$$

3 BOOST components

BOOST controller integrates the compensation network, it is then needed to provide externally only the diode, the inductor and the output capacitor. The controller implements a peak current mode strategy. The implementation block diagram is reported in Figure 4.

Figure 4. **BOOST Functional block diagram**



3.1 Output inductor

The inductor value depends on the allowed ripple current in the coil, directly related to V_{IN}, V_{OUT} and f_{SW}.

In the specific Boost case, the maximum inductor value acceptable is limited by RHP zero value. The RHP (Right-Half-Plane) zero limits the cross frequency and is evaluated with the following equation:

$$f_{Z,\ RPH} = \frac{R_{LOAD}\left(\frac{V_{IN}}{V_{OUT}}\right)^2}{2\pi\, L} \quad (47)$$

From this, it is possible to obtain the inductor value for a specific $f_{Z,\ RPH}$ choice, for example with $f_{Z,\ RPH} = \frac{f_{SW}}{\pi}$ the L is reported in the equation:

$$L\ =\ \frac{V_{IN}\,(1-D)}{2\,I_{LOAD}\,f_{SW}} \quad (48)$$

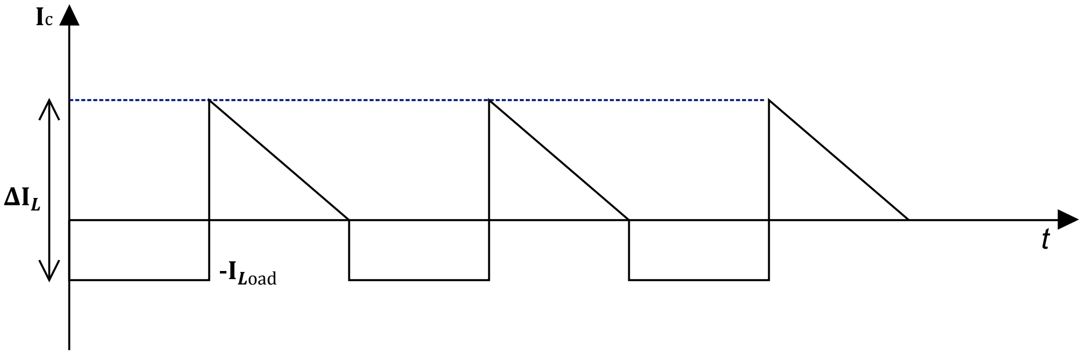
With $D =\ 1 - \frac{V_{IN}}{V_{OUT}}$ phase duty-cicle.

This result is obtained with the choice of a specific ΔI_L reported in the equation:

$$\Delta I_L = \frac{2\,D}{(1-D)}\,I_{LOAD} \quad (49)$$

That results in the condition of zero current (see Figure 5) on output capacitor when the low side turns on.

Figure 5. **BOOST output capacitor ripple current**



3.2 Output capacitor

The output capacitor choice directly impacts on two important aspects, the transient response and the output static ripple. The assumption made here is to simplify the overall system response by cancelling the zero defined by the compensation network with the main pole generated with the external components choice.

The two frequencies, the zero f_{ZC} and the pole f_{P1} are evaluated with the following equations:

$$f_{ZC} = \frac{1}{2\pi\, R_{C1} C_{C1}} \quad (50)$$

$$f_{P1} = \frac{\left((1-D)^3 \frac{\left(0.5 + \frac{S_e}{S_n}\right)}{L\, C_L\, f_{sw}} + \frac{2}{R_L\, C_L}\right)}{2\pi} \quad (51)$$

In which $C_{C1} = 240\, pF$ and $R_{C1} = 42\, K\Omega$ are the capacitor and the resistor of the internal compensation network. Instead, S_e is the slope compensation coefficient in the specific implementation defined as $S_e = 0.528\, A/\mu s$ and S_n in the inductance current slope during ON phase evaluated with the equation:

$$S_n = \frac{V_{IN}\ - \frac{(ESR_L + R_{SW})}{1-D} I_{OUT}}{L} \quad (52)$$

In which R_{SW} is the total equivalent ON resistance (0.7 Ω) and ESR_L is the equivalent series resistance related to the chosen inductor.

The following equation, to evaluate the minimum value for the output capacitor, is obtained forcing the condition $f_{ZC} =\ f_{P1}$:

$$C_{OUT} = R_{C1} C_{C1} \left((1-D)^3 \frac{\left(0.5 + \frac{S_e}{S_n}\right)}{L\ f_{sw}} + \frac{2}{R_L} \right) \tag{53}$$

As a final check it is possible to compute the output static ripple $V_{OUT(Ripple)}$ with the following equation to confirm that it is in the acceptable range for the specific application case.

$$V_{OUT(Ripple)} = \frac{I_{OUT}\ D}{C_{OUT}} \frac{1}{f_{SW}} \tag{54}$$

To improve the overall performance, it is a good practice to choose output capacitors with low ESR.

As a direct implication of the BOOST inner compensation, which is fixed, the maximum acceptable output capacitor needs to be selected based on compensation, bandwidth and phase margin.

3.3 Output diode

The reverse voltage of selected diode needs to be at least $1.25\ V_{OUT}$ of the boost.

The peak current rating of the diode must be greater than the maximum inductor current.

To reduce the power losses, it is a good practice to choose a Schottky diode. The power dissipation of the diode is estimated with the equation:

$$P_{D(MAX)} = V_{FD}\ I_{OUT} \tag{55}$$

In which V_{FD} is diode forward drop voltage.

3.4 Input capacitor

The input capacitor is chosen based on $V_{IN(Ripple)}$ and can be calculated as below.

$$C_{IN} > \frac{I_{RIPPLE}}{4\ V_{IN(Ripple)}\ f_{SW}} \tag{56}$$

$$ESR > \frac{V_{IN(Ripple)}}{2\ I_{IN(Ripple)}} \tag{57}$$

3.5 Specific sizing example

Considering a configuration in which the BOOST output voltage is $V_{OUT} = 5\,V$ and the input voltage $V_{IN} = 3.3\,V$, it is provided by a pre-regulator. With the output voltage chosen the current in the inductor is limited to $I_{lim} = 0.6\,A$ that defines also the maximum output current as calculated in the equation:

$$I_{OUT(MAX)} = I_{lim}\frac{(1-D)}{(1+D)} \tag{58}$$

In the case under analysis $D = 1 - \frac{V_{IN(MIN)}}{V_{OUT}} = 1 - \frac{3}{5} = 0.4$

As a result $I_{OUT(MAX)} = 257\,mA$

With this info:

$$L = \frac{V_{IN}\,(1-D)}{2\,I_{LOAD}\,f_{SW}} = 1.45\,\mu H \tag{59}$$

A reasonable choice can be $L = 1.5\,\mu H$

With L value assigned the S_n can be calculated with Eq. (52):

$$S_n = 1.8\,A/\mu s \tag{60}$$

The minimum capacitance value $C_{OUT(MIN)} = R_{C1}C_{C1}\left((1-D)^3\frac{\left(0.5+\frac{S_e}{S_n}\right)}{L\,f_{sw}} + \frac{2}{R_L}\right) = 1.36\,\mu F$

A reasonable choice can be $C = 1.8\,\mu F$

Output voltage ripple can be evaluated for the chosen values considering the equation:

$$V_{OUT(Ripple)} \approx 23\,mV \tag{61}$$

4 Conclusion

The present application note is intended to explain and facilitate the correct BUCK and BOOST external components sizing into the different applicative conditions. The main info to highlight is to keep the selected value close to the calculated one due to the high impact of external components on the stability of the overall system.

Revision history

Table 1. **Document revision history**

Date	Revision	Changes
09-Feb-2023	1	Initial release.

Contents

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