Introduction
This TIP is aimed at improving the knowledge of engineers and sales people, as it is not really possible to delve into that level of details on LDO datasheets. On the pages that follow, you will learn that current limiter/current foldback circuits of LDO’s come in many different forms. Moreover, we will show that, by using the $V_{OUT}$ vs. $I_{OUT}$ characteristics, you can often anticipate –at least partially- how the output voltage and output current of the LDO will vary at start-up. This concept, briefly explained on the “XC6219 Current Foldback Circuit” TIP for one type of LDO, will be further detailed here. Finally, since output current waveforms at start-up include a significant amount of inrush current, this document will highlight as well the benefits of Torex LDO’s with inrush current protection.

Types of Current limiting/Current foldback Circuits

The current limiting/current foldback circuits used by Torex LDO’s can be divided into 4 main types:
A) Current limiter, then current foldback;
B) Current foldback only;
C) Current limiter, then current limiter;
D) Current foldback, then current limiter.

Please note that the order selected is based on when the LDO is enabled and an excessive amount of output current is requested on the output side of the LDO. For a “type A” LDO, this means that the current limiter is activated first, followed by the current foldback, hence the above statement: “A) Current limiter, then current foldback”.

The below figure shows the typical VOUT vs. IOUT waveforms for these 4 circuits.
Moreover, the below table highlights which type of current limiting/current foldback circuitry is used by the main Torex LDO’s.

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<tr>
<th>LDO series</th>
<th>Limiter TYPE</th>
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<tr>
<td></td>
<td>Type A</td>
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<td>XC6204</td>
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<td>XC6209</td>
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<td>XC6701</td>
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In this table, most of the older Torex LDO’s (XC6204, XC6219, etc) are of type A, where the current limiter circuit was added due to the lack of accuracy of the current foldback circuit.

Then, around the year 2005, it became possible to use the foldback circuit as a current limiter too. So Torex introduced LDO’s of type B, with a current foldback circuit that can detect accurately when an over-current condition occurs. The protection circuits required for types A and B LDO’s are smaller than the protection circuits for types C and D LDO’s, making it possible to integrate types A and B LDO’s inside smaller packages. For example, ultra small-size LDO’s such as the XC6224 and XC6504 are of type A.

However, using current foldback can sometimes prevent the LDO from starting up when the initial output voltage on customers’ applications is slightly negative (down to -0.2V). Using an LDO whose first limiting circuit (at start-up) is a current limiter instead of a current foldback can circumvent this issue. This is why type C LDO’s (XC6223, XC6503, etc) were introduced. Despite it may appear obvious to many, we shouldn’t forget that the main reason for including a current limiter in types A and C LDO’s is the high accuracy of the set current limit. But, although type C LDO’s fix a problem at start-up, they create a new problem when an over-current condition occurs because the decrease in $V_{OUT}$ activated by their over-current protection circuit is not accompanied by a decrease in output current until $V_{OUT}$ drops below 1V, leading to more over-heating than types A and B.

Whereas both type D and type C LDO’s can solve the problem faced by types A and B LDO’s during start-up, type D LDO’s can also avoid the aforementioned issue faced by type C LDO’s during an over-current condition. So Torex recently started the development of such LDO’s with the XC6505 series. It is worth noting as well that, thanks to the addition of a thermal shutdown circuit, some type C LDO’s don’t face the over-heating problem during an over-current condition.

Because of all the above explanations, most of the new Torex LDO’s will be of type C or type D. Moreover, Torex keeps on improving and reducing the size of these limiter circuits, so that they can be integrated in ultra small-size packages.
Further comments before delving into details

We are now going to introduce the behavior at start-up for various LDO’s: 1 of type A, 1 of type B and 2 of type C. Since the XC6505 is currently the only Torex LDO of type D, it was considered unnecessary to dedicate a full chapter to it. Please note that series differ from one another. As a consequence, since the below example for “type A” LDO focuses only on the XC6219 series, you shouldn’t use it to draw any conclusion regarding the behavior of other series of “type A” LDO’s at start-up, as it is possible that they will behave differently. The same remark applies for types B, C and D LDO’s. In any case, this document is a good starting point and can be kept as a reference whenever you need to investigate the start-up behavior of a Torex LDO.

Since the waveforms that will follow often include the output current $I_{OUT}$ of the LDO, let’s clarify where this output current is measured with the following circuit diagram. As can be seen, the current probe should be inserted between the output pin $V_{OUT}$ of the LDO and the output capacitor $C_L$. If the current probe is positioned after $C_L$, critical information is lost as all the start-up generated inrush current will be absorbed by $C_L$.

\[\text{Current probe to measure } I_{OUT}\]

Unless stated otherwise, $C_{IN} = C_L = 1\mu F$ and the input voltage $V_{IN}$ is always set 1.0V above the regulated output voltage of the LDO. For example, when the regulated output voltage of the LDO is 3.0V, $V_{IN}$ is set to 4.0V.

Case studies

1) LDO of Type A

Our first example is going to be the XC6219B302MR. For that matter, the below 3 graphs are showing how the output current varies when the XC6219B is enabled via its CE pin and needs to supply 3 different values of continuous current (20mA, 80mA and 150mA) to an output load. All $I_{OUT}$ waveforms look similar, apart from the fact that they peak at slightly different values.

Please note that for the below graphs—and for all graphs that follow—, the output current was set with a variable resistor.
We are now going to study the start-up waveforms in further details, by using the case when the LDO is enabled and needs to supply 20mA. For that matter, the below waveforms are simply zoomed waveforms of the above-left graph. Characteristic graph below exhibits the $V_{OUT}$ vs. $I_{OUT}$ characteristics of the XC6219B302MR. The waveforms below are simply zoomed waveforms of the above-left graph.

Initially, both $V_{OUT}$ and $I_{OUT}$ are at 0V. Then, as was explained on the “XC6219 Current Foldback Circuit” TIP, $V_{OUT}$ and $I_{OUT}$ have got the remain on the current foldback curve during start-up, so the values of $V_{OUT}$ and $I_{OUT}$ always correspond to a point of the current foldback curve, as we are now going to see. First of all, the output current starts ramping up to about 20mA whereas $V_{OUT}$ remains at 0V (see V1, I1). Then, as $V_{OUT}$ starts increasing, $I_{OUT}$ increases as well, but in such a way that $V_{OUT}$ and $I_{OUT}$ always correspond to the coordinates of a point of the current foldback curve (see for example V2, I2). Following that, the output current reaches the end of the current foldback curve, which is as well the beginning of the current limiter curve (see V3, I3). The output current hardly increases any further, while the output voltage ramps up to its set value. Finally, when $V_{OUT}$ reaches its set value (see V4, I4), the output current is stripped of its inrush current component and decreases down to the continuous current value requested by the output load (see V5, I5). In the case of the XC6219, the latter step between (V4, I4) and (V5, I5) is a bit noisy for the output current.

There are a few points worth mentioning regarding the above behavior: in a way, at start-up, the current foldback circuit acts like some kind of inrush protection circuit by forcing the output current $I_{OUT}$ to always remain on the foldback curve of the $V_{OUT}$ vs. $I_{OUT}$ characteristics. Take for example the above case when $V_{OUT} = V2 = 0.7V$. Due to inrush current, $I_{OUT}$ wants to increase as high as possible, but it can’t because it is forced to remain on the foldback curve. So $I_{OUT} = I2 = 100mA$.

As you will notice by looking at the below graph, inrush current is controlled by the current foldback circuit until $V_{OUT}$ reaches its set value. Then $I_{OUT}$ goes into stable and becomes the current value required by the output load. The continuous current in this example is 0mA.
As we have just seen, when $V_{\text{OUT}}$ ramps up towards its set value, $I_{\text{OUT}}$ is forced to follow so that any $(V_{\text{OUT}}, I_{\text{OUT}})$ coordinates can remain on the foldback curve. This is exactly what happens on the above graph, and this causes the output current to ramp up to 258mA despite the actual output current demand is 0mA. But, then, without current foldback, the output current would probably peak at an even higher value under the same conditions.

One can say that the $I_{\text{OUT}}$ waveform during start-up is shaped by the current foldback circuit. We already knew that the $V_{\text{OUT}}$ vs. $I_{\text{OUT}}$ characteristics of the LDO clearly describe its behavior in the case of an over-current condition. But, in addition to that, we have now demonstrated that, by going in the opposite direction on the same waveform (the direction of the red arrows on the previous $V_{\text{OUT}}$ vs. $I_{\text{OUT}}$ graph), we can as well anticipate the behavior at start-up of an LDO with current foldback such as the XC6219B.

Further insight on the operation of the current limiter/current foldback for type A LDO’s can be gained by referring to Appendix A.1.

2) LDO of type B
Let’s carry on with the XC6221A302MR, which uses current foldback only (type B). The below 3 graphs are showing how the output current varies when the XC6221A is enabled via its CE pin and needs to supply 3 different values of continuous current (20mA, 80mA and 150mA) to an output load. As can be seen, in all cases, the output current seems to follow the same pattern during start-up, and ramping up to 260mA by keeping linearity according to the operating current of foldback circuit, finally setting to the current value required by the output load, please note that, in all 3 cases, $C_{\text{IN}} = C_{\text{L}} = 1\mu\text{F}$.

We are now going to study the start-up waveforms in further details, by using the case when the LDO is enabled and needs to supply 20mA as the same condition as XC6219B. The graph exhibits the $V_{\text{OUT}}$ vs. $I_{\text{OUT}}$ characteristics of the XC6221A302MR. The waveforms next are simply zoomed waveforms of the above-left graph.
We are starting from the first red dot at voltage $V_1$ and current $I_1$. Initially, when the CE pin of the XC6221 becomes “high”, the LDO is activated and some inrush current tries to flow towards the output capacitor $C_L$ of the LDO. At this stage, the foldback current circuit works and suppresses the inrush current around 30mA. Then, as $V_{OUT}$ starts ramping up, the inrush current increases as well to the corresponding value on the foldback curve.

When $V_{OUT}$ ramps up to $V_2$ during start-up, $I_{OUT}$ will always be equal to $I_2$, not more, not less.

This slow increase of both $V_{OUT}$ and $I_{OUT}$ along the foldback curve carries on until $V_{OUT}$ reaches its set value (see $V_3$), at what point the output current is equal to the value of the current limit of the XC6221 during normal operation (see $I_3$).

Then, the output current decreases down to the requested amount of output current -20mA here (see $I_4$).

As was shown previously with the XC6219B, the current foldback circuit forces the output current to remain on the foldback curve.

Since the output current remains on the foldback curve while $V_{OUT}$ ramps up, the output current will reach the current limit value before settling down to the $I_{OUT}$ value requested by its output load—as was the case with the XC6219B.

When we focus on the XC6223F series later on this document, we will see how such problems can be avoided with an LDO including a dedicated circuit for inrush current protection.

3) LDO of type C

Now, we are going to show the behavior at start-up for two LDO’s of type C, the XC6223F and XC6223B series, which are respectively with and without inrush current protection.

**XC6223B series**

The below 3 graphs show how the XC6223B301 (without inrush current protection) reacts when it is enabled via its CE pin and needs to supply respectively 20mA, 80mA and 150mA of output current. Once again, the output current waveforms all follow the same pattern at start-up. However, please notice that, compared with the XC6221, the initial high current spikes have disappeared.

These high current spikes -or actually, the lack of them- can be more clearly observed on the below figure, which shows zoomed versions of the waveforms on the above-left graph. We are now going to use these zoomed waveforms as well as one additional graph (see below) in order to detail the behavior of the XC6223B301 when it is enabled via its CE pin and needs to supply a continuous current of 20mA to an output load. These are the same conditions as used for the previous XC6219B and XC6221 case studies).
When the IC is enabled via its CE pin, the output current is limited to 50mA until $V_{OUT}$ reaches about 0.8V (see V2, I2). Then the current limit is increased to about 115mA (see V3, I3), but only for a few µs. After that, all what limits the output current is the higher current limit of the IC, so the output current increases fast until it reaches this limit (see V4, I4). It is worth noting that, between the points (V3, I3) and (V4, I4), the output current is not on the $V_{OUT}$ vs. $I_{OUT}$ waveform, as was the case for the XC6221 with current foldback (once again, it is only for LDO’s whose current foldback circuit activates first at start-up that the over-current and start-up waveforms stay on the same $(V_{OUT}, I_{OUT})$ curve—with opposite directions). Finally, $V_{OUT}$ reaches 3.0V, and the output current decreases down to the value of continuous current (20mA) required by the output load (see V5, I5).

In the XC6223B01, the output current still peaks at about 370mA afterwards, no matter what continuous current is required by the output circuitry until the output voltage reaches its set voltage. This 370mA peaking can be reduced by opting for an LDO with dedicated circuitry for inrush current protection, such as the XC6223F.

### XC6223F series

The below 3 graphs show how the XC6223F301 (with inrush current protection) reacts when it is enabled via its CE pin and needs to supply respectively 20mA, 80mA and 150mA of output current. In order to highlight how low the output current peaks at start-up, we have used the same scale as with the XC6221 and XC6223B. However, compared with the previous cases when 3 graphs were lined up next to each other, the timescale has now been increased from 10µs/division to 40µs/division. Said differently, the XC6223F ramps up slightly slower than the XC6221 and XC6223B, but this spreading of the inrush current over a longer interval is what prevents any unwanted output current peaks over the whole start-up procedure.

Since the output current waveforms differ quite a bit between the above-left and right graphs, let’s study both graphs in further details. First of all, the below zoomed waveforms and “$V_{OUT}$ vs. $I_{OUT}$” characteristics will be used to explain the behavior of the XC6223F301 under the same start-up conditions as the previous detailed examples for the XC6219B, XC6221 and XC6223B (the LDO is enabled and needs to supply 20mA). Please note that the below timescale has been reduced from 40µs/division down to 10µs/division compared with the above-left graph.
Initially, when the XC6223F is enabled, the output current (mainly its inrush current component) is immediately restricted by the lower current limit, in a similar way to what was observed with the XC6223B301. While the inrush current is limited to about 50mA, the output voltage starts rising (V2, I2). When the output voltage reaches about 0.8V, the current limit is increased to about 115mA and remains at this value until a timer delay elapses. So \( V_{\text{OUT}} \) keeps on increasing whereas the output current is prevented to rise above 115mA (see V3, I3). Finally, the output voltage reaches its set voltage and the output current is reduced to the 20mA of continuous current requested by its output load.

It is possible for the output current waveform to differ from the previous one. This happens when the output current has not reached its set voltage when the timer delay of the second current limit (115mA) elapses.

For that purpose, we are going to use another example of the XC6223F301 behavior when the output current is increased to 150mA.

To generate the same state, we could have increased the value of the output capacitor from 1µF to 10µF. But this wouldn’t reflect most customer designs. So, instead of that, we will simply increase to 150mA the amount of output current that the LDO needs to supply when enabled.

For that matter, please refer to the following graph and waveforms. A timescale of 40µs/division has been used.

At first, the waveforms are similar to the previous example: the output current is initially limited to about 50mA (V2, I2) until \( V_{\text{OUT}} \) rises to about 0.8V, then the output current gets limited to about 115mA for a certain timer delay while the output voltage carries on increasing (see V3, I3). However, in the present case, the output current increases until \( V_{\text{OUT}} \) reaches its set value (see V4, I4). Then the output current decreases down to 150mA.

These two examples using the XC6223F have highlighted that the “\( V_{\text{OUT}} \) vs. \( I_{\text{OUT}} \)” waveforms at start-up for such an IC can actually be a multitude of different waveforms. The following graph shows 3 of the possible waveforms in red, orange and yellow. The yellow waveform is an exaggerated case which corresponds to conditions that most customers are unlikely to encounter (output capacitor of 10µF instead of 1µF, combined with a high output current requirement at start-up). However, it was included in order to make you realize that it is possible for the inrush current of the XC6223F to reach well over 150mA even in such case.

Another conclusion to draw from the below graphs is that, as opposed to LDO’s such as the XC6219B and XC6221, using the \( V_{\text{OUT}} \) vs. \( I_{\text{OUT}} \) characteristics of the XC6223F in order to anticipate its start-up behavior is not very practical.
Summary

This document has shed some light on the behavior of current foldback and current limiter circuits. As was shown, these circuits come in many different forms and with their own advantages. For example, a current foldback circuit is often included amongst the protection circuits of Torex LDO’s because it offers some sort of cheap inrush protection at start-up in addition to its main purpose, which is to reduce the output current in the event of over-current condition. Of course, when proper inrush current protection is required, we have shown that a current foldback circuit can’t really compete with a circuit dedicated to inrush current protection. However, we mustn’t forget that the latter will require additional circuitry and will render the LDO slightly slower at start-up.