

LDO Current Foldback/Current Limiter Circuits



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.

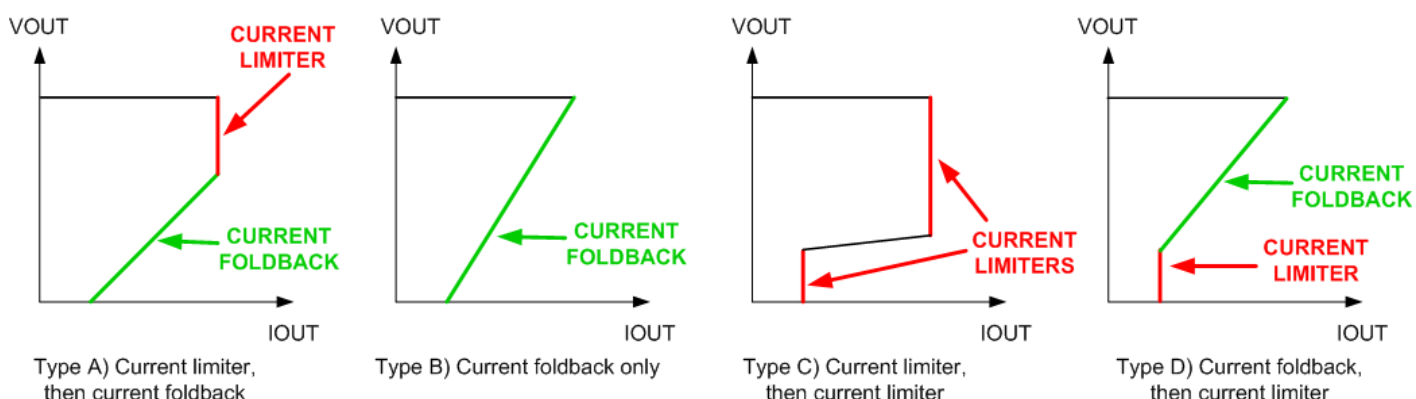
TYPES OF CURRENT LIMITING/CURRENT FOLDBACK CIRCUITS

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 V_{OUT} vs. I_{OUT} 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.

LDO series	Limiter TYPE			
	Type A	Type B	Type C	Type D
XC6204	X			
XC6209	X			
XC6210	X			
XC6214		X		
XC6215		X		
XC6216		X		
XC6217		X		
XC6218		X		
XC6219	X			
XC6220	X			
XC6221		X		
XC6222		X		
XC6223			X	
XC6224	X			
XC6227		X		
XC6501		X		
XC6503			X	
XC6504	X			
XC6505				X
XC6602		X		
XC6701		X		

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.

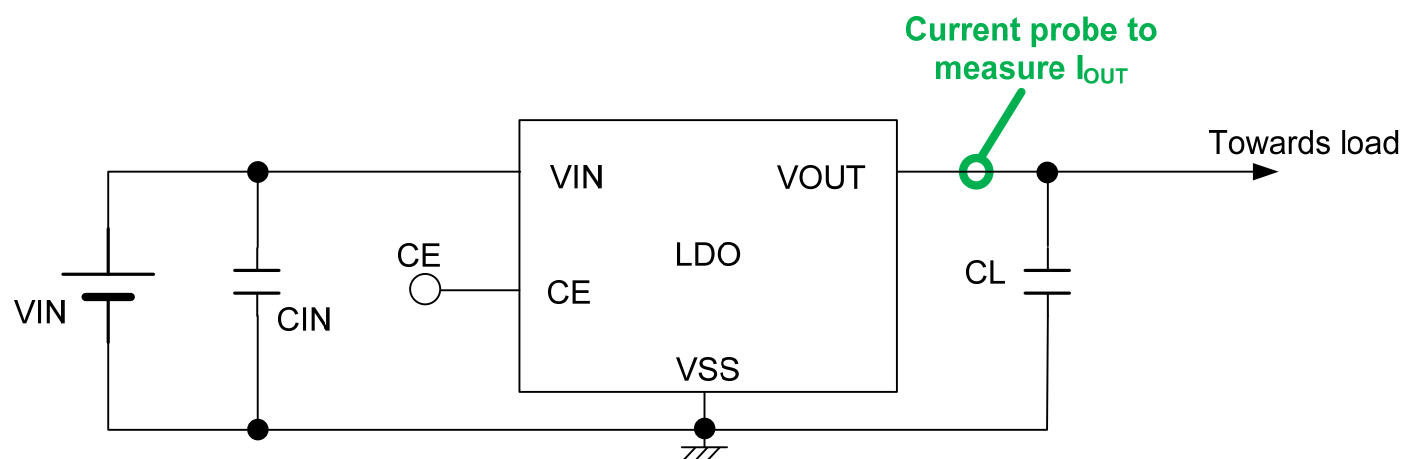
Whereas both **type D** and type C LDO's can solve the problem faced by types A and B LDO's during start-up, type D LDO's can also avoid the aforementioned issue faced by type C LDO's during an over-current condition. So Torex recently started the development of such LDO's with the XC6505 series. It 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 .



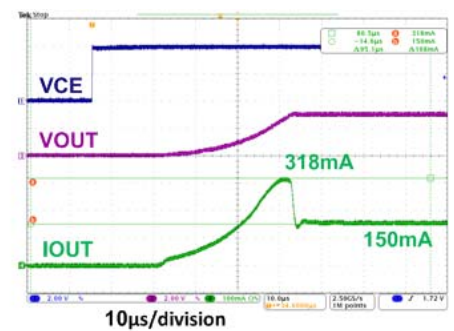
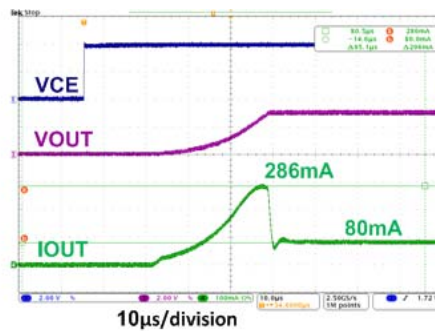
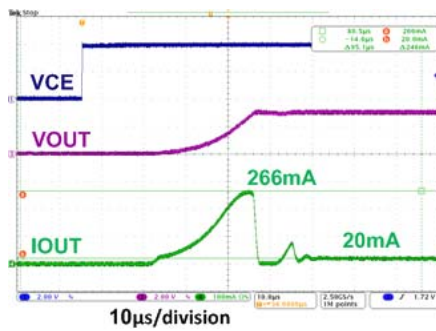
Unless stated otherwise, $C_{IN} = C_L = 1\mu F$ and the input voltage V_{IN} is always set 1.0V above the regulated output voltage of the LDO. For example, when the regulated output voltage of the LDO is 3.0V, V_{IN} is set to 4.0V.

CASE STUDIES

1) LDO of Type A

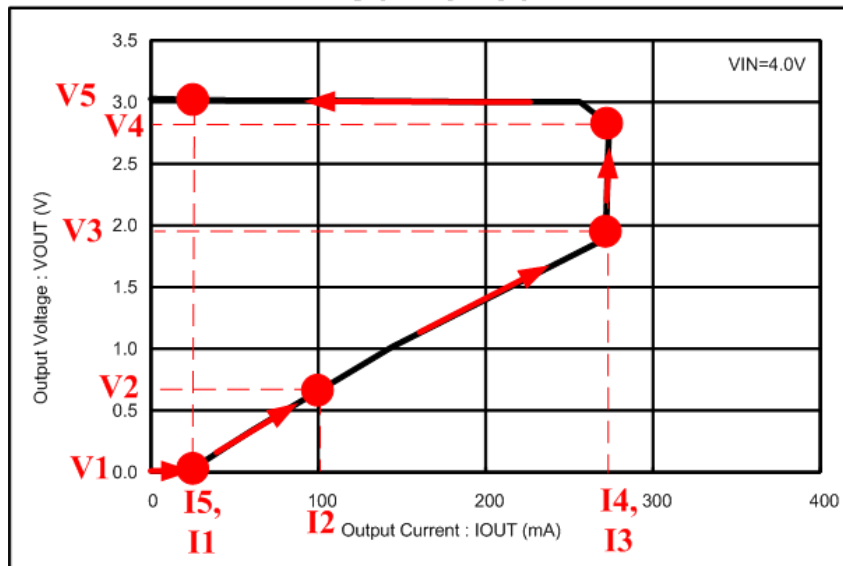
Our first example is going to be the XC6219B302MR. For that matter, the below 3 graphs are showing how the output current varies when the XC6219B is enabled via its CE pin and needs to supply 3 different values of continuous current (20mA, 80mA and 150mA) to an output load. All I_{OUT} waveforms look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

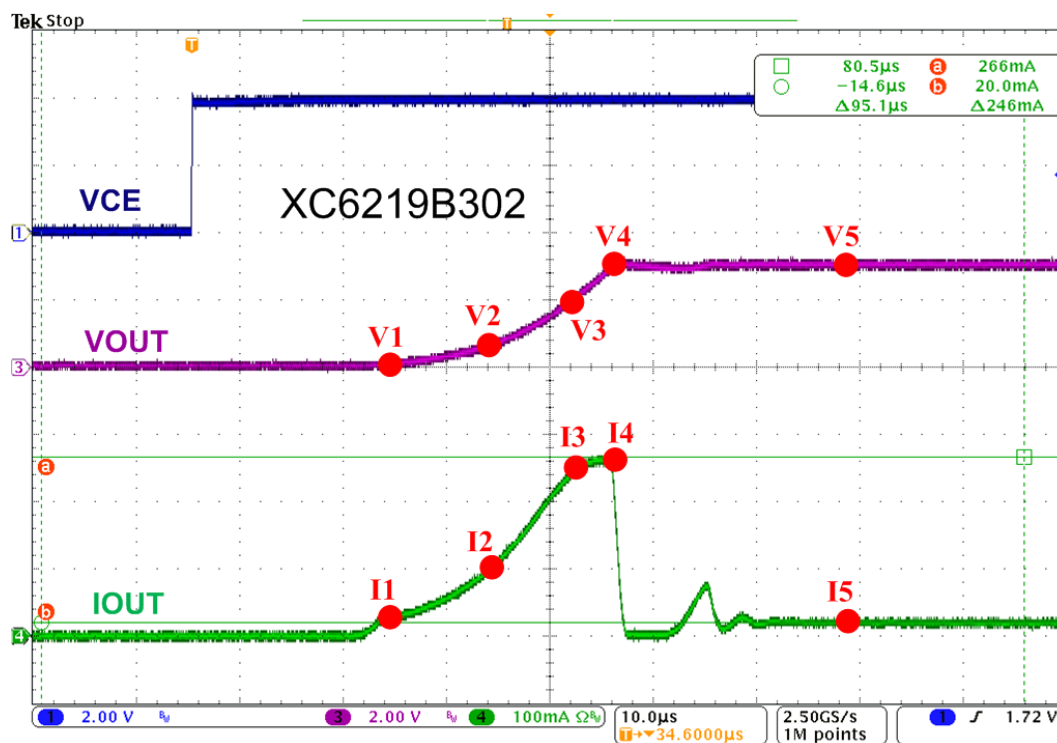
Please note that for the below graphs –and for all graphs that follow–, the output current was set with a variable resistor.



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. In addition to that, a second plot exhibits the V_{OUT} vs. I_{OUT} characteristics of the XC6219B302MR.

XC6219B302

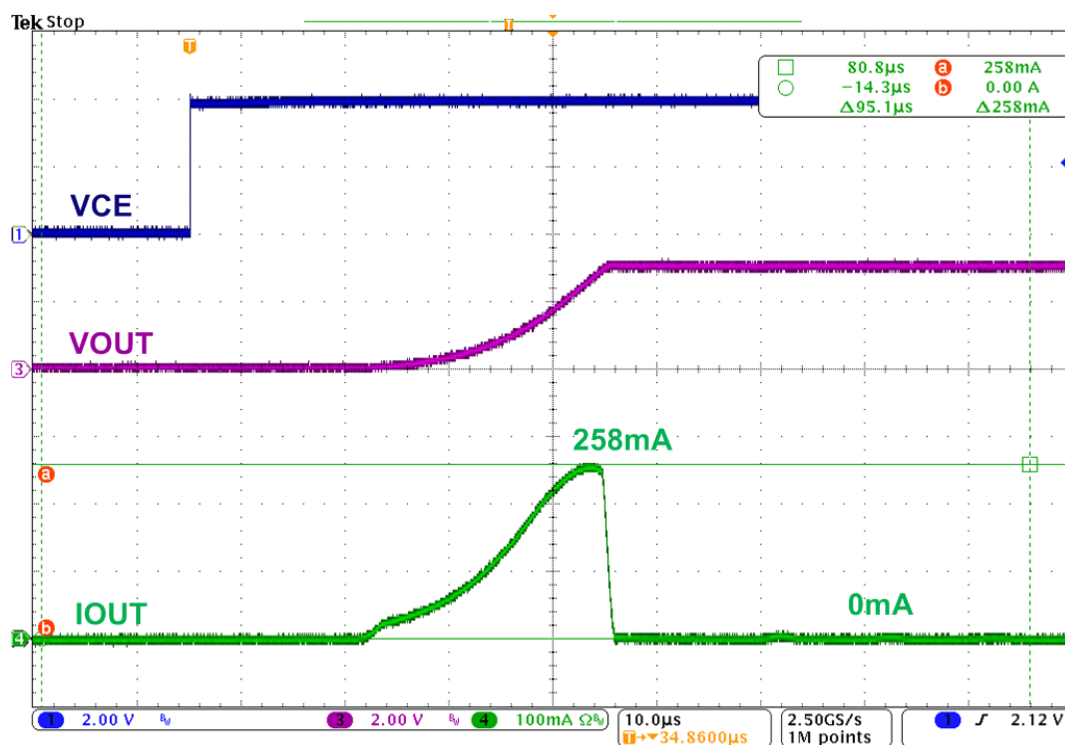




Initially, both V_{OUT} and I_{OUT} are at 0V. Then, as was explained on the “XC6219 Current Foldback Circuit” TIP, V_{OUT} and I_{OUT} have got to remain on the current foldback curve during start-up, so the values of V_{OUT} and I_{OUT} always correspond to a point of the current foldback curve, as 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 $I_{OUT} = I2 = 100mA$.

But the current foldback circuit is not a perfect inrush protection circuit, as you will notice by looking at the below graph, where the LDO is enabled but the actual output current demand from the output load is 0mA.



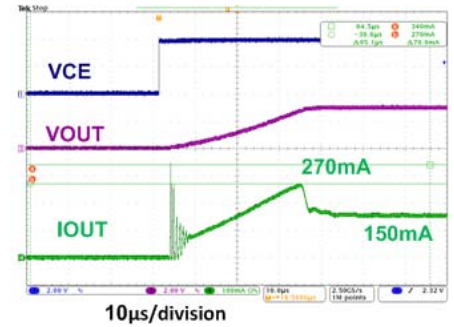
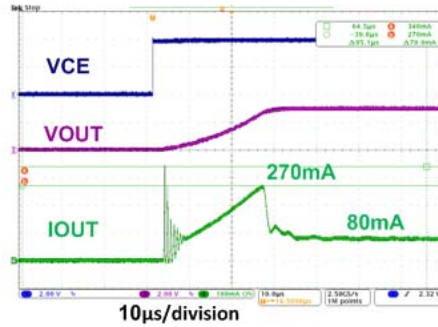
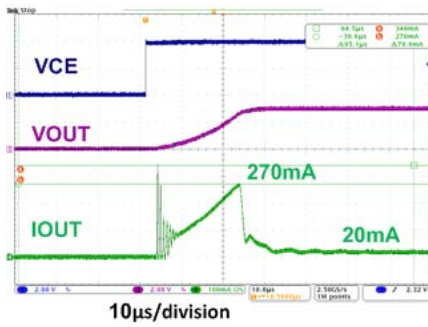
As we have just seen, when V_{OUT} ramps up towards its set value, I_{OUT} is forced to follow so that any (V_{OUT}, I_{OUT}) coordinates can remain on the foldback curve. This is exactly what happens on the above graph, and this causes the output current to ramp up to 258mA despite the actual output 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_{OUT} waveform during start-up is shaped by the current foldback circuit. We already knew that the V_{OUT} vs. I_{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_{OUT} vs. I_{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.

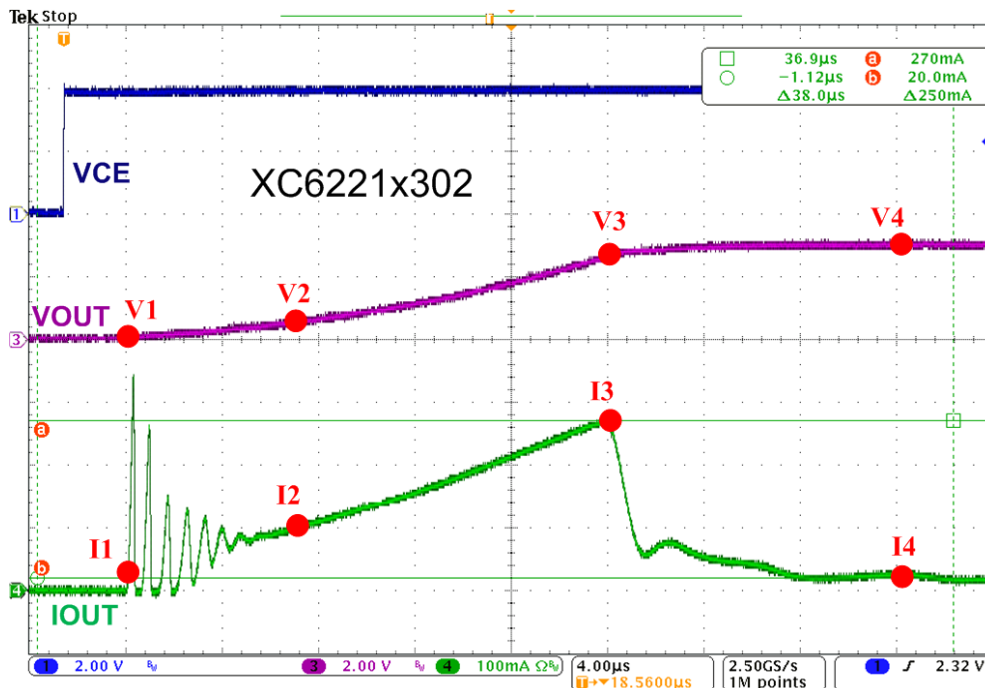
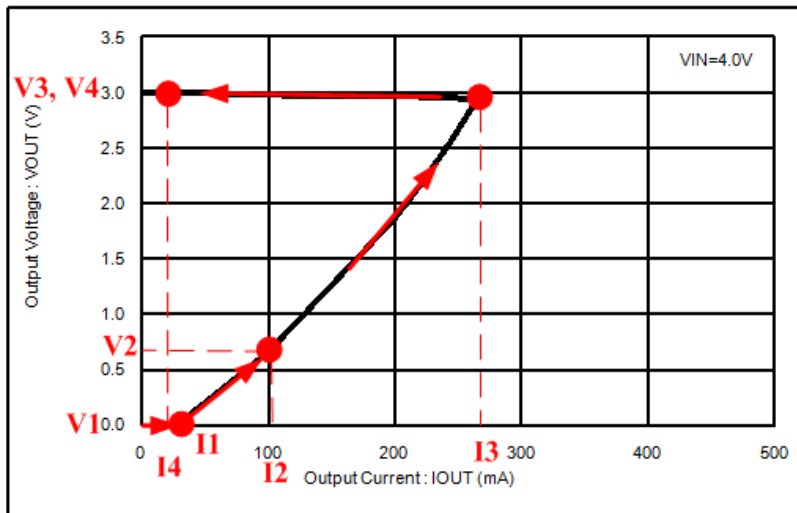
2) LDO of Type B

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, with initial spikes of about 340mA, followed by a linear ramping up to 270mA before finally settling to the current value required by the output load. Once again, please note that, in all 3 cases, $C_{IN} = C_L = 1\mu F$.



We are now going to study the start-up waveforms in further details, by using a case study with similar conditions as the previous XC6219B example, i.e. the LDO is enabled and needs to supply 20mA. For that matter, the below waveforms are simply zoomed waveforms of the above-left graph. In addition to that, a second plot exhibits the V_{OUT} vs. I_{OUT} characteristics of the XC6221A302MR.

XC6221x302



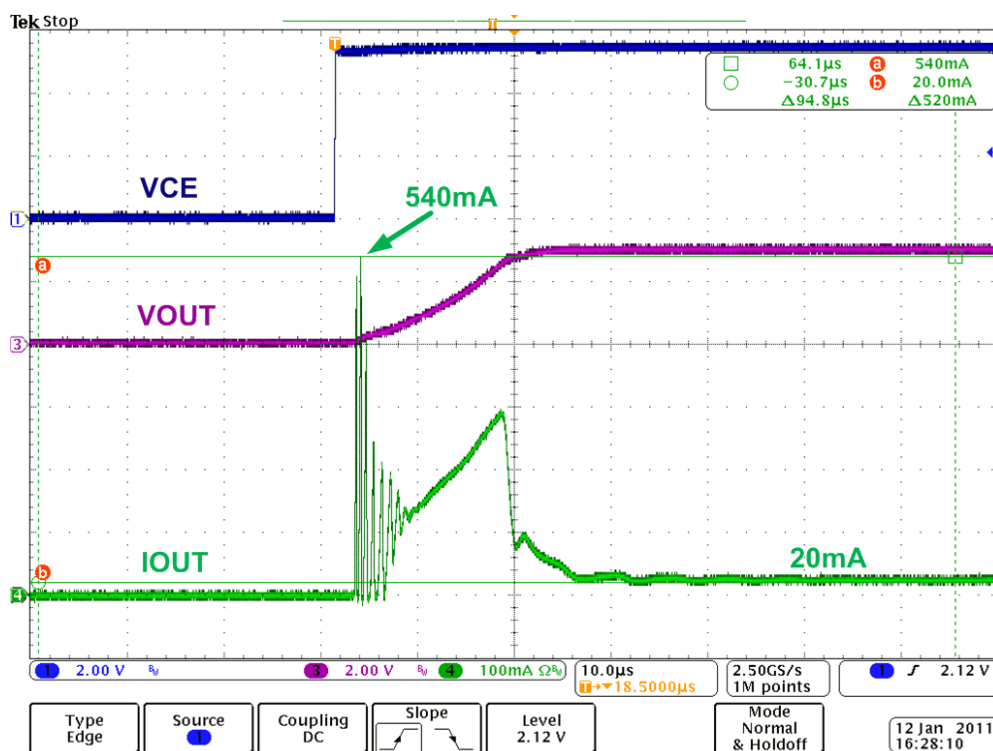
We are starting from the first red dot at voltage V1 and current I1. Initially, when the CE pin of the XC6221 becomes “high”, the LDO is activated and some inrush current tries to flow towards the output capacitor C_L of the LDO. This start-up is not as smooth as with the XC6219, because it takes a few μs for the current foldback circuitry of the XC6221 to react and restrict the available current, which is why some current peaks are briefly visible at the output of the LDO. 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 V2 during start-up, I_{OUT} will always be equal to I2, 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 V3), at what point the output current is equal to the value of the current limit of the XC6221 during normal operation (see I3).

Then, the output current decreases down to the requested amount of output current -20mA here (see I4).

As was shown previously with the XC6219B, the current foldback circuit forces the output current to remain on the foldback curve. However, the current foldback circuit of the XC6221 presents too many imperfections to be considered as some kind of inrush current protection circuit:

- 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.
- Since the current foldback is slow to react, some high inrush current peaks appear for a few μs at the output of the LDO when V_{CE} initially ramps up- the XC6219B didn't exhibit this problem. Please note that these initial peaks can be higher under various sorts of conditions, amongst others when V_{IN} is increased (see the 540mA peaks on the graph that follows, where $V_{\text{IN}}=5.5\text{V}$ – V_{IN} was set to 4.0V in all previous examples). Of course, such peaks will be absorbed by C_L , so it is not really a problem, but still...



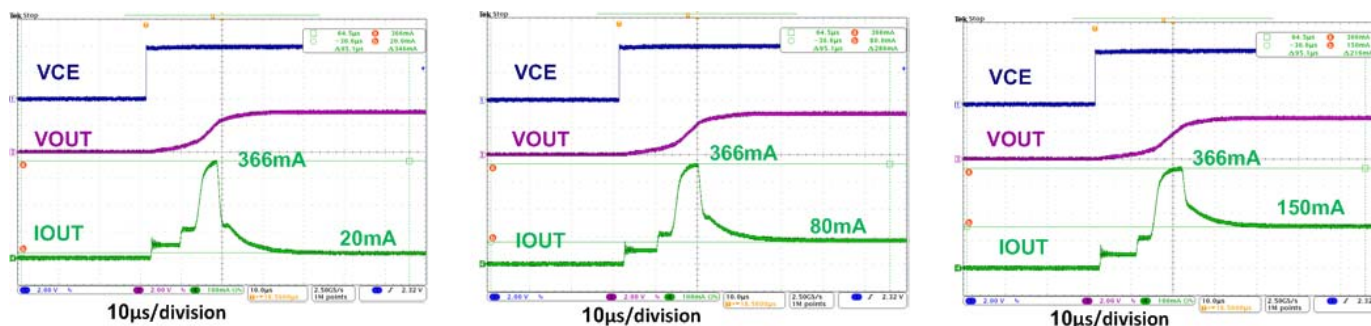
When we focus on the XC6223F series later on this document, we will see how such problems can be avoided with an LDO including a dedicated circuit for inrush current protection.

3) LDO's 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.

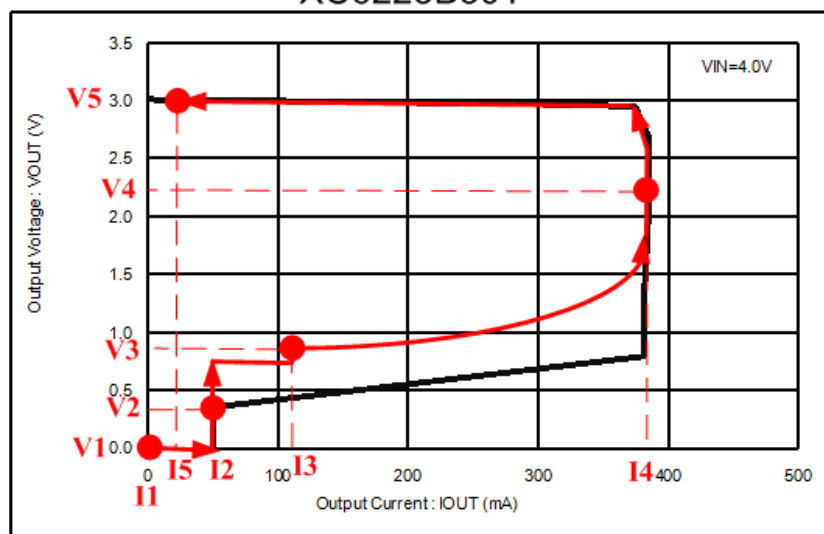
3.1. XC6223B series

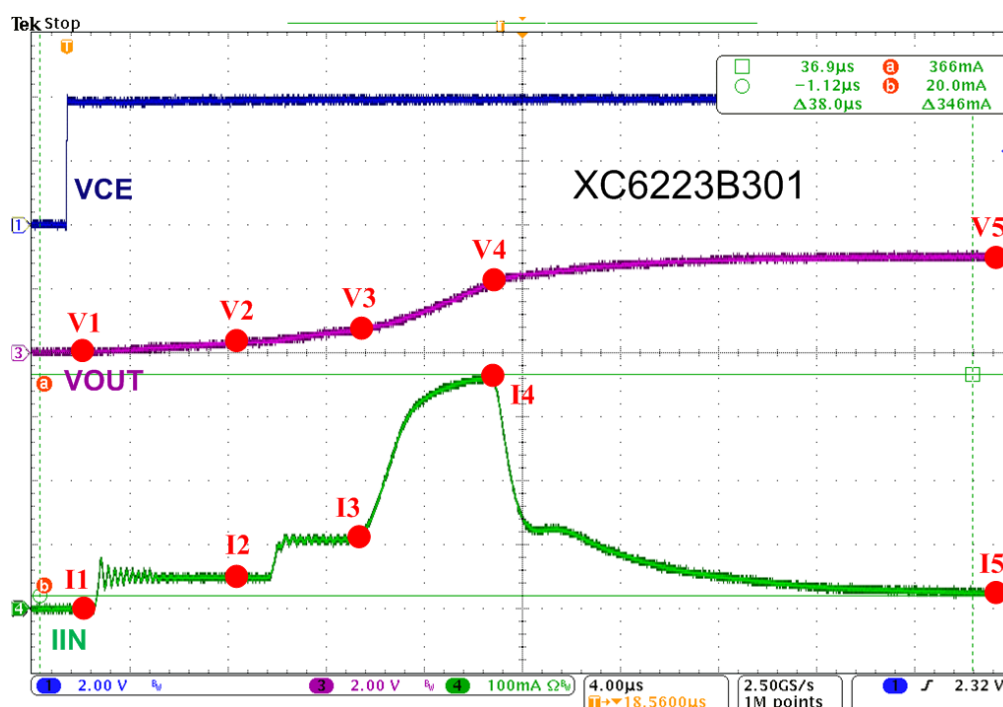
The below 3 graphs show how the XC6223B301 (without inrush current protection) reacts when it is enabled via its CE pin and needs to supply respectively 20mA, 80mA and 150mA of output current. Once again, the output current waveforms all follow the same pattern at start-up. However, please notice that,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

XC6223B301





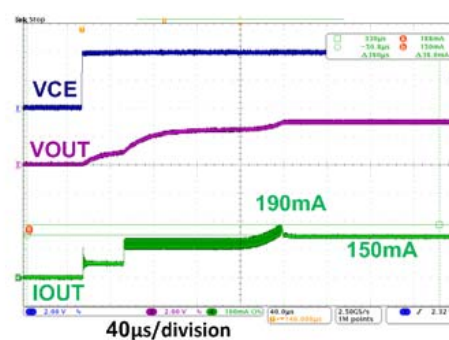
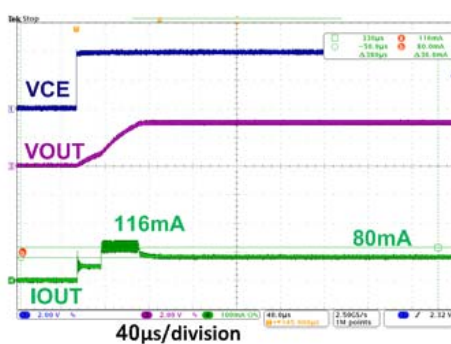
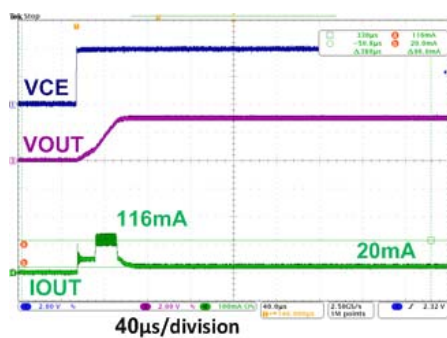
When the IC is enabled via its CE pin, the output current is limited to 50mA until V_{OUT} reaches about 0.8V (see V2, I2). Then the current limit is increased to about 115mA (see V3, I3), but only for a few μ s. After that, all what limits the output current is the higher current limit of the IC, so 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).

As was previously mentioned, the XC6223B didn't exhibit the high output current peaks that were observed with the XC6221. This is because the lower current limiter that gets activated at start-up with the XC6223B reacts faster than the current foldback circuit of the XC6221.

This reduction of the initial high current peaks is welcome. However, the output current still peaks at about 370mA afterwards, no matter what continuous current is required by the output circuitry. This 370mA peaking can be reduced by opting for an LDO with dedicated circuitry for inrush current protection, such as the XC6223F.

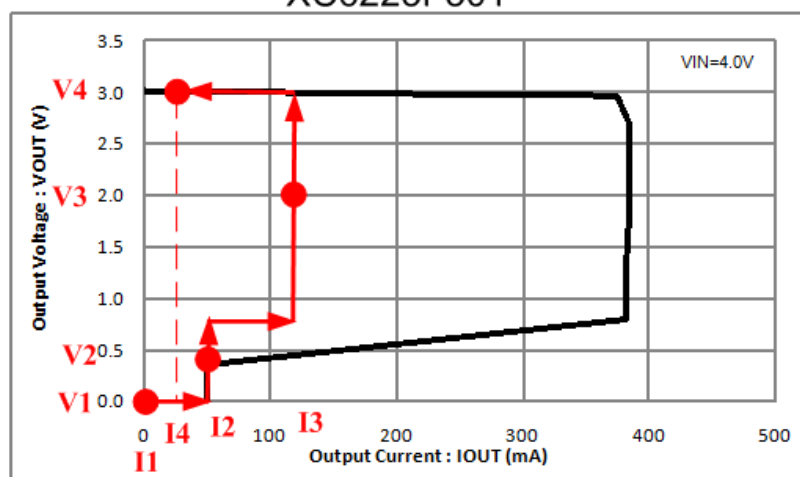
3.2. XC6223F series

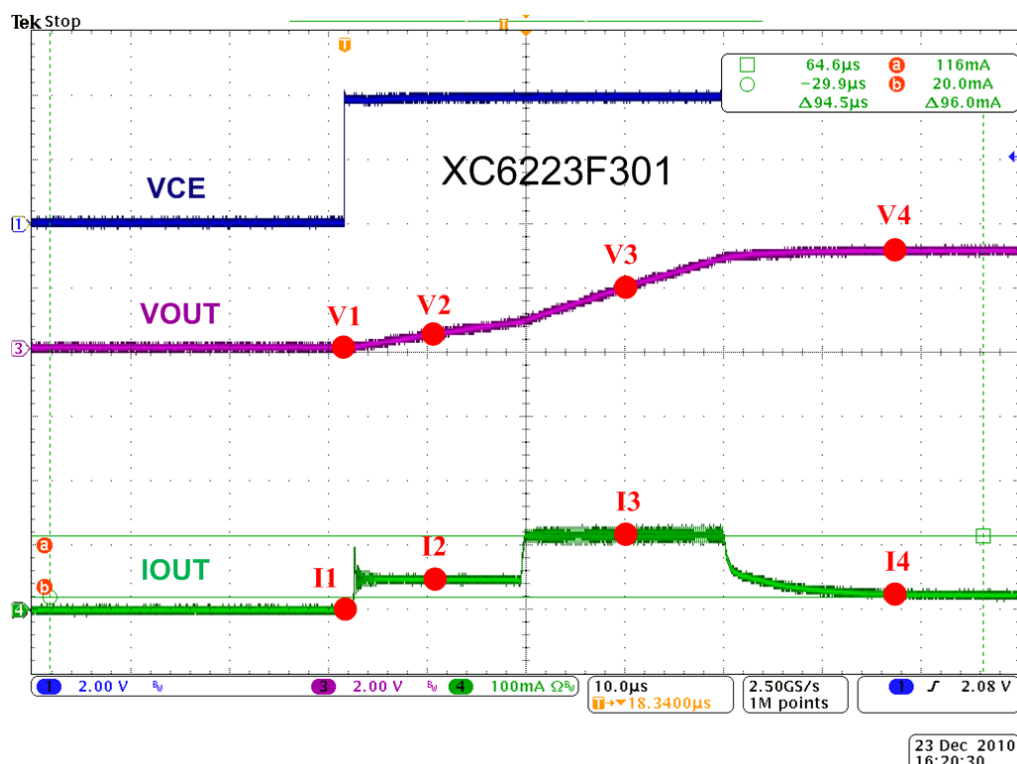
The below 3 graphs show how the XC6223F301 (with inrush current protection) reacts when it is enabled via its CE pin and needs to supply respectively 20mA, 80mA and 150mA of output current. In order to highlight how low the output current peaks at start-up, we have used the same scale as with the XC6221 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 10 μ s/division to 40 μ s/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.

XC6223F301





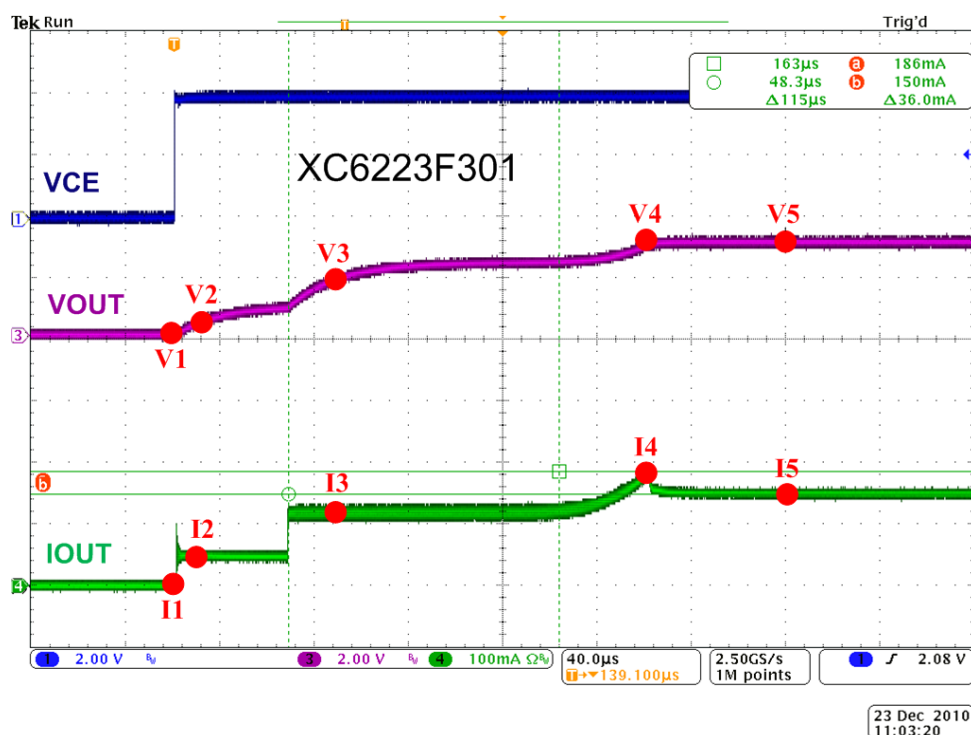
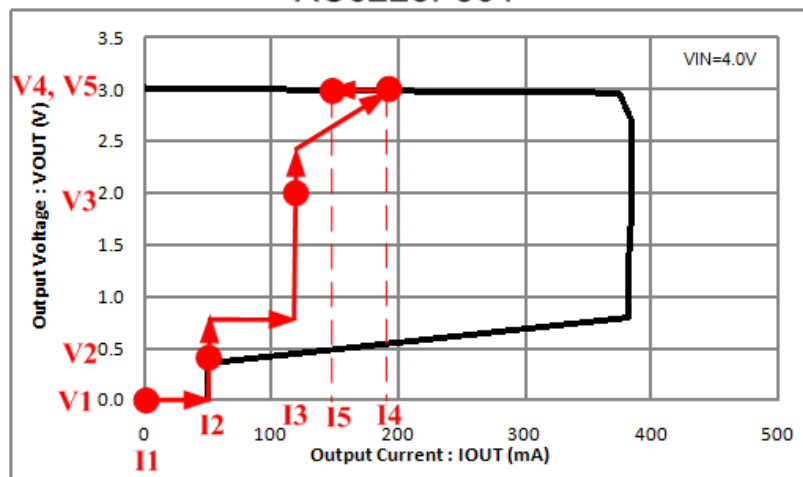
Initially, when the XC6223F is enabled, the output current (mainly its inrush current component) is immediately restricted by the lower current limit, in a similar way to what was observed with the XC6223B301. While the inrush current is limited to about 50mA, the output voltage starts rising (V2, I2). 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_{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 (the inrush current component of the output current has disappeared).

It is possible for the output current waveform to differ from the previous one. This happens when the inrush current has not fully disappeared when the timer delay of the second current limit (115mA) elapses or when the continuous output current requested by the load is higher than this second current limit.

For that purpose, we are going to use another example of the XC6223F301 behavior at start-up, but this time under conditions that generate much more inrush current at start-up compared with the previous example. To generate much more inrush current at start-up, we could have increased the value of the output capacitor from 1 μ F to 10 μ F. 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 40 μ s/division has been used.

XC6223F301

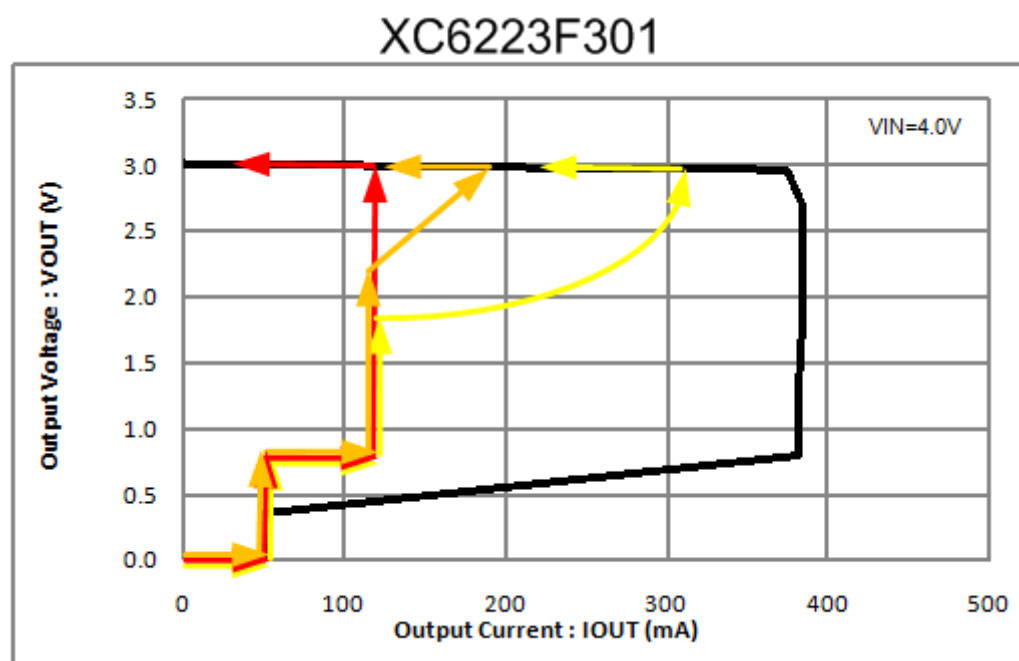


At first, the waveforms are similar to the previous example: the output current is initially limited to about 50mA (V2, I2) until V_{OUT} rises to about 0.8V, then the output current gets limited to about 115mA for a certain timer delay while the output voltage carries on increasing (see V3, I3). However,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

These two examples using the XC6223F have highlighted that the " V_{OUT} vs. I_{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 under particularly adverse conditions.

Another conclusion to draw from the below graphs is that, as opposed to LDO's such as the XC6219B and XC6221, using the V_{OUT} vs. I_{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.