Introduction

The new STMicroelectronics L6472 and L6474 motor drivers provide two new patented advanced current control systems evolving from traditional peak current control systems: automatic decay adjustment and the predictive current control.

Using automatic decay adjustment, the L6472 and L6474 devices allow current ripple to be reduced and control robustness to be increased especially in microstepping applications. The predictive current control regulates the average current instead of the peak current, obtaining a more precise positioning, and reduces the variation of the power stage switching frequency.

Automatic decay adjustment and predictive current control allow stepper motors to be operated with less torque ripple, fewer vibrations and much more smoothly at low speed.

This document describes the basic principles and the operation of the new control systems and provides suggestions on parameter setup in order to obtain optimal results.
List of tables

Table 1. Phase driving sequence for a clockwise rotation of a 4-steps per round stepper motor. ................................................................. 5
Table 2. Phase driving sequence for a clockwise rotation of a 200-steps per round stepper motor. ................................................................. 6
Table 3. Driving sequences ........................................................................ 8
Table 4. Microstepping current level examples .................................................. 10
Table 5. Peak current control parameters ......................................................... 21
Table 6. Predictive current control parameters ............................................... 25
Table 7. Control system parameters and performance relation ........................... 28
Table 8. Document revision history ................................................................. 33
List of figures

Figure 1. Basic two-phase bipolar stepper motor ........................................... 5
Figure 2. Torque during a step change .......................................................... 7
Figure 3. Magnetic field directions in full step and half step driving modes ............ 8
Figure 4. Microstepping phase currents ......................................................... 9
Figure 5. Full step driving versus microstepping motor torque ............................ 11
Figure 6. Current control system for each motor phase ................................... 12
Figure 7. Motor phase electrical model ........................................................ 13
Figure 8. Constant off-time control sequence (low-side recirculation) ................. 14
Figure 9. Peak current control stability conditions ......................................... 15
Figure 10. Back electromotive force limiting the slow decay effectiveness .............. 16
Figure 11. Constant off-time control using fast decay .................................... 17
Figure 12. Minimum on-time ...................................................................... 18
Figure 13. Peak current control unstable ................................................... 18
Figure 14. Peak current control in microstepping (slow decay only) ....................... 19
Figure 15. Peak and average current and stator magnetic field .......................... 20
Figure 16. Minimum on-time threshold and on-time limit relation ....................... 22
Figure 17. Decay selection according to on-time duration ................................. 22
Figure 18. Decay strategy change due to second on-time threshold violation ........... 23
Figure 19. Fast decay time regulation ........................................................ 23
Figure 20. Current control at rising step (reference current increased) ................. 24
Figure 21. Current control at falling step (reference current decreased) ............... 25
Figure 22. Predictive current control basic principle ...................................... 26
Figure 23. Off-time automatic adjustment ...................................................... 27
Figure 24. On-time measurement ................................................................ 29
Figure 25. TOFF_FAST and TON_MIN parameter relations .............................. 30
Figure 26. Falling step - 8 microstep example ............................................... 31
Figure 27. High FAST_STEP value example ............................................... 32
Figure 28. Low FAST_STEP value example ................................................. 32
1 Stepper motor basics

A stepper motor is a particular kind of synchronous electrical motor designed to reach and keep an angular position. Each position is obtained as a steady-state of the rotor according to one of the four possible directions of the magnetic field generated by a pair of windings (called phases) on the stator. The distance between the next two angular positions is called step and the number of steps composing a full mechanical rotation is a key characteristic of this kind of motor. A simplified representation of a stepper motor is shown in Figure 1.

Forcing a current in one phase at a time, the four positions shown in Figure 1 can be reached by the rotor. When the driving sequence listed in Table 1 is generated, the rotor performs a complete rotation in a clockwise direction. According to the step definition, the model in Figure 1 is a 4-step motor.

<table>
<thead>
<tr>
<th>Phase A current</th>
<th>Phase B current</th>
<th>Stator magnetic field position</th>
<th>Rotor position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>Zero</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Zero</td>
<td>Positive</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Negative</td>
<td>Zero</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Zero</td>
<td>Negative</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Increasing the complexity of the stator and rotor design, the number of available positions for each driving condition can be increased obtaining a high number of steps per round. The driving sequence making the motor rotate is the same, but a full rotation of the magnetic field of the stator (electrical cycle) does not correspond to a full rotation of the rotor (mechanical rotation). Table 2 shows the driving sequence of a 200-step stepper motor.
The torque applied to the stator at each step change is directly proportional to the stator magnetic field, which is proportional to the current flowing into the phase and the sine of the displacement angle between the rotor and the target step electrical positions. This relation is described by Equation 1.

**Equation 1**

\[ T_{\text{Mot}} = I_{\text{Phase}} \cdot \alpha \cdot \sin(\theta_{\text{Stat}} - \theta_{\text{Rotor}}) \]

When a step change is applied, the magnetic field is rotated by 90° in a clockwise or counterclockwise direction. As a consequence, the torque applied to the motor shaft reaches its maximum value (according to the phase current) because the displacement angle \( \theta_{\text{Stat}} - \theta_{\text{Rotor}} \) is about 90° (see Figure 2). During the approach of the rotor to the target position, the torque decreases until it is equal to that of the load. The displacement angle corresponding to the load torque applied to the shaft (\( \theta_{\text{HOLD}} \)) determines the actual motor position at the end of motion.

<table>
<thead>
<tr>
<th>Phase A current</th>
<th>Phase B current</th>
<th>Stator magnetic field position</th>
<th>Rotor position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>Zero</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Zero</td>
<td>Positive</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Negative</td>
<td>Zero</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Zero</td>
<td>Negative</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Positive</td>
<td>Zero</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Zero</td>
<td>Positive</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Negative</td>
<td>Zero</td>
<td>3</td>
<td>199</td>
</tr>
<tr>
<td>Zero</td>
<td>Negative</td>
<td>4</td>
<td>200</td>
</tr>
</tbody>
</table>
1.1 Full step and half step

The driving sequence described in the previous section is called full step one phase on (or wave driving) because the rotor is moved by one step at a time feeding only one of the two phases of the motor at a time.

It is also possible to drive both the phases in order to generate a magnetic field positioned halfway between the two phases (1a, 2a, 3a and 4a positions in Figure 3). This driving mode is called full step two-phase on (or normal driving). In this case, at the same phase current, the magnetic field is higher by a factor of $\sqrt{2}$ and the corresponding motor torque is multiplied by the same factor.
Mixing the above mentioned two full step driving modes, half step driving is obtained. In half step driving the stator magnetic field is rotated by 45° at a time (i.e.: half of the full step rotation) and the resulting rotor movement is half of that obtained using full step driving.

*Table 3* summarizes the driving sequences for the different driving modes.

**Table 3. Driving sequences**

<table>
<thead>
<tr>
<th>Full step 1ph on (wave driving)</th>
<th>Full step 2ph on (normal driving)</th>
<th>Half step</th>
<th>Phase A current</th>
<th>Phase B current</th>
<th>Stator magnetic field position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Positive</td>
<td>Zero</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>Positive</td>
<td>Positive</td>
<td>1a</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>Zero</td>
<td>Positive</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4</td>
<td>Negative</td>
<td>Positive</td>
<td>2a</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>5</td>
<td>Negative</td>
<td>Zero</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
<td>Negative</td>
<td>Negative</td>
<td>3a</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>7</td>
<td>Zero</td>
<td>Negative</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>8</td>
<td>Positive</td>
<td>Negative</td>
<td>4a</td>
</tr>
</tbody>
</table>
1.2 Microstepping

The driving methods considered in the previous section imply a constant current flowing into the motor phases and the magnetic field being rotated by turning on/off and reversing the currents.

Modulating the phase currents, the available positions of the stator magnetic field, and then the intermediate positions between the subsequent steps, can be increased without any theoretical limit. This driving method is called microstepping and the intermediate positions are called microsteps.

As shown in Figure 4, in order to obtain a rotating magnetic field with constant module, the two-phase current must be sinusoidal and with a phase difference of 90° (sine and cosine).

![Figure 4. Microstepping phase currents](image)

The currents applied to the motor phases are not actually continuous sinewaves, but a sequence of samples of sinewaves generated using the formula of Equation 2, where \( N_{\text{microstep}} \) is the microstepping resolution (defined by the number of samples composing a sinewave quarter which is equivalent to a full step) and \( n \) is the incremental number generating the sequence (some examples are shown in Table 8 on page 33). Different microsteppings are identified according to their resolution (1/4 step, 1/8 step, etc.).
Equation 2

\[ I_{PHA} = I_{peak} \cdot \sin\left(\frac{\pi}{2N_{microstep}} \cdot n\right) \]

\[ I_{PHB} = I_{peak} \cdot \cos\left(\frac{\pi}{2N_{microstep}} \cdot n\right) \]

Table 4. Microstepping current level examples

<table>
<thead>
<tr>
<th>1/2 step (^{(f)})</th>
<th>1/4 step</th>
<th>1/8 step</th>
<th>Phase A current</th>
<th>Phase B current</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+100% I_{peak}</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>4</td>
<td>+71% I_{peak}</td>
<td>+71% I_{peak}</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>8</td>
<td>+100% I_{peak}</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>12</td>
<td>+71% I_{peak}</td>
<td>-71% I_{peak}</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>12</td>
<td>+71% I_{peak}</td>
<td>-71% I_{peak}</td>
</tr>
<tr>
<td>7</td>
<td>14</td>
<td>16</td>
<td>+20% I_{peak}</td>
<td>-98% I_{peak}</td>
</tr>
<tr>
<td>9</td>
<td>18</td>
<td>20</td>
<td>-20% I_{peak}</td>
<td>-98% I_{peak}</td>
</tr>
<tr>
<td>11</td>
<td>22</td>
<td>24</td>
<td>-98% I_{peak}</td>
<td>-98% I_{peak}</td>
</tr>
<tr>
<td>13</td>
<td>26</td>
<td>28</td>
<td>-98% I_{peak}</td>
<td>-98% I_{peak}</td>
</tr>
</tbody>
</table>
The microstepping driving technique results in less vibration and higher positioning resolution. The magnetic field rotation corresponding to a full step is split into a sequence of smaller rotations in the same number of the microstepping resolution. Each of these small displacements causes a lower torque variation than a full step change (see Figure 5), so the torque ripple is lower than in full step driving (smoother motion).

When this driving technique is used, the maximum output torque of the motor is lower than the one obtained using the full step because the intensity of the stator magnetic field is lower than a $\sqrt{2}$ factor.

**Table 4. Microstepping current level examples (continued)**

<table>
<thead>
<tr>
<th>1/2 step(1)</th>
<th>1/4 step</th>
<th>1/8 step</th>
<th>Phase A current</th>
<th>Phase B current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>-56% $I_{\text{Peak}}$</td>
<td>+83% $I_{\text{Peak}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-38% $I_{\text{Peak}}$</td>
<td>+92% $I_{\text{Peak}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-20% $I_{\text{Peak}}$</td>
<td>+98% $I_{\text{Peak}}$</td>
</tr>
</tbody>
</table>


The microstepping driving technique results in less vibration and higher positioning resolution. The magnetic field rotation corresponding to a full step is split into a sequence of smaller rotations in the same number of the microstepping resolution. Each of these small displacements causes a lower torque variation than a full step change (see Figure 5), so the torque ripple is lower than in full step driving (smoother motion).

When this driving technique is used, the maximum output torque of the motor is lower than the one obtained using the full step because the intensity of the stator magnetic field is lower than a $\sqrt{2}$ factor.

**Figure 5. full step driving versus microstepping motor torque**

![Figure 5. full step driving versus microstepping motor torque](AM5107v1)
2 Phase current control in stepper motor driving

In order to impose a constant current in the stepper motor phases, a current control algorithm must be implemented.

The most common control system is shown in Figure 6 and is composed of:
- A power H-bridge used to drive the phase
- A current sensor (usually a shunt resistor)
- A controller driving the power bridge
- The motor phase electrical model.

This system is applied to both phases.

Figure 6. Current control system for each motor phase

The motor phase electrical model is shown in Figure 7 and is made up of:
- The equivalent phase resistance $R_{Ph}$
- The equivalent phase inductance $L_{Ph}$
- The back electromotive force generator $V_{BEMF}$
The back electromotive force (BEMF) is the voltage generated by the rotating magnetic field of the rotor as an effect of Faraday’s law of induction. Its effect can be modeled as a sinewave voltage generator with frequency equal to a quarter of the motor full step rate and amplitude proportional to the rotation speed (see Equation 3).

**Equation 3**

\[
\begin{align*}
A & \quad V_{\text{BEMF}} = K_e \cdot f_{\text{BEMF}} \\
B & \quad f_{\text{BEMF}} = \frac{f_{\text{step}}}{4}
\end{align*}
\]

The BEMF effect on the current control system is to counter the voltage applied by the power stage limiting the phase current (especially at high speed). In general, as explained in the following paragraphs, the BEMF voltage may make it more difficult to regulate the desired current.

The algorithm implemented by the controller determinates the performance of the application, in particular when microstepping driving is used.
3 Peak current control with PWM and constant off-time

The peak current control with PWM and constant off-time is one of the most common algorithms implemented by stepper motor controllers.

The phase current is measured through a shunt resistor and the resulting voltage (see Equation 4 A) is sent to a comparator input. The other input is a reference voltage setting the peak current forced into the motor phase (Equation 4 B).

Equation 4

\[ V_{\text{Sense}} = I_{\text{ph}} \cdot R_{\text{SHUNT}} \]
\[ V_{\text{Ref}} = I_{\text{Peak}} \cdot R_{\text{SHUNT}} \]

At the beginning of driving, the motor phase currents are zero and the controller turns on one of the diagonals of the power bridge according to the expected current direction. The phase current is increased until the target reference voltage is reached, then the controller switches off the forcing side of the bridge making the phase current recirculate in the bottom side of the power stage. The same effect may be obtained recirculating the current on the top side; in this case the forcing side of the bridge is kept on and the opposite side is turned on.

Figure 8. Constant off-time control sequence (low-side recirculation)
During the recirculation, the current decreases according to the discharge of the equivalent RL series circuit.

After a fixed $t_{OFF}$ time, the forcing bridge is switched on (or it is kept on) and the opposite bridge is switched off (or it is kept off) according to the recirculation mode and the phase current returns to increase.

The stability of the peak current control algorithm with constant off-time is based on Equation 5.

**Equation 5**

$$\Delta I_{phOFF} = \Delta I_{phON}$$

In every control cycle (on-time + off-time) the total current variation should be zero; in particular, the current drop of the off-time ($\Delta I_{phOFF}$) should be equal to the current increase obtained during the on-time ($\Delta I_{phON}$), as shown in Figure 9.

**Figure 9. Peak current control stability conditions**

<table>
<thead>
<tr>
<th>$\Delta I_{phOFF}$</th>
<th>$\Delta I_{phON}$</th>
<th>$\Delta I_{phOFF}$</th>
<th>$\Delta I_{phON}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{phOFF}$</td>
<td>$I_{phON}$</td>
<td>$I_{phOFF}$</td>
<td>$I_{phON}$</td>
</tr>
</tbody>
</table>

### 3.1 Slow decay and fast decay

The recirculation of the phase current in low-side or high-side switches of the power bridge is called slow decay. The name highlights the fact that the current is reduced only using the RL discharge. The effectiveness of this approach is strongly reduced when the BEMF contribution becomes significant.

As shown in Equation 6, the BEMF voltage changes the current drop during the slow decay and in some cases may make it negative (i.e.: the current increases instead of decreasing) causing a current control fail, see Figure 10.

**Equation 6**

$$\Delta I_{ph} \approx (R_{ph} \cdot I_{ph} + V_{BEMF}) \cdot L_{ph} \cdot t_{OFF}$$
When the slow decay is not able to decrease the phase current, the fast decay method can be used. The fast decay forces the current reduction applying the supply voltage in reverse direction. This way the current is actively reduced using the same voltage used to force it into the phase during the on-time.

In this case the current drop and then the ripple are greater than with slow decay, but the peak current is kept under control (see Equation 7).

**Equation 7**

\[ \Delta I_{Ph} \approx (R_{Ph} \cdot I_{Ph} + V_{BUS}) \cdot L_{Ph} \cdot t_{OFF} \]
Both decay methods have pros and cons: the slow decay allows a lower current ripple to be obtained, but at low current values or at high speed (significant BEMF value) the current control may fail. The fast decay, on the other hand, keeps the current under control at the cost of a higher ripple.

3.2 Minimum on-time limit

The control system, according to its structure, is usually not able to check the phase current immediately after the beginning of the on-phase (usually a blanking time is adopted to avoid spurious triggering of the current comparator), as shown in Figure 12. This limits the minimum on-time the power bridge must remain in the on-phase. The minimum current increase related to the $t_{\text{comm}}$ can be estimated through Equation 8 (back electromotive force has not been taken into account for simplicity).
Equation 8

$$\Delta I_{ph} = V_{BUS} \cdot L_{ph} \cdot t_{comm}$$

When the current drop $\Delta I_{phOFF}$ becomes lower than $\Delta I_{phON,Min}$, the stability equation can no longer be satisfied and the current control fails. The current starts to increase until stability is restored (it is possible because $\Delta I_{phOFF}$ increases with the current) and the actual peak current is different than the target one. The minimum on-time limit is usually reached at low target currents, motor windings with a high $L_{ph}/R_{ph}$ ratio, and when slow decay is used during the off-time.
3.3 Microstepping

As described in Section 1.2 on page 9, by driving the stepper motor phases with sinusoidal currents the step resolution and the motion smoothness can be improved (microstepping).

In order to obtain a microstepping operation using the peak current control with fixed off-time, the reference voltage ($V_{\text{Ref}}$) of each phase must be varied in order to obtain the respective microstep current pairs in the proper sequence (see Equation 2 on page 10 and Table 4 on page 10).

During the positive slope of the sinewave, the reference current value is increased at each microstep change and the control algorithm reaches the new target value in a single control cycle, as shown in Figure 14. During the negative slope of the sinewave, the current reference is progressively reduced down to the zero and the control algorithm may fail to properly follow the variations (Figure 14).

![Figure 14. Peak current control in microstepping (slow decay only)](image)

The key point is that, except for particular implementations, the phase current can be sensed during the on-time only. As a consequence, the reference increase can be easily managed extending the on-time until the new threshold is reached, but the decrease must be performed as a sequence of off-time which slowly decreases the phase current until the attainment of the threshold.

This issue is particularly critical when the slow decay is used because of the limited current decay during the off-time. On the other hand, when the fast decay is used, the large current drop may limit the microstepping effectiveness causing a current ripple bigger than the minimum microstep-to-microstep variation.

Another limitation of the microstepping implementation through the peak current control algorithm is the impossibility of effectively controlling the average phase current. Whereas the actual average position of the stator magnetic field is related to the average phase current values (see Figure 15), the peak current control introduces an error in its positioning and then in microstepping implementation.
Figure 15. Peak and average current and stator magnetic field
4 STMicroelectronics enhanced current control

The new L6472 and L6474 devices implement a new advanced current control algorithm that increases the system performance in both full step and microstepping driving.

As discussed in previous paragraphs, the decay mode of a peak current control algorithm is a critical choice concerning performance and stability of the system.

In particular, the control system must choose between slow and fast decay considering the following trade-off:

- Slow decay allows lower current ripples (more accurate average current, lower power dissipation, lower noise), but it may fail to reduce the current bringing the system into a minimum on-time limit condition (see Section 3.2 on page 17).
- Fast decay increases the robustness to the minimum on-time limit, but it implies a higher current ripple (higher average current error, higher power dissipation).

The best solution is a compromise between the two methods, where the fast decay is used only when needed and for the shortest time possible. The auto adjusted decay system addresses this balance.

4.1 Peak current control with auto adjusted decay

The new current control algorithm is based on the parameters listed in Table 5.

Table 5. Peak current control parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{OFF}$</td>
<td>Off-time</td>
<td>It sets the current decay duration of the control cycle (fixed off-time control).</td>
</tr>
<tr>
<td>$t_{ON_MIN}$</td>
<td>Target minimum on-time</td>
<td>It defines which is the shortest on-time (i.e. the time to reach reference current) which guarantees a correct operation of the control algorithm (Figure 16). This parameter should be set to a value higher than the intrinsic minimum on-time of the system.</td>
</tr>
<tr>
<td>$t_{OFF_FAST}$</td>
<td>Maximum fast decay time</td>
<td>It is the maximum duration of a fast decay during operation of the current control system.</td>
</tr>
<tr>
<td>$t_{FAST_STEP}$</td>
<td>Maximum step fall time</td>
<td>It is the maximum duration of a fast decay during reference current changing.</td>
</tr>
</tbody>
</table>

The first three parameters are used when the system keeps the phase current constant; the fourth parameter is used when the reference current is decreased only (see Section 4.1.2).
At every control cycle the on-time is measured and it is compared to the programmable threshold $t_{ON\_MIN}$. If the measured on-time is longer than the programmed threshold the current is well controlled and no fast decay is needed, so slow decay is used (Figure 17).

As the slow decay reduces its effectiveness, the on-time is reduced until the programmed $t_{ON\_MIN}$ is reached. When $t_{ON}$ is shorter than $t_{ON\_MIN}$, a fast decay is used in order to increase the current drop (Figure 17) and to avoid the failure of the current control algorithm due to the minimum on-time limit (see Section 3.2 on page 17). In the first occurrence of this event the fast decay duration is 1/8th of the maximum programmed value ($t_{OFF\_FAST}$).

If the next on-time is longer than the $t_{ON\_MIN}$ threshold, the control system returns using the slow decay, as shown in Figure 17.

When two or more minimum on-time violations occur at the same reference current value (i.e. the electrical position of the motor is not changed), the control system changes the decay strategy using slow decay followed by a fast decay (Figure 18). The total duration of the decay phase is equal to the programmed off-time ($t_{OFF}$) and the fast part is equal to the last $t_{FAST}$ used.
The $t_{\text{FAST}}$ value is regulated according to the following rules:

- At the first occurrence of the minimum on-time violation, the fast decay duration is set to $t_{\text{OFF\_FAST}} / 8$.
- If a further minimum on-time violation occurs, a new fast decay is used with double the length of the previous one ($t_{\text{FAST}} = 2 \times t_{\text{FAST}}$).
- The maximum $t_{\text{FAST}}$ value is set by the $t_{\text{OFF\_FAST}}$ parameter.

At the next minimum on-time violation the sequence starts from the last $t_{\text{FAST}}$ value used (except if a current reference change occurred, see Section 4.1.1).

The $t_{\text{FAST}}$ value obtained using this sequence is used by the control system during the decay phase when the slow and fast decay combination is used. Figure 19 shows an example of the system operation.

**Figure 19. Fast decay time regulation**

### 4.1.1 Rising and falling steps (reference current changes)

In microstepping operation the current reference changes according to the point of the current sinewave which must be obtained.

When the reference value is changed, there are two cases:

1. The reference current is increased. This event is called "rising step".
2. The reference current is reduced. This event is called "falling step".

These events are managed by the L6472 and L6474 current control, as follows.

In the case of rising step the phase is immediately turned on regardless of the control cycle conditions and the system switches to slow decay strategy. If the $t_{\text{FAST}}$ value has been increased during the previous microstep (see Section 4.1), it is halved ($t_{\text{FAST}} = t_{\text{FAST}} / 2$).
Figure 20 shows the system behavior in the case of a rising step.

**Figure 20. Current control at rising step (reference current increased)**

In the case of falling step a sequence of fast decays is immediately used regardless of the control cycle conditions. The decay strategy and the respective $t_{\text{FAST}}$ value are unchanged. The system behavior in the case of a falling step is described in detail in Section 4.1.2.

When the reference current is set to zero (zero crossing of the current sinewave) or when the motor is stopped, the control system is reset to the default: slow decay only and $t_{\text{FAST}}$ equal to 1/8th of $t_{\text{OFF,FAST}}$.

### 4.1.2 Auto adjusted duration of fast decay at falling steps

When the reference current is reduced by a microstep change (falling step), the control system immediately uses a fast decay in order to reach the new target value as soon as possible. The fast decay duration is adjusted using an algorithm similar to the one used during normal operation (see Section 4.1).

At first occurrence of this event, the fast decay length is set to a quarter of the programmed maximum step fall time ($t_{\text{FAST,STEP}}$). At the end of the decay, the phase is turned on and the on-time is measured; if its duration is below the programmed minimum threshold ($t_{\text{ON,MIN}}$) a further fast decay is performed with double the length of the previous. The maximum fast decay duration is imposed by the $t_{\text{FAST,STEP}}$ parameter.

The fast decay sequence continues until the on-time exceeds the programmed minimum limit (see Figure 21).

At the next falling step occurrence the last fast decay value is used. When the reference current is set to zero (zero crossing of the current sinewave) or the motor is stopped, the fast decay time is reset to the starting value of $t_{\text{FAST,STEP}}/4$.

**Note:** The fast decay time used during falling step sequence is totally independent from the one used during the current control.
4.2 Predictive current control\(^{(a)}\)

The peak current control with fixed off-time has two cons:
- The average current value is not controlled, so the actual rotor position is affected by some errors (see Section 3.3 on page 19).
- The PWM frequency is not fixed but it is determined by the on-time which varies according to several conditions (current value, BEMF, etc.).

The new predictive current control provided by the L6472, which is based on the peak current control described in Section 4.1 on page 21, allows these limits to be reduced and removed in some cases.

The control system operation can be configured through the parameters listed in Table 6.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>t(_{SW})</td>
<td>Target switching time</td>
<td>It sets the target PWM frequency of the control system.</td>
</tr>
<tr>
<td>t(_{ON_MIN})</td>
<td>Target minimum on-time</td>
<td>It defines which is the shortest on-time (i.e.: the time to reach reference current) which guarantees a correct operation of the control algorithm (Figure 16).</td>
</tr>
<tr>
<td>t(_{OFF_MIN})</td>
<td>Minimum off-time</td>
<td>It defines which is the shortest off-time (i.e.: the current decay duration) which guarantees a correct operation of the control algorithm.</td>
</tr>
<tr>
<td>t(_{OFF_FAST})</td>
<td>Maximum fast decay time</td>
<td>It is the maximum duration of a fast decay during operation of the current control system.</td>
</tr>
<tr>
<td>t(_{FAST_STEP})</td>
<td>Maximum step fall time</td>
<td>It is the maximum duration of a fast decay during reference current changing.</td>
</tr>
</tbody>
</table>

The t\(_{ON\_MIN}\), t\(_{OFF\_FAST}\) and t\(_{FAST\_STEP}\) parameters act as described in Section 4.1, but t\(_{OFF}\) listed in Table 5 on page 21 is replaced by the t\(_{SW}\) and t\(_{OFF\_MIN}\) combination as described in Section 4.2.2.

\(^{(a)}\) Not available for the L6474.
4.2.1 Predictive on-time and average current regulation

The classic peak current control limits the maximum current value (peak) but cannot control the value of the average current.

The predictive current control adds an extra on-time \( t_{\text{pred}} \) after reaching the reference current which is the two-step average of the last on-time values, as described in Equation 9 (see Figure 22).

\[
\text{Equation 9} \quad t_{\text{pred}}(n) = \frac{t_{\text{on}}(n) + t_{\text{on}}(n-1)}{2}
\]

Figure 22. Predictive current control basic principle

When the system reaches the stability, \( t_{\text{on}} \) and \( t_{\text{pred}} \) are equal and the resulting average current value is equal to the reference threshold.

In order to avoid instability, all those conditions causing the on-time to be excessively long or short must be carefully managed. The following cases should be considered:

- The motor has been stopped
- The bridges have just been enabled (exit from high impedance status)
- The current threshold has been changed (both falling and rising steps)
- The on-time is below the minimum on-time limit \( t_{\text{ON_MIN}} \)
- The on-time is over the target switching time \( t_{\text{SW}} \).

In these cases the measured on-time is excluded from the average calculation and the previous \( t_{\text{pred}} \) is used. If the next on-time does not fall under the cases listed above, its value is used in the \( t_{\text{pred}} \) calculation.

4.2.2 Off-time regulation and target switching frequency

In the control system described in Section 4.1 on page 21, the decay phase of the current (namely, off-time) is constant and it is set through the \( t_{\text{OFF}} \) parameter. Because of this, the PWM frequency of the control system may vary significantly depending on situations (current value, BEMF, etc.).

The predictive current control automatically adjusts the off-time duration in order to obtain a PWM frequency near to the target value. This function is configured through the \( t_{\text{SW}} \) and \( t_{\text{OFF_MIN}} \) parameters.

At every current reference change the off-time of the control system is recalculated according to Equation 10, where \( t_{\text{pred}}(n-1) \) is the last predictive on-time used. If the new value is lower than the \( t_{\text{OFF_MIN}} \) parameter, \( t_{\text{OFF_MIN}} \) is used instead.
Equation 10

\[ t_{\text{off}} = t_{\text{sw}} - 2 \cdot t_{\text{pred}}(n-1) \]

**Figure 23. Off-time automatic adjustment**

Considering that the on-time and the predictive time at the steady-state of two subsequent current levels is almost the same (see Figure 23), the resulting switching time \( t_{\text{switch}} \) is almost equal to the target \( t_{\text{SW}} \) value.
5 Setup and optimization

In the following sections the optimization of the parameters of the control system is investigated.

5.1 Auto adjusted decay

The parameters used in the peak current control with auto adjusted decay and their relation with system performance are listed in Table 7.

Table 7. Control system parameters and performance relation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower values</th>
<th>Higher values</th>
</tr>
</thead>
<tbody>
<tr>
<td>TON_MIN</td>
<td>Less frequent use of the fast decay</td>
<td>More frequent use of the fast decay</td>
</tr>
<tr>
<td></td>
<td>Lower ripple</td>
<td>Higher ripple</td>
</tr>
<tr>
<td></td>
<td>Higher probability of control fail</td>
<td>Higher control stability</td>
</tr>
<tr>
<td>TOFF(1)</td>
<td>Higher switching frequency</td>
<td>Lower switching frequency</td>
</tr>
<tr>
<td></td>
<td>Lower ripple</td>
<td>Higher ripple</td>
</tr>
<tr>
<td></td>
<td>Higher probability of control fail</td>
<td>Higher control stability</td>
</tr>
<tr>
<td></td>
<td>More frequent use of the fast decay</td>
<td>Less frequent use of the fast decay</td>
</tr>
<tr>
<td>TOFF_FAST</td>
<td>Lower ripple</td>
<td>Higher ripple</td>
</tr>
<tr>
<td></td>
<td>Longer on-fast sequences</td>
<td>Shorter on-fast sequences</td>
</tr>
<tr>
<td></td>
<td>Higher probability of control fail</td>
<td>Higher control stability</td>
</tr>
<tr>
<td>FAST_STEP</td>
<td>Longer on-fast sequences during falling steps</td>
<td>Shorter on-fast sequences during falling steps (less commutations)</td>
</tr>
<tr>
<td></td>
<td>(more commutation)</td>
<td>Deeper current undershoot at falling steps</td>
</tr>
</tbody>
</table>

1. The same considerations are valid for TSW when predictive current control is used.

The optimal setup depends on several factors such as supply voltage, load current, motor characteristics and microstepping resolution.

5.1.1 TON_MIN

The minimum on-time value determinates the frequency of use of fast decay during current control and limits the minimum duty cycle value of the control.

The on-time measurement starts as soon as a turn-on is requested by the power bridges of the device, as shown in Figure 24. TON_MIN should always be longer than the commutation time of the power bridge, otherwise the minimum on-time condition is always satisfied and the fast decay is never used (the auto adjusted decay feature is actually disabled). This condition causes the current control to fail when the slow decay reduces its effectiveness (see Section 3.1 on page 15 and Section 3.2 on page 17).
In order to obtain the lowest current ripple possible, the TON_MIN value should be slightly longer than the commutation time. Using longer TON_MIN increases the current ripple but forces a higher minimum duty cycle value increasing the robustness of the control system.

### 5.1.2 TOFF

The off-time of the control system sets the maximum PWM frequency of the control system $f_{SW,\text{max}}$ (minimum on-time violation events excluded), as described in Equation 11.

**Equation 11**

$$f_{SW,\text{max}} = \frac{1}{(t_{\text{ON_MIN}} + t_{\text{OFF}})}$$

In general, motors having a lower $L_{Ph}/R_{Ph}$ ratio (weak inductive motor) require higher control frequencies and then lower TOFF values. On the contrary, higher TOFF values and then lower control frequencies may be needed when the $L_{Ph}/R_{Ph}$ ratio is higher (strong inductive motor).

### 5.1.3 TOFF_FAST

The maximum fast decay duration should be set taking into account that its value is directly proportional to the ripple of the current control algorithm.

High current ripple increases the noise, causes higher power dissipation and reduces the positioning precision in microstepping operation. In general, the current ripple should be as low as possible.

The minimum fast decay, which is one-eighth of TOFF_FAST, must be longer than TON_MIN to avoid subsequent minimum on-time violations (see Figure 2.5).
5.1.4 FAST_STEP

The FAST_STEP parameter defines the fast decay duration used at current reference changes; the shorter fast decay value (FAST_STEP/4) is used in the first falling steps, then the algorithm increases the fast time up to the longer value (FAST_STEP) which is used in the final part of the sinewave (see Figure 26 and Section 4.1.2 on page 24).
In parameter dimensioning the microstepping resolution of the system should be considered; the higher the resolution, the shorter the fast step time. In fact, the drop between subsequent microsteps decreases with the resolution.

Long FAST_STEP timings may cause deep undershoots in the first part of the negative slope of the sinewave, but give better performance in the final part where the drop between the microsteps is higher (see Figure 27).

Short FAST_STEP timings fit better to the drops of the first falling steps, but require a longer fast decay sequence in the final part of the negative slope of the sinewave, causing more commutations (see Figure 28).

The optimal trade-off between the starting and the final part of the negative slope requires a fine tuning.

In any case, the minimum fast decay (one-fourth of FAST_STEP) must be longer than TON_MIN to avoid subsequent minimum on-time violations.
5.2 Predictive current control

When the predictive current control is used, two more parameters need to be set: the target switching time $T_{SW}$ and the minimum off-time $T_{OFF\_MIN}$.

The $T_{SW}$ parameter is equivalent to the $T_{OFF}$ parameter described in Section 5.1.2 and it should be set according to the same considerations.

The $T_{OFF\_MIN}$ limits the variation of the off-time imposing its minimum value. It is equivalent to the $T_{OFF}$ parameter described in Section 5.1.2 and it should be set according to the following golden rules:

- $T_{OFF\_MIN} < T_{SW}$
- $T_{OFF\_MIN} > T_{OFF\_FAST}$
- $T_{OFF\_MIN} + 2 \times T_{ON\_MIN} > 1/f_{SW,max}$, where $f_{SW,max}$ is the maximum allowed switching frequency of the system.
6 Revision history

Table 8. Document revision history

<table>
<thead>
<tr>
<th>Date</th>
<th>Revision</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-Sep-2012</td>
<td>1</td>
<td>Initial release.</td>
</tr>
</tbody>
</table>
Replaced “dSPIN family of motor drivers” by “L6472” and note a.: “Not available for the easySPIN family of stepper motor drivers.” by  
“Not available for the L6474” in Section 4.2 on page 25.  
Updated cross-references throughout whole document.  
Minor modifications throughout document. |
IMPORTANT NOTICE – PLEASE READ CAREFULLY

STMicroelectronics NV and its subsidiaries ("ST") reserve the right to make changes, corrections, enhancements, modifications, and improvements to ST products and/or to this document at any time without notice. Purchasers should obtain the latest relevant information on ST products before placing orders. ST products are sold pursuant to ST’s terms and conditions of sale in place at the time of order acknowledgement.

Purchasers are solely responsible for the choice, selection, and use of ST products and ST assumes no liability for application assistance or the design of Purchasers’ products.

No license, express or implied, to any intellectual property right is granted by ST herein.

Resale of ST products with provisions different from the information set forth herein shall void any warranty granted by ST for such product.

ST and the ST logo are trademarks of ST. All other product or service names are the property of their respective owners.

Information in this document supersedes and replaces information previously supplied in any prior versions of this document.

© 2015 STMicroelectronics – All rights reserved