The Secrets of a Closed-Loop, Sensorless Sine Wave BLDC Motor Controller Unveiled

Simple and fast configuration of BLDC motor control without a microcontroller

Introduction

Brushless DC (BLDC) motors provide a wealth of advantages over their brushed DC counterparts. They deliver more torque in the same form factor, generate less electrical and audible noise, and demand significantly less maintenance. However, like with any benefit, there are also some challenges. Without brushes to support mechanical commutation, commutation must be implemented electronically. To achieve this, the electronics required are slightly more complex than would be required for a brushed motor. One challenge is understanding the angle of the rotor so that software can determine the next commutation step and compensate for any changes in load. Sensors attached to the rotor are one option, but these push up the solution cost and require additional wiring and larger connectors, something that most engineers would like to keep to a minimum.

Luckily, there are approaches that can determine rotor angle without a sensor, even when the rotor is stationary. Many of these solutions are available as software suited to a specific semiconductor vendor's microcontroller series. However, not everyone needs an additional microcontroller, preferring to attach a highly integrated motor controller to a system without any microcontroller.

Comparing trapezoidal and sine wave BLDC control

Not all BLDC motors are the same. Depending on their construction, they develop either a trapezoidal or sine wave back-EMF signal. Those generating a trapezoidal back-EMF are typically termed BLDC motors, while those generating a sine wave are known as permanent magnet synchronous motors (PMSM). Should an unknown motor be lying around, the easiest way to determine whether it is a BLDC or PMSM motor is to connect the terminals to an oscilloscope and rotate the rotor by hand. PMSM motors generate an unmistakable sine wave signal, while a BLDC motor will generate an output that looks more like a triangular wave or a square wave with sloping rising and falling edges.

PMSM motors are preferred in applications where lower torque ripple is needed, quieter operation, and higher efficiency. However, these advantages come at a price. A sinusoidal drive signal must be generated for the motor coils, something that requires careful evaluation of the switching losses in the inverter to maintain optimal efficiency. Driving a BLDC motor faster simply requires applying more current to the coils. But, for a PMSM, faster rotational speeds require application of a higher frequency sine wave to the coils. Because the shape of the sine wave must be calculated, and because these calculations are computationally complex, a high-performance processor, field-programmable gate array (FPGA), or a device with hardware acceleration is typically required.

Motor control pre-driver for sensorless sine wave control

Today, highly integrated MCU-less solutions are available for PMSM motor control, offering simple configurability without a rotor sensor requirement. This is the case with the TC78B011FTG (Figure 1), a sine wave pre-driver for sensorless three-phase brushless motor control offered in a compact QFN36 package (5.0 × 5.0 × 0.8 mm). The pulse-width modulated (PWM) chopper pre-driver is suitable for N-channel MOSFETs in both the low and high sides that offers eight selectable levels of gate drive current, allowing for a scalable inverter implementation to match a range of different motors and optimization of electromagnetic compatibility (EMC) test results. Operating from 5.5V to 27V, with an absolute maximum rating of 30V, the device is ideal for driving Delta or Wye configured motors in fans, pumps, and portable vacuum applications.

While the device provides open-loop speed control, a built-in closed-loop speed controller with an adjustable speed curve is probably the key capability engineers are searching for. The precise operation mode is configured via the I^2C interface, with the option to store the settings in a non-volatile memory (NVM). This means suitable settings can be programmed during manufacture for circuits that do not use a microcontroller or processor, enabling a constant rotation speed unaffected by power supply or load variations. Motor speed can also be set via I^2C if required, but provision is also available for setting the speed using either a PWM input or an analog signal. Braking and direction control is available via pins and the I^2C interface. To save power, a standby mode is available that reduces current consumption to below 10µA from a maximum of 18mA. During motor operation, the motor current and rotation speed are available at the device's pins.

The TC78B011FTG is also well protected from a range of failure modes. Abnormality of operation is signalled through an output pin, as is thermal shutdown, under voltage, charge pump low voltage, output current limit, and over current conditions.

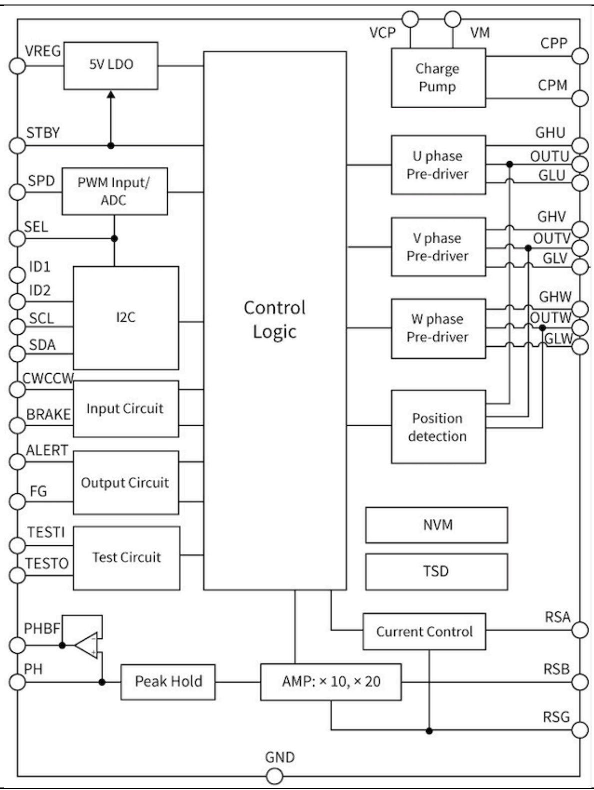

Figure 1: Block diagram of the TC78B011FTG.

Getting the rotor moving

One of the advantages of the mechanically commutated brushed DC motor is that the commutation point is physically defined. Regardless of where the rotor last stopped, reapplication of power will ensure the correct coils are engaged to start the motor correctly. This is why sensors are often fitted to brushless motors. The sensor provides the current mechanical rotor angle, allowing the appropriate coils to be excited and the rotor to begin rotating in the correct direction.

In sensorless BLDC operation, novel techniques are needed to determine the stationary rotor's angle before energising the coils to ensure the rotor and anything attached to it do not whip back in the wrong direction. When the coils are energised, this has to be undertaken in a manner that does not generate too much noise and vibration (through PWM switching) during a period where no useable back-EMF is available to determine rotor angle. In essence, the motor control algorithm is driving the motor blind. Once sufficient back-EMF is available, the motor controller can switch to the chosen control method.

After power is applied, the TC78B011FTG retrieves the stored device configuration from the NVM (Figure 2). If enabled, a brake sequence, generated by shorting the appropriate coils through the motor inverter, is applied for between one and seven seconds. This helps to guarantee that the rotor is stationary before attempting to start rotation. Once the initialisation sequence is complete (around 3.5ms), the motor driver enters idle mode with all MOSFETs turned off and awaits further instruction from the host system.

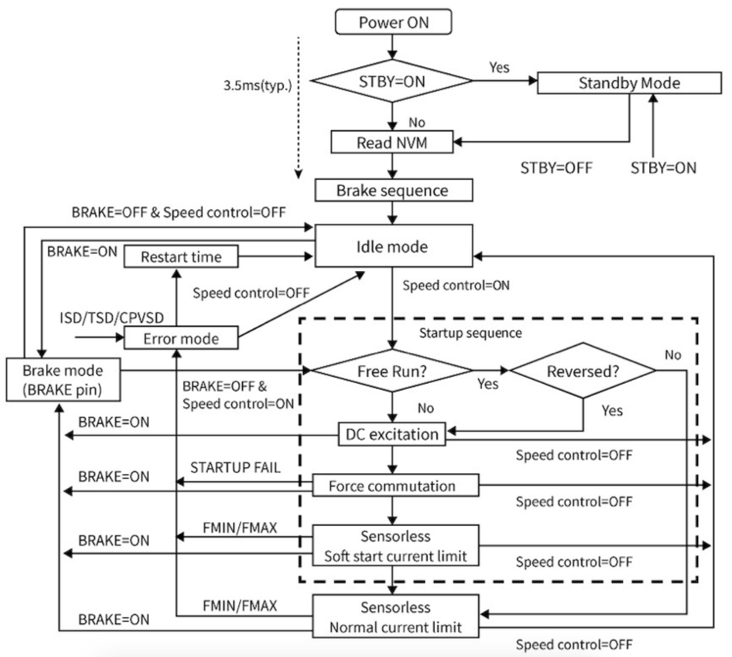

Figure 2: Operational flowchart showing initialisation of NVM configuration and forced commutation motor start-up.

Upon reception of the speed control command, which can be written via I^2C to the speed command register (SPD), or a PWM or analogue signal applied to the SPD pin, the motor start-up sequence is engaged. The process begins with a DC excitation of the motor coils that determines the starting position of the rotor. Once complete, the forced commutation of the motor starts. At this stage, a rough electrical field is applied in 120° commutation to generate an initial back-EMF. A configurable soft start feature is also included (Figure 3), limiting the current drawn when spinning up the motor. All speed control at this stage is open loop.

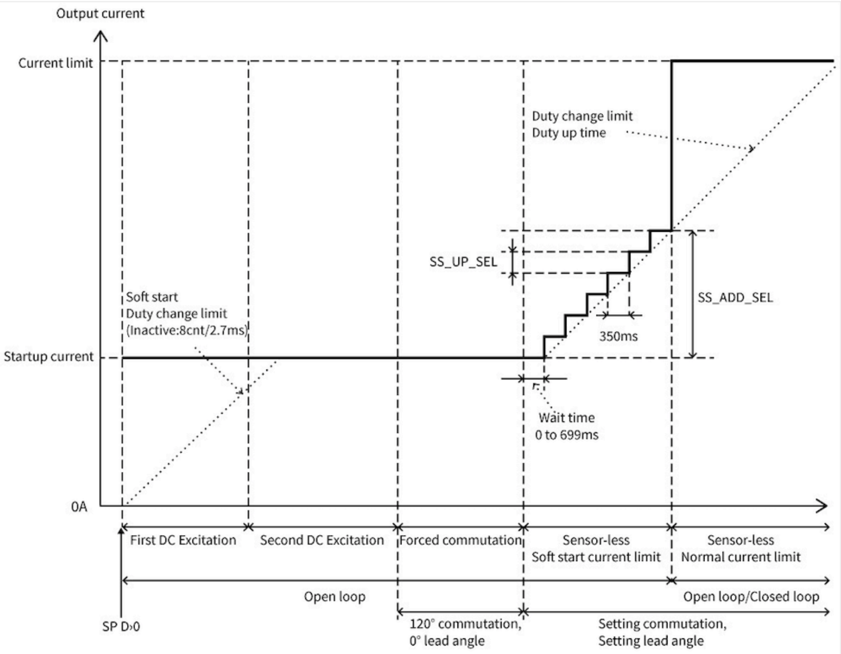

Figure 3: Output current limit during start-up.

Once the motor rotates fast enough to generate a back-EMF usable for the control algorithm, the TC78B011FTG switches to sensorless control with the current limit set for normal operation. If selected, closed-loop speed control is also engaged.

Should the rotor already be rotating (known as idling or windmilling), perhaps due to air passing over a fan's blades, the motor driver will skip the initial excitation and forced commutation steps and proceed directly with sensorless operation. However, it should be noted that the back-EMF measurement capability used to monitor rotor speed and determine optimal commutation can prove to be too sensitive in some cases. Thus, there is a possibility that the motor driver makes an unwarranted attempt to skip the first open loop start-up stages. The COM_HYS register setting can be modified to change the minimum RPM that is considered fast enough to skip the start-up process. To avoid the challenges associated with starting an idling motor, the motor controller can be configured to apply its braking sequence after leaving standby or power on, enabling the rotor to always start from a stopped state.

Motor control tuning

With the start-up sequence and basic operation understood, the next step is to tune the other capabilities of the TC78B011FTG to meet the application's needs. The first is acceleration and deceleration. With closed-loop operation selected, the time between each step increase/decrease in speed is configurable to either 2.7ms or 10.8ms using the DUTY_UP_TIME register. How quickly speed change can occur is further defined using the DUTYCHGLIMIT register, with options ranging from 2/8 to 56/8. Thus, with a DUTY_UP_TIME of 2.7ms and a DUTYCHGLIMIT of 6/8, for a 9-bit counter (2^9 = 512), changing the duty cycle by one will require 2.7ms / (6/8) = 3.6ms. Moving from a duty cycle of 0 to 512 will take 512 × 2.7ms / (6/8) = 1.8432s.

The supported speed settings are also configurable, with a range of options available. For example, the starting, stopping, and maximum duty cycles may be set individually, along with the RPM associated with the start and maximum values (Figure 4). Up to two speed slopes between the start and maximum RPM may be defined.

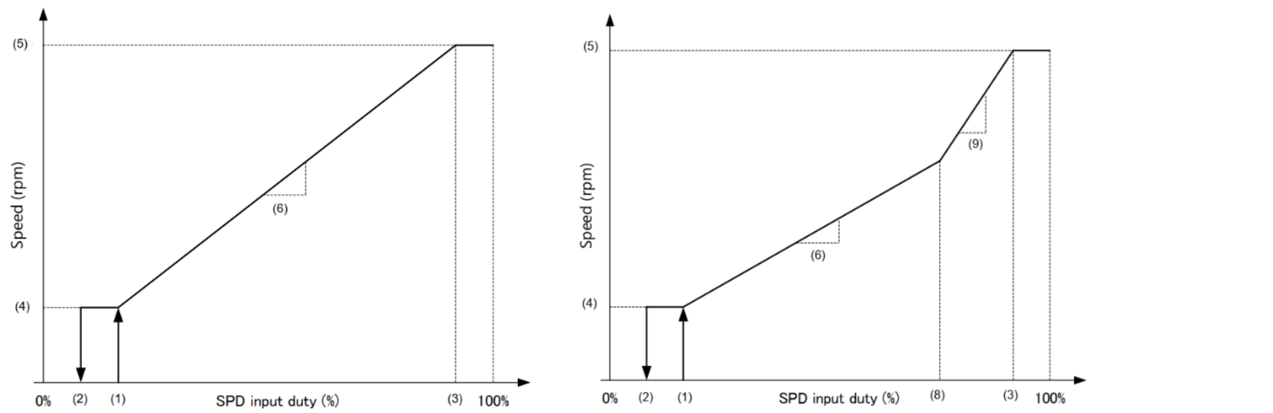

Figure 4: Minimum, with hysteresis, and maximum RPM can be set, along with up to two different speed slopes.

The frequency used for the PWM output may be fixed or set to increase as motor speed increases automatically. The available frequency range lies between 23.4kHz and 187.5kHz and can be configured in eight different combinations. This is implemented using the FPWM register. This setting may also help with fulfilling electromagnetic compatibility (EMC) testing.

Closed loop control is optimized to avoid overshooting or oscillation using the PI controller's registers KI and KP, noting that changing one value also impacts the other. The settings should be changed to attain the fastest response to a change in requested speed without overshoot or oscillation.

Finally, the lead angle should be set so that back-EMF and motor current are in phase. This ensures the most efficient operation of the motor. Lead angle can also be adjusted according to the rotational speed, responding to the electrical frequency.

MOSFET selection

The three integrated half-bridge pre-drivers support n-channel MOSFETs. These can supply a gate-source (V_{GSS}) voltage of up to 8V above the motor supply voltage. The gate-source (I_{GSS}) current for both high- and low-side MOSFETs is configurable from 10 mA to 100mA, while the sink current rang
e is 20mA to 200mA. Applying the electrical brake function or reversing the direction could cause shoot-through in the switches. An ANTITHROUGH register coupled with a DEADTIME setting avoids this with dead time options from 250ns to 1500ns.

The highest usable switching frequency may be limited by the MOSFET choice and motor used. Back-EMF is measured during the off-time of the PWM. Thus, if the motor inductance is high, the switching performance of the MOSFETs is low, or the current drawn is high, the position detection algorithm that relies on the back-EMF may fail to work. The best course of action is to undertake sufficient testing under all usage conditions and FPWM settings.

Protection and feedback features and their configuration

Operational information is provided via both I^2C and the pins of the TC78B011FTG. Rotational speed is provided in RPM through the hz_cnt register or the open drain FG pin, whose pulse-per-rotation are configured according to the pole pairs of the motor.

Other abnormalities in operation are indicated using the open drain ALERT pin. An under-voltage condition is only indicated through the ALERT pin, while all other abnormal conditions are additionally accessible via registers using I^2C. The ALERT pin can also be set to operate active high or low. The output indicates excessive current draw, low voltage in the charge pump, thermal shutdown, and start-up failure. What happens after an abnormal condition can also be defined. In latched configuration, the motor controller awaits a command from an external source. Otherwise, in auto recovery mode, the device will attempt to restart the motor any time between immediately and a 10-second pause, depending on the TRE register configuration.

Operation outside maximum and minimum rotation speeds can also cause an ALERT. In both cases, the motor is turned off and, if below the minimum speed, the brake is applied if so configured. The same occurs if the rotor is blocked from turning.

External monitoring of the motor current is available via the PHBF pin when coupled with an RC filter consisting of a 0.1µF capacitor and a 10kΩ resistor. A peak hold current output is also provided at the PH pin, which needs a 0.1µF capacitor and a 100kΩ resistor RC filter.

Accelerating prototyping with the Brushless 23 Click

To speed up evaluation and development, the TC78B011FTG is available from MIKROE on the Brushless 23 Click board (Figure 5). Coupled with six SSM6K513NU N-channel MOSFETs offering a drain-source voltage of 30V and a continuous drain current of up to 15A, the board is suitable for the efficient operation of blowers, pumps, and high-velocity fans for servers.

Brake and speed control selection, along with I^2C address configuration, are provided through four miniature slide switches. Terminals for power and the chosen motor are at the end of the board, avoiding interference with other circuitry, and the remaining pins follow the MIKROE mikroBUS™ standard. The FG and ALERT pins are additionally connected to LEDs.

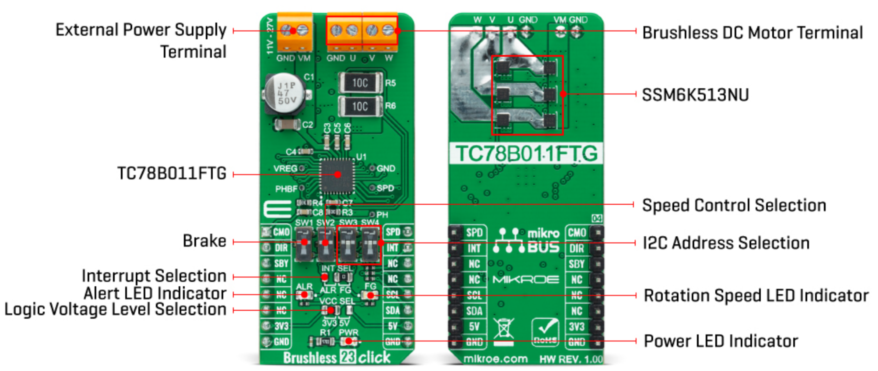

Figure 5: The Brushless 23 Click board is ready for MCU-less, closed-loop sine wave PMSM control. (Source: MIROE) [https://www.mikroe.com/brushless-23-click]

A source code driver also supports the board, available via MIKROE's NECTO Studio IDE[1], their LibStock[2] repository, or simply via GitHub[3]. The programming interface (API) is fully documented and easy to use (Figure 6).

```
void application_task ( void )
{
  static int8_t duty_cnt = 3;
  static int8_t duty_inc = 1;
  float duty = duty_cnt / 10.0;

  brushless23_pwm_set_duty_cycle ( &brushless23, duty );
  log_printf( &logger, " Duty cycle: %u%%\r\n", ( uint16_t )( duty_cnt * 10 ) );

  float motor_speed_hz = 0;
  if ( BRUSHLESS23_OK == brushless23_get_motor_speed ( &brushless23, &motor_speed_hz ) )
  {
    log_printf( &logger, " Speed: %.1f Hz\r\n", motor_speed_hz );
  }

  if ( 8 == duty_cnt )
  {
    duty_inc = -1;
  }
  else if ( 2 == duty_cnt )
  {
    duty_inc = 1;
    log_printf( &logger, " Switch direction\r\n\n" );
    brushless23_switch_direction ( &brushless23 );
  }
  duty_cnt += duty_inc;

  Delay_ms( 500 );
}
```

Figure 6: Example application that continuously runs the duty cycle between 20% to 80%, switching direction each time at the lowest speed. (Source: MIKROE)
[https://github.com/MikroElektronika/mikrosdk_click_v2/tree/master/clicks/brushless23]

Summary

The move to a more efficient, brushless motor for pump and fan applications doesn't always require a microcontroller-based solution. The TC78B011FTG, thanks to its NVM configuration, can operate standalone once the parameters for the chosen inverter and motor combination have been found. However, just because no microcontroller is present doesn't mean that developers have to do without performance or features. The motor driver easily adapts to the chosen n-channel MOSFETs, and variable PWM frequencies ensure optimal operation over the desired RPM range. Furthermore, adjustable lead angle provides the most efficient operation, while soft-start and abnormal operation monitoring ensure the system is safe and protected from various failure conditions. Closed-loop control and a parameterizable speed setting deliver accurate control regardless of supply voltage deviations and changes in load. Finally, the Brushless 23 Click prototyping board coupled with the available software is available to enable developers to move quickly from concept to solution.

TOSHIBA

References

1. NECTO IDE - https://www.mikroe.com/necto
2. LibStock - https://libstock.mikroe.com/projects/view/4953/brushless-23-click
3. MIKROE on GitHub - https://github.com/MikroElektronika/mikrosdk_click_v2/tree/master/clicks/brushless23

Restrictions On Product Use

Toshiba Corporation and its subsidiaries and affiliates are collectively referred to as “TOSHIBA”.
Hardware, software and systems described in this document are collectively referred to as “Product”.

- TOSHIBA reserves the right to make changes to the information in this document and related Product without notice.
- This document and any information herein may not be reproduced without prior written permission from TOSHIBA. Even with TOSHIBA’s written permission, reproduction is permissible only if reproduction is without alteration/omission.
- Though TOSHIBA works continually to improve Product’s quality and reliability, Product can malfunction or fail. Customers are responsible for complying with safety standards and for providing adequate designs and safeguards for their hardware, software and systems which minimise risk and avoid situations in which a malfunction or failure of Product could cause loss of human life, bodily injury or damage to property, including data loss or corruption. Before customers use the Product, create designs including the Product, or incorporate the Product into their own applications, customers must also refer to and comply with (a) the latest versions of all relevant TOSHIBA information, including without limitation, this document, the specifications, the data sheets and application notes for Product and the precautions and conditions set forth in the “TOSHIBA Semiconductor Reliability Handbook” and (b) the instructions for the application with which the Product will be used with or for. Customers are solely responsible for all aspects of their own product design or applications, including but not limited to (a) determining the appropriateness of the use of this Product in such design or applications; (b) evaluating and determining the applicability of any information contained in this document, or in charts, diagrams, programs, algorithms, sample application circuits, or any other referenced documents; and (c) validating all operating parameters for such designs and applications. TOSHIBA ASSUMES NO LIABILITY FOR CUSTOMERS’ PRODUCT DESIGN OR APPLICATIONS.
- PRODUCT IS NEITHER INTENDED NOR WARRANTED FOR USE IN EQUIPMENTS OR SYSTEMS THAT REQUIRE EXTRAORDINARILY HIGH LEVELS OF QUALITY AND/OR RELIABILITY, AND/OR A MALFUNCTION OR FAILURE OF WHICH MAY CAUSE LOSS OF HUMAN LIFE, BODILY INJURY, SERIOUS PROPERTY DAMAGE AND/OR SERIOUS PUBLIC IMPACT ("UNINTENDED USE"). Except for specific applications as expressly stated in this document, Unintended Use includes, without limitation, equipment used in nuclear facilities, equipment used in the aerospace industry, lifesaving and/or life supporting medical equipment, equipment used for automobiles, trains, ships and other transportation, traffic signalling equipment, equipment used to control combustions or explosions, safety devices, elevators and escalators, and devices related to power plant. IF YOU USE PRODUCT FOR UNINTENDED USE, TOSHIBA ASSUMES NO LIABILITY FOR PRODUCT. For details, please contact your TOSHIBA sales representative or contact as via our website.
- Do not disassemble, analyse, reverse-engineer, alter, modify, translate or copy Product, whether in whole or in part.
- Product shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable laws or regulations.
- The information contained herein is presented only as guidance for Product use. No responsibility is assumed by TOSHIBA for any infringement of patents or any other intellectual property rights of third parties that may result from the use of Product. No license to any intellectual property right is granted by this document, whether express or implied, by estoppel or otherwise.
- ABSENT A WRITTEN SIGNED AGREEMENT, EXCEPT AS PROVIDED IN THE RELEVANT TERMS AND CONDITIONS OF SALE FOR PRODUCT, AND TO THE MAXIMUM EXTENT ALLOWABLE BY LAW, TOSHIBA (1) ASSUMES NO LIABILITY WHATSOEVER, INCLUDING WITHOUT LIMITATION, INDIRECT, CONSEQUENTIAL, SPECIAL, OR INCIDENTAL DAMAGES OR LOSS, INCLUDING WITHOUT LIMITATION, LOSS OF PROFITS, LOSS OF OPPORTUNITIES, BUSINESS INTERRUPTION AND LOSS OF DATA, AND (2) DISCLAIMS ANY AND ALL EXPRESS OR IMPLIED WARRANTIES AND CONDITIONS RELATED TO SALE, USE OF PRODUCT, OR INFORMATION, INCLUDING WARRANTIES OR CONDITIONS OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, ACCURACY OF INFORMATION, OR NONINFRINGEMENT.
- Do not use or otherwise make available Product or related software or technology for any military purposes, including without limitation, for the design, development, use, stockpiling or manufacturing of nuclear, chemical, or biological weapons or missile technology products (mass destruction weapons). Product and related software and technology may be controlled under the applicable export laws and regulations including, without limitation, the Japanese Foreign Exchange and Foreign Trade Law and the US Export Administration Regulations. Export and re-export of Product or related software or technology are strictly prohibited except in compliance with all applicable export laws and regulations.
- Please contact your TOSHIBA sales representative for details as to environmental matters such as the RoHS compatibility of Product. Please use Product in compliance with all applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive. TOSHIBA ASSUMES NO LIABILITY FOR DAMAGES OR LOSSES OCCURRING AS A RESULT OF NONCOMPLIANCE WITH APPLICABLE LAWS AND REGULATIONS.