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M16C/Tiny Sensor-less PMSM Driving Platform by 120-Degree Trapezoidal Wave Commutation

M16C/Tiny

User's Manual

RSBJ

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PREFACE

About this manual

This user's manual discusses how to use three-phase motor control timer function, and a sample application of how to implement position-sensor-less driving of an SPMSM by 120-degree trapezoidal wave commutation, which is a method that makes use of the induced voltage of the motor.

This example applies to MCUs in the MC16C/TinyGroup

Section 1 About this platform

Gives specification on hardware and software

Section 2 Description of Software

Describes software for motor control

Section 3 Finite State Machine of Motor Control

Describes state transition for motor control

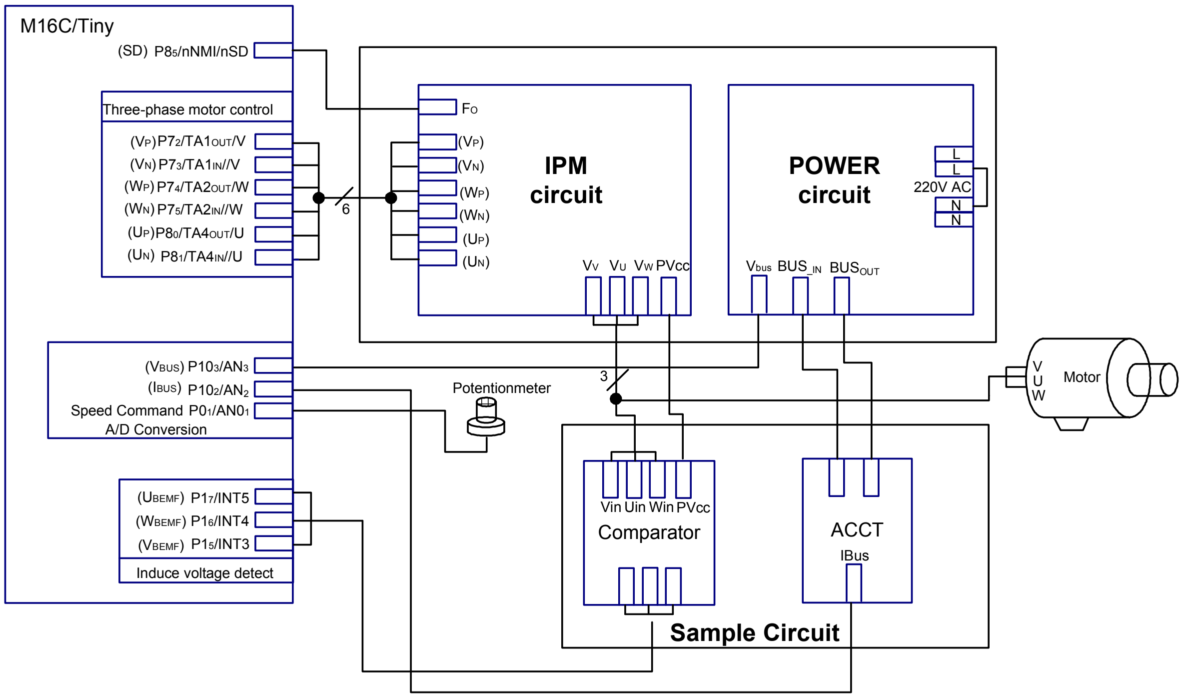
Section 4 Control flow

Gives program flowchart.

Contents

1. About This Platform

1.1 The hardware block diagram



1.2 The hardware resource assignment table

Used SFR	Function Description	Used I/O Port	Function Description
TA1	U phase PWM wave	P1$_5$/ $\overline{INT_3}$ /IDV	V phase induced voltage detection
TA2	V phase PWM wave	P16/ $\overline{INT_4}$ /IDW	W phase induced voltage detection
TA4	W phase PWM wave	P1$_7$/ $\overline{INT_5}$ /IDU	U phase induced voltage detection
TB1	50us cycle inquiry	P0$_1$/AN0$_1$	Rotation Speed Command
TB2	Carrier wave cycle control	P10$_2$/AN$_2$	Bus current sample
		P10$_3$/AN$_3$	Bus voltage sample
		P7$_2$/V	V phase voltage
		P7$_3$/ $\overline{V}$	$\overline{V}$ phase voltage
		P7$_4$/W	W phase voltage
		P7$_5$/ $\overline{W}$	$\overline{W}$ phase voltage
		P8$_0$/U	U phase voltage
		P8$_1$/ $\overline{U}$	$\overline{U}$ phase voltage

1.3 software specifications

Motor type	permanent magnet synchronous motor(PMSM)
Numbers of pole pairs	2
Control method	120-degree commutation using trapezoidal waves
Motor Position Detection	Detected by three phase induced voltage of motor
Carrier Frequency	5kHz
Range of Rotation Speed Command	Single Direction 1000rpm to 7200 rpm
Error detection	The Fo signal (forced shut-down signal) of the IPM is input to the NMI pin of the MCU. Thus, if the Fo signal goes low, the three-phase output is forcibly stopped and the three-phase output pins are placed in the high-impedance state.

2 Description of Software

2.1 Output Pattern Switching

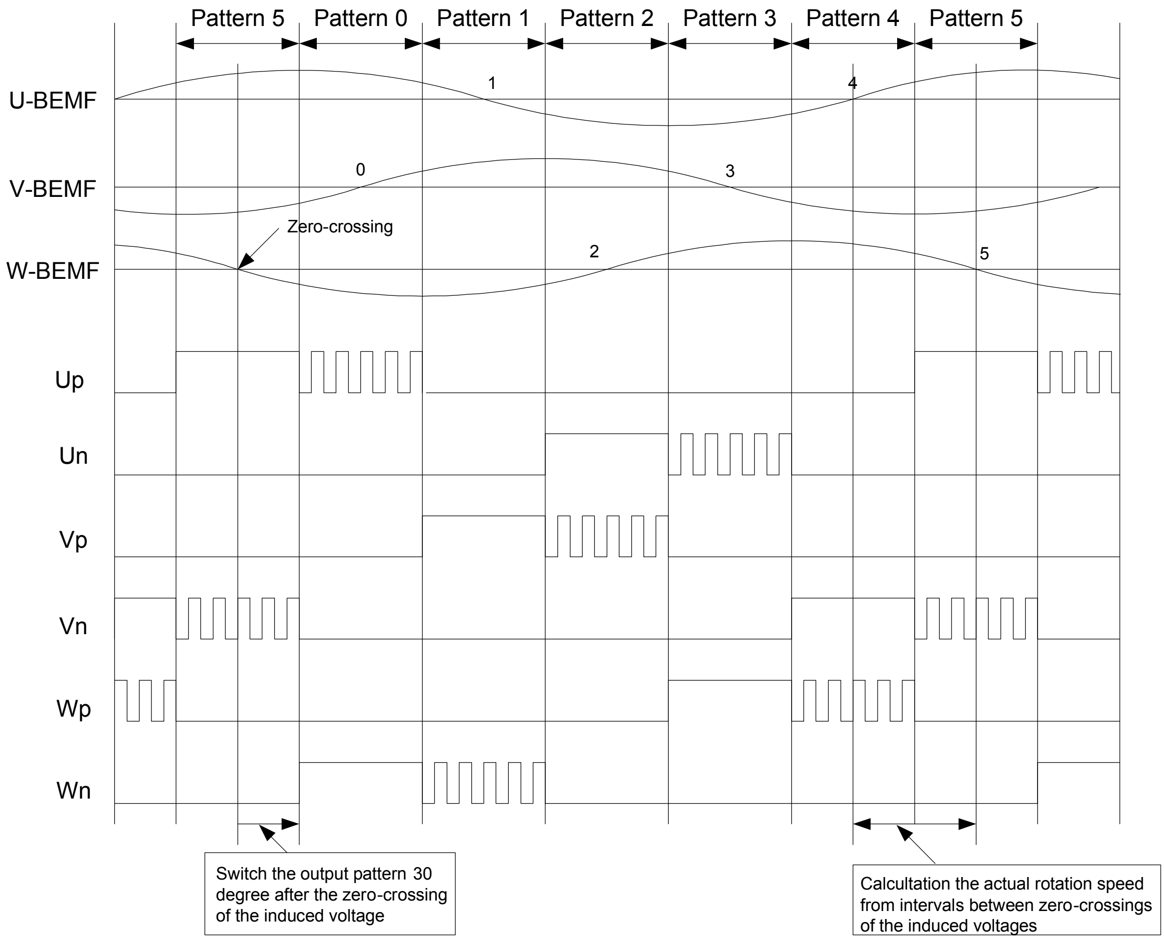


Figure 3.1.1 Time Charting

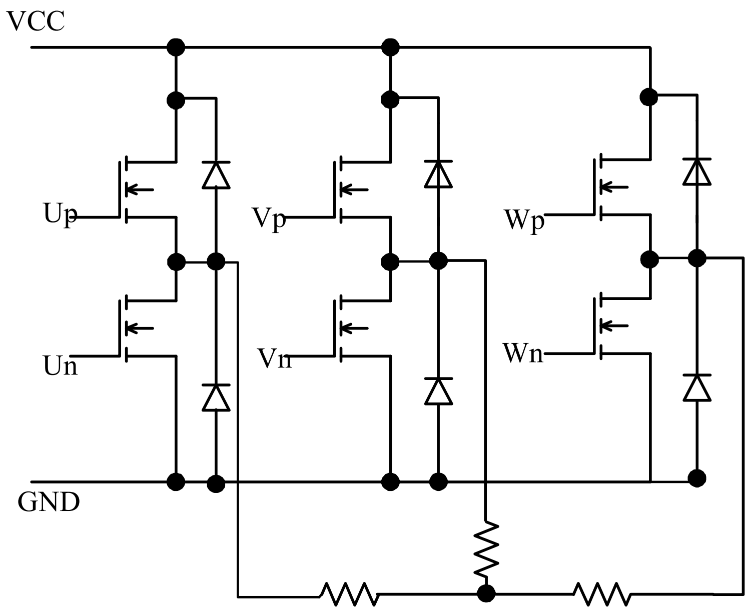


Figure 3.1.2 Three-phase IGBT inverter circuit

In the 120 degree trapezoidal communication mode, three phase IGBT circuit turn-on sequence is UpWn→WnVp→VpUn→UnWp→WpVn→VnUp, two IGBT are conducted every 60 electrical degrees. Accordingly, PWM wave have 6 output pattern switching. It is shown as the figure 3.1.1 and figure 3.1.2

Output pattern is switched when motor rotor angles 60 electrical degree every time. Zero-crossings of the induced voltages is at the mid of each output pattern (30 electrical degree).

In this program, the function of output pattern switching is carried out by PFCR register of M16C62A. It can control each bit in the PFCi (i=0 to 5) to enable each one of three-phase PWM output pins. When setting the PFCi (i=0 to 5) to "0", three-phase PWM output pin functions act as I/O port and can output "H" level state and "L" level state.

In order to outputting PWM wave when motor rotor angles 360 electrical degrees, PFCR register should be set based the following table.

			Wn	Wp	Vn	Vp	Un	Up
	X	X	PFC5	PFC4	PFC3	PFC2	PFC1	PFC0
Pattern 0	0	0	0	0	0	0	0	1
Pattern 1	0	0	**1**	0	0	0	0	0
Pattern 2	0	0	0	0	0	**1**	0	0
Pattern 3	0	0	0	0	0	0	**1**	0
Pattern 4	0	0	0	**1**	0	0	0	0
Pattern 5	0	0	0	0	**1**	0	0	0

Table 3.1.1 PFCR correspond to different output pattern

The three-phase PWM output pins have three states, PWM wave, "H" and "L", the output states depend on PFCR register, Pi register and PDi register. The output states table is shown on Table 3.1.2.

PFCi	PDi	Pi	Output
0	1	0	"L"
0	1	1	"H"
1	X	X	PWM

Table 3.1.2 three states of output pin

2.2 Detection of Induced Voltages

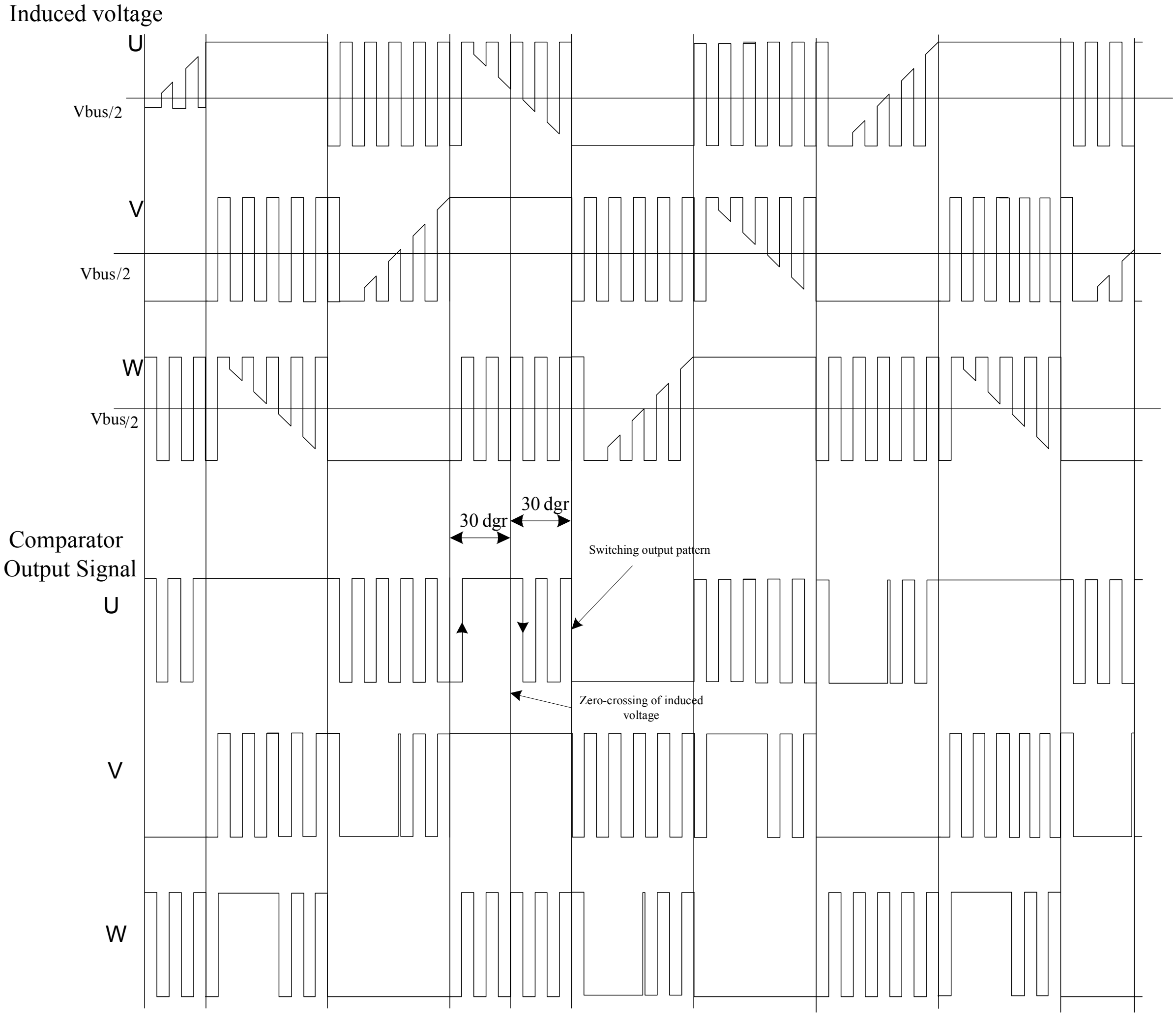


Figure 3.1.3 Detection of zero-crossing of induced voltage and comparator output

The output pattern of the MCU depends on position information of induced voltages. The voltages output by the inverter are compared with half the bus voltage, and the results are fed to the MCU. The following table shows the connection between MCU pins and induced voltage signals.

Input pin	BEMF signal
$P1_5 / \overline{INT3}$	V_BEMF
$P1_6 / \overline{INT4}$	W_BEMF
$P1_7 / \overline{INT5}$	U_BEMF

Table 3.1.3 the connection of input pin and induce voltage

In our program, when motor mode changes into turnon mode, TB1 interrupt is enabled, after the next carrier wave cycle interrupt, motor woke mode become run mode. Every 50us, TB1 interrupts. If the TB1 interrupt request bit is set to 1, after another 50us, the TB1 interrupt request bit is still set to 1, the zero-crossing of induced voltages is detected, and it is at the mid-point (30 electrical degrees) of each output pattern. Switching of the output pattern is delayed by 30 electrical degrees from zero-crossing detected. The process avoid occurring wrong pulses to be mistaken the detection of zero-crossing of induced voltages because of motor demagnetization at the point of output pattern switching. The U phase processing is shown as figure 3.1.2
When motor work mode changes into stop mode, tb1s is set to “0”, TB1 interrupt stops but interrupt enable is still open. The detection of induced voltage is shown as figure 3.1.1

2.3 Calculation of Actual Rotation Speed

The actual rotation speed is calculated by interval between two zero-crossings of induced voltages. The interval comprises certain carrier wave cycle pulses. In the PWM mode, 6 intervals are passed every 360 electrical degree. So if counting the carrier wave pulses every a rotate, the actual rotation speed can be calculated by the following formula.

$$\text{Actual rotation speed}=\frac{2\pi\times 5\text{kHz}}{\text{Zero}-\text{crossing interval}\times 6} \qquad (3.3.1)$$

In the actual programming, the method of lookup table can be used. Given an array of zero-crossing interval pulses, the corresponding actual rotation speed can be calculated based the above formula. A zero-crossing interval pulses is subtracted 13, the corresponding actual rotation speed can be looked up using the sequence number of array.

2.4 Calculation of Target Rotation Speed

The target rotation speed is brought towards the current rotation speed command at a rate of 0.5 rad/s every certain interval until target rotation speed is approach to the rotation speed command. If knowing current target rotation speed, the carrier wave cycle pulses between intervals of zero-crossings can be calculated using the above formula.

2.5 Calculation of PWM Duty Cycle

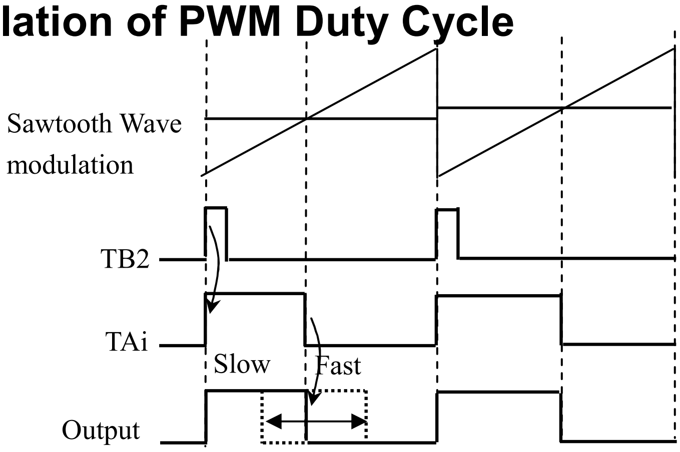


Figure 3.1.4 Relationship between PWM Duty Cycle and Rotation Speed Command

PWM duty cycle depends on counting values of TAi. The actual rotation speed is proportion to PWM duty cycle, the bigger is PWM duty cycle, the faster is the actual rotation speed. In the course of approaching rotation speed command, the carrier wave cycle pulses can be acquired by target rotation speed every time. Every result is saved a 1dimension array including 12 data units. Then 12 elements are added to calculate average value, a current carrier wave pulses between zero-crossings can be gotten.

According to formula 3.3.1, the current actual rotation speed will be gotten. Consequently, the PWM duty cycle is changed according to the conditions given below.

Condition	Amount of change
Target rotation speed > Actual rotation speed	+ Δ duty
Target rotation speed > Actual rotation speed	- Δ duty

2.6 List of function modules

Module name	Label name	Input	Output	Description
Motor control main processing	Main_PWM_120slc20_PFCR( )	——		Main processing
Initialization processing	PWMInitial( )	——		Set initial values for AD conversion, zero-crossing detection ,and three phase PWM
PWM interrupt processing	PWMInt( )	——		Call the turnoff, bootstrap, turnon and run processing
Turn off processing	TurnoffPWM( )	——		Turns off the three pahse PWM outputs and checks whether to proceed to startup operation
Turn on Processing	TurnonPWM( )	——		Performs startup operation and check run mode switch
Bootstrap processing	BootstrapPWM ( )	——		Charging for 3-phase IGBT circuit
TB1 int processing	TB1Int ( )	——		Performs 50us timer inquiry and detect induced voltage
Run Processing	RunPWM ( )	——		Normal PWM operation processing
Run calculation processing	Cal PwmRun ( )	——		Performs sensor-less control and Output pattern switching
PWM duty calculation processing	CalPWMDuty ( )	——		Calculates actual rotation speed and PWM duty
Stop check processing	StopCheck( )		UNIT_16 Stop check result	Check whether the processing is stopped by a rotation speed command or an error
Calculate Rotation Speed Command	CalSpeedCnd( )	UINT_16 Ad Input Value	UNIT_16 rotation speed command	Convert AD value to rotation speed command

2.7 List of vrialbles

Item	Label	Data Type	Resolution	Description
Stop state	s_StopMode	UINT_16	2^0	
Output state	g_OutputMode	UINT_8	2^0	Operation mode
Output angle	g_MotTheta	UINT_16	2^11	
Startup control counter	s_StartCnt	UINT_16	2^0	
Target rotation speed calculation counter	s_TargetCnt	UINT_16	2^0	Counter used to provide the period (2ms) of target rotation speed calculation.
Rotation speed command	g_SpeedCnd	UINT_16	2^1	ADC input rpm = SpeedCnd /2^1/(2p)/ number of pole pairs×60
Target rotation speed	g_SpeedTgt	UINT_16	2^1	The value changed toward the rotation speed command value at a rate of 0.5 rad per 2 ms.
Actual rotation speed	g_SpeedAct	UINT_16	2^1	Detect from the zero-crossing interval of the induced voltages
Zero-crossings interval counter	s_DltCnt	UINT_16	2^0	Counter that measures the interval between zero-crossings (60°). Counter clock period is the carrier period.
Delay time counter for switching to the next output pattern	s_ReloadCnt	UINT_16	2^0	Counter used to provide a time period from a pattern switching until detection of induced voltage zero-crossings is enabled. Counter clock period is the carrier period
output pattern	g_Stage	UINT_16	2^0	Current output pattern
Next output Pattern	s_ReloadStg	UINT_16	2^0	Next pattern that is determined based on the induced-voltage zero-crossing detection.
PWM duty clcye	g_PwmDuty	UINT_16	2^13	
Bootstrap charge delay counter	s_BootstpCnt	UINT_16	2^0	A period delay for charging for every IGBT
Bootstrap charge Step counter	s_BootstpStep	UINT_8	2^0	Three-phase IGBT circuit bootstrap
Current zero-crossings interval counter	g_DltCntRef	UINT_16	2^0	
Former zero-crossings interval counter	g_PreDltCnt	UINT_16	2^0	
Zero-crossing interval array	g_DltCntArray[12]	UINT_16	2^0	Save 12 times zero-crossing interval pulses
Average zero-crossing interval pulse	g_AvrDltCnt	UINT_16	2^0	
External Interrupt counter	s_IntCnt	UINT_16	2^0	Detect two INTi interrupts for induced voltage
AD rotation speed command	s_ADSpeed	UINT_16	2^12	Change AD value into rotation speed
AD rotation speed sum	s_ADSum	UINT_32	2^12	16 times AD value sum
zero-crossing interval array pointer	s_CalCnt	UINT_8	2^0	Calculate average zero-crossing

				interval pulse
AD sample interval	g_swtime	UINT_16	2^0	Sample once every 16 carrier wave interrupt
Induced voltage detection disable time counter	g_ChkOnCnt	UINT_16	2^0	Counter used to provide a time delay for detect a induced voltage zero-crossing.

2.8 List of Macro definition

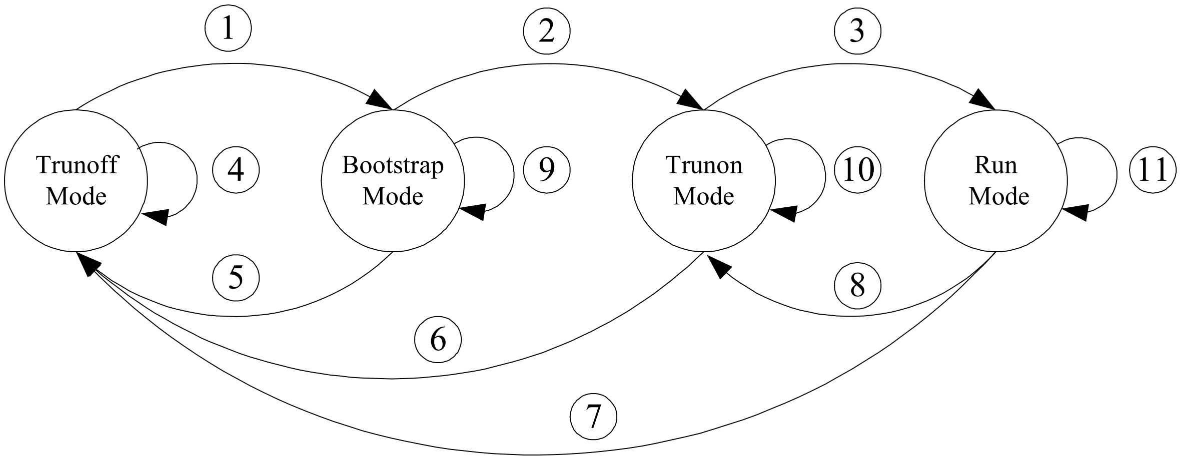
Macro name	Macro value	Resolution	Description
M_CTRL_TS	6711	2^25	Control cycle 0.0002* 2^25
M_K_SPEED_AD_REF	6032	2^12	A-D conversion ratio (240*2*pi/1024)* 2^12
M_Sft_SPEED_AD_RE	11		
M_Start_Hz	419	2^1	Carrier wave cycle 5k, startup rotation speed
M_Sft_TURNON_MODE	15	2^0	
M_TURNON_MODE_TIME	1500	2^0	Start up time
M_THETA_60DEG	2145	2^11	Pi/3* 2^11
M_THETA_360DEG	12868	2^11	2*Pi*2^11
M_CARR_CNT	4000	2^0	Carrier wave cycle is 5k
M_TURNOFF	0	2^0	Turnoff work mode
M_BOOTSTRAP	1	2^0	Bootstrap work mode
M_TURNON	2	2^0	Turnon work mode
M_RUN	3	2^0	Run work mode
M_INI_DUTY_120	1600	2^15	Initial PWM duty (0.08*2^15)
M_MIN_DUTY_120	328	2^15	Min PWM duty (0.01*2^15)
M_MAX_DUTY_120	29488	2^15	Max PWM duty (0.9*2^15)
M_BOOT_DUTY_120	3276	2^15	Bootstrap PWM duty (0.1*2^15)
M_Sft_DUTY_120_TIME	15	2^0	
M_BOOTSTRAPSTEP	3		Bootstrap mode step

2.9 List of constant variable

Item	Label	Data Type	Description
Output pattern switching table	PFCRTbl[ ]	UINT_8	Comprise 6 output pattern PWM wave
Zero-crossing interval counter table	Tgt_Dlt_Conv[ ]	UINT_8	Convert target rotation speed to zero-crossing interval pulse
Actual rotation speed table	Dlt_Act _Conv[ ]	UINT_8	Convert zero-crossing interval pulse to actual rotation speed
PFCR output table for bootstrap mode	PFCRTblBoot[ ]	UINT_8	Include three elements for three phase IGBT circuit charging

3 Finite State Machine of Motor Control

The state of motor control can be shown by finite state machine (FSM). The following figure is the FSM of BLDC in this software. It concludes four states, the states can be switched to other states under the certain conditions.



3.1 State Discription

1. Turnoff mode expresses that the rotation speed command from A/D converts is 0, and MCU will not output PWM wave. Under this mode, if rotation speed command from A/D converts is not equal to zero, motor work mode changes into bootstrap mode, the target rotation speed and actual rotation are set to the minimum rotation speed, 1000rpm.

2. Bootstrap mode indicate that under the condition of single power supply for IPM module, bootstrap circuit finish the function of charging for upper arm IGBT of 3 phase IGBT circuit. This method is implemented by MCU outputting bootstrap-duty PWM wave. In order to prove to enough charging time of upper arm IGBT, the bootstrap mode last certain time. When three phase IGBT circuit bootstrap mode is finished, the motor work mode changes into turnon mode, otherwise the bootstrap mode is continue.

When no rotation speed command is detected or three phase motor output control timer is disabled, the motor work mode come back turnoff mode.

3. Turnon mode points motor starts to run while MCU outputs initial-duty PWM wave. Output pattern switching is forcibly implemented by controlling PWM duty changing amount to calculate motor rotation angle. Passing 1500 carrier wave cycle interrupt, motor work mode changes into Run mode, or it will continue turnon mode.

When no rotation speed command is detected or three phase motor output control timer is disabled, the motor work mode come back turnoff mode.

4. Run mode indicates that motor works normally while MCU outputs PWM wave by inputting certain rotation speed command. And the rotation speed command is synchronous to rotate magnetic field frequency, so zero-crossing of induced voltage can be detected accurately to decide to output pattern stwiching by 50us timer interrupt.

When no rotation speed command is detected or three phase motor output control timer is disabled, the motor work mode come back turnoff mode.

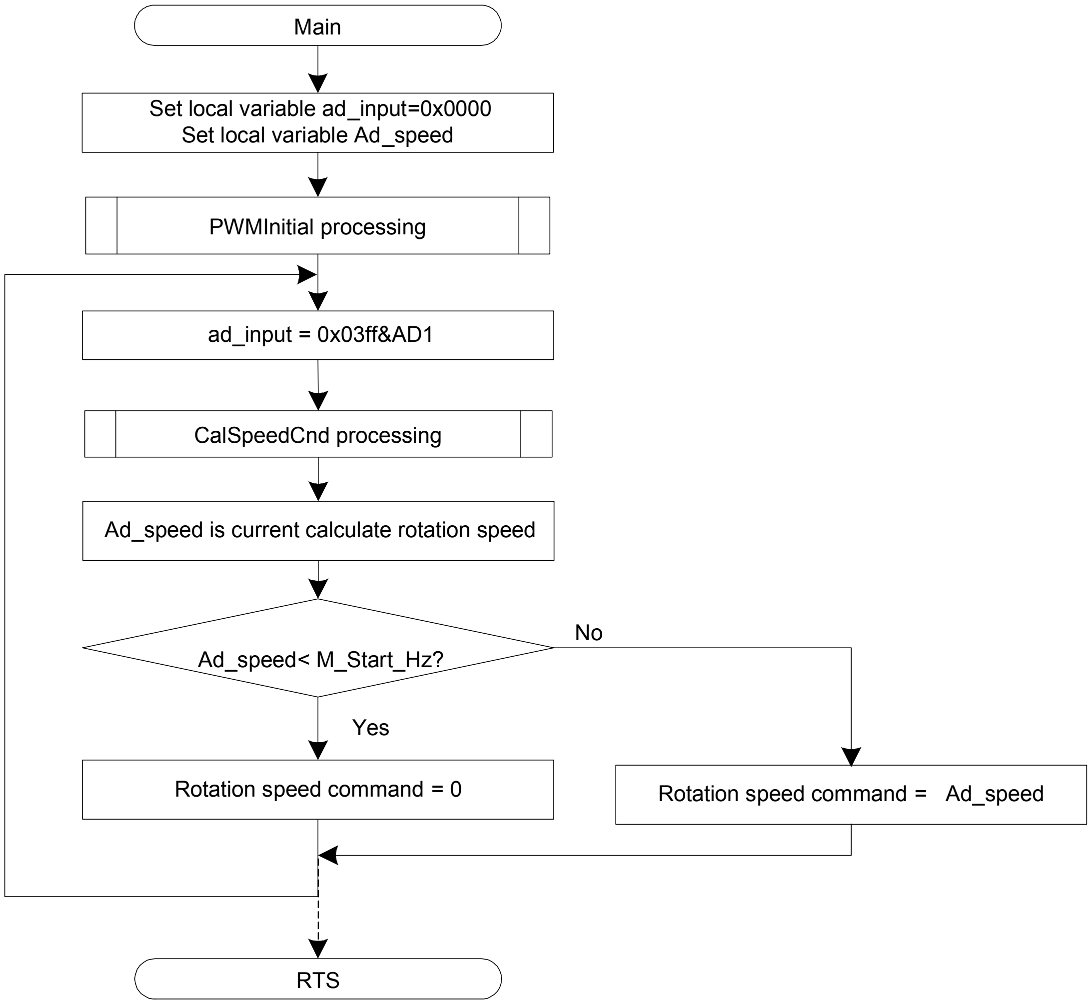
No intervals of zero-crossing of induced voltages are detected when counter of zero-crossing interval exceeds certain values, the motor work mode change into turnon mode.

3.2 Condition Description

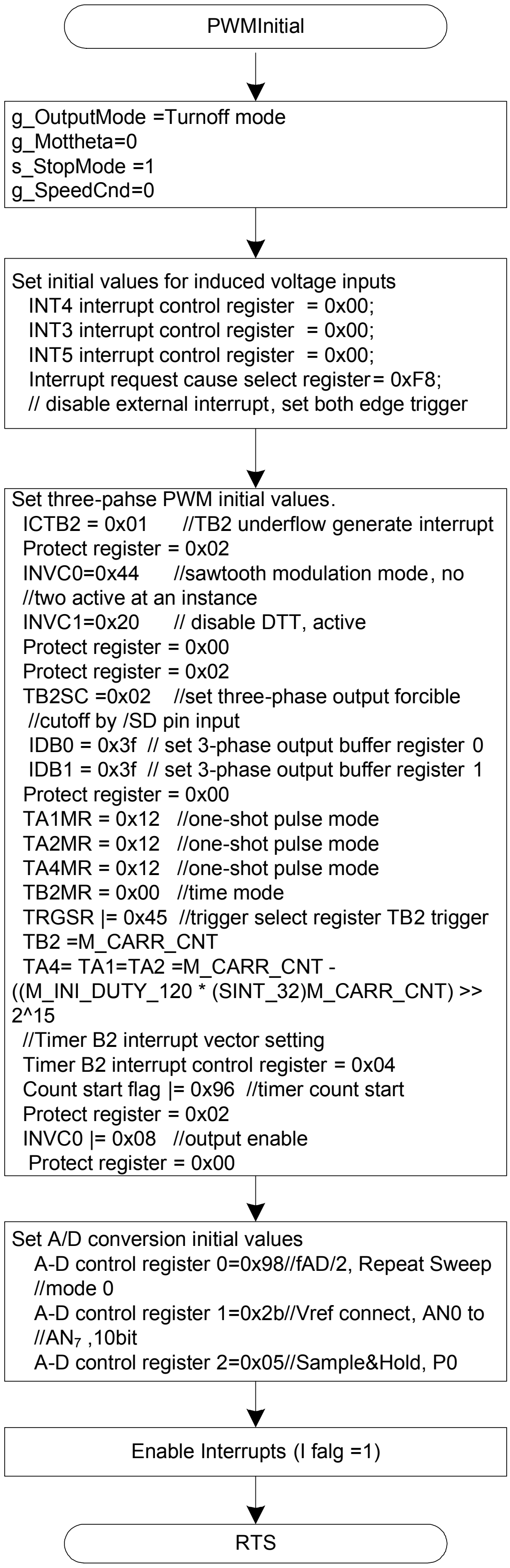
Condition number	Description
①	Rotation speed command is not equal to zero
②	The three phase IGBT charging process is over
③	Motor rotation speed is synchronous to rotate magnetic field frequency after passing some carrier wave cycle interrupts
④	No rotation speed command
⑤ ⑥ ⑦	Rotation speed command is equal to zero or three phase motor output control timer disable
⑧	No intervals of zero-crossing of induced voltages are detected
⑨	The three phase IGBT charging process is not over
⑩	Don't satisfied condition No.3 and No.6
⑪	Always acquire accurate motor position information

4 Control flow

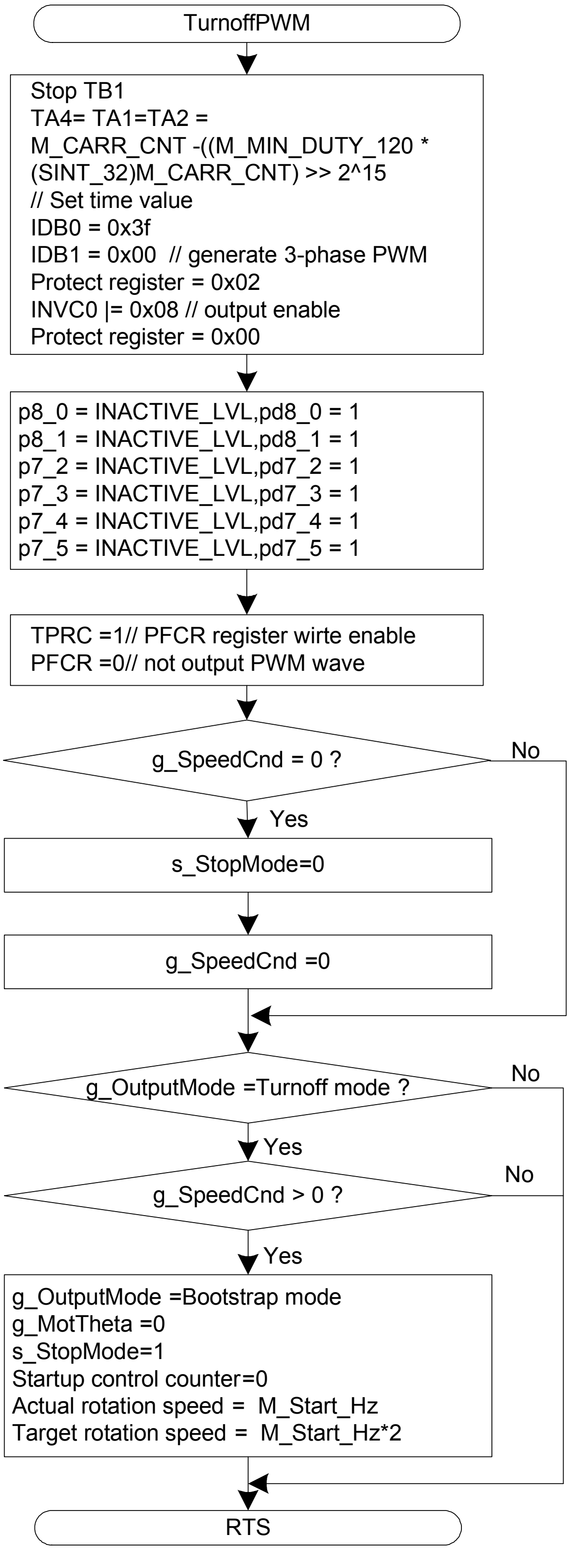
4.1 Main processing for sensor-less driving of an SPMSM by 120-degree trapezoidal wave commutation.



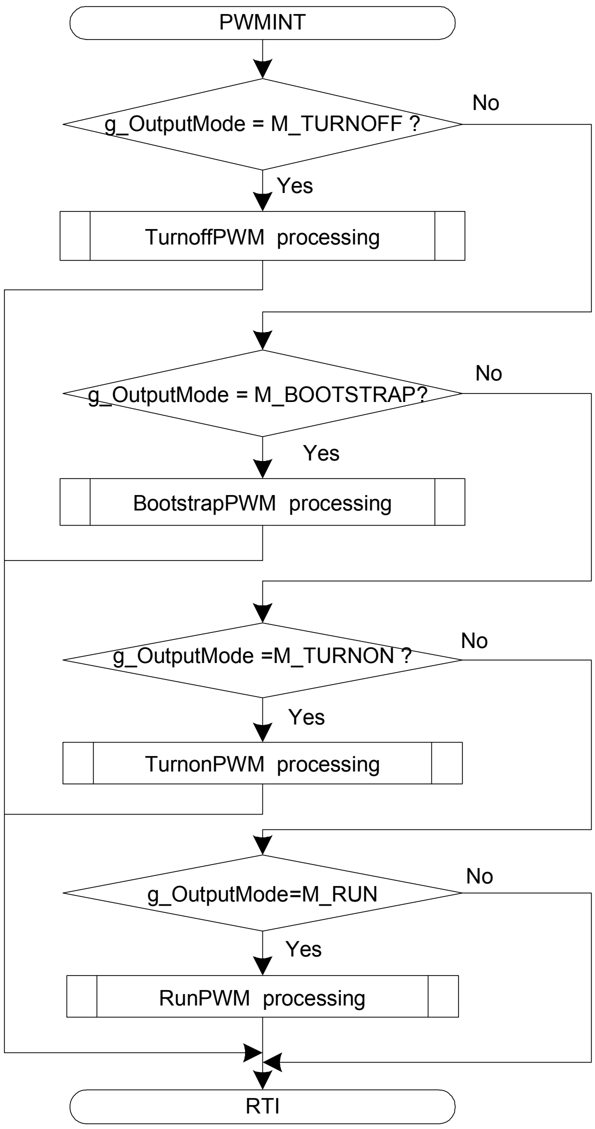
4.2 Initialization Processing



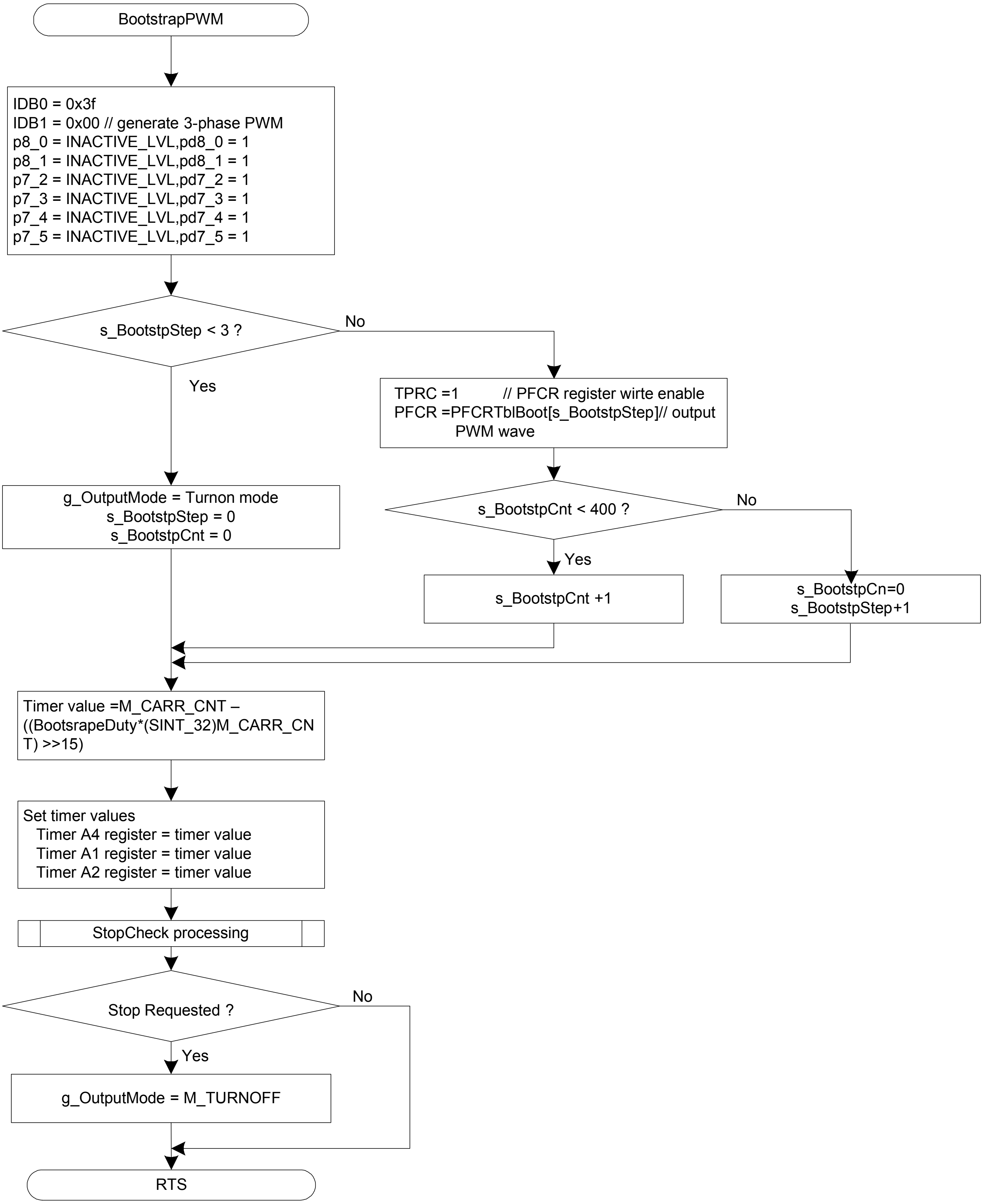
4.3 Turn-off Processing



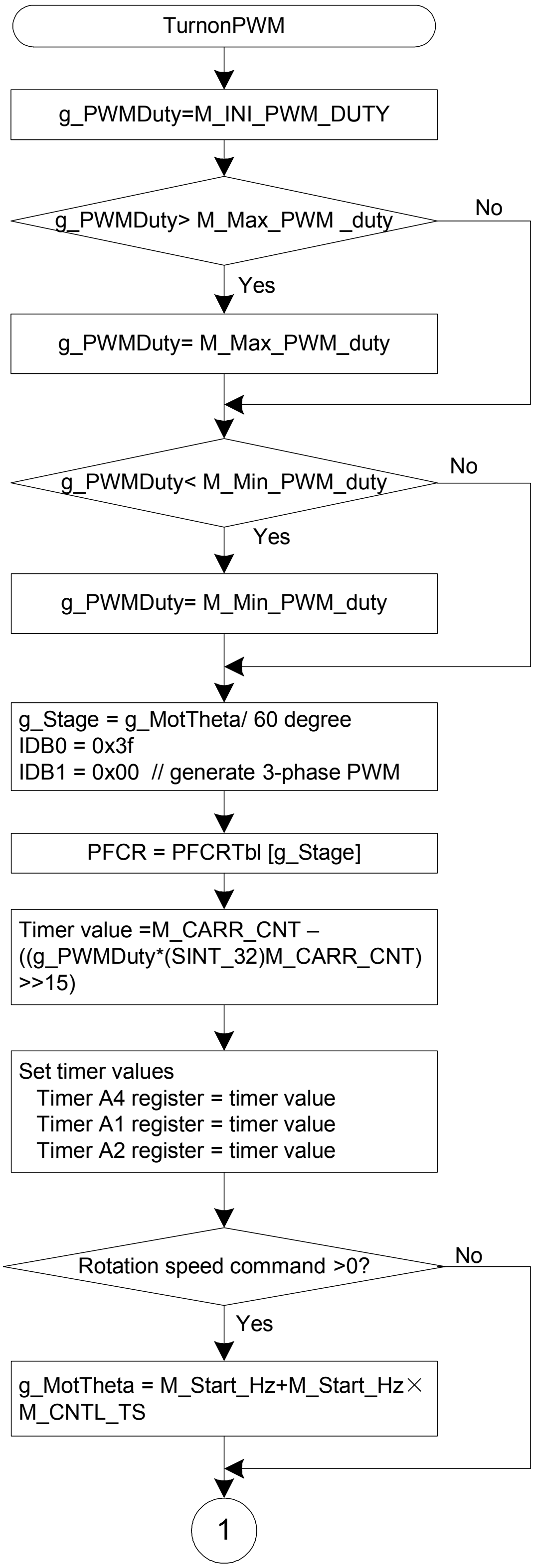
4.4 PWM Interrupt Processing

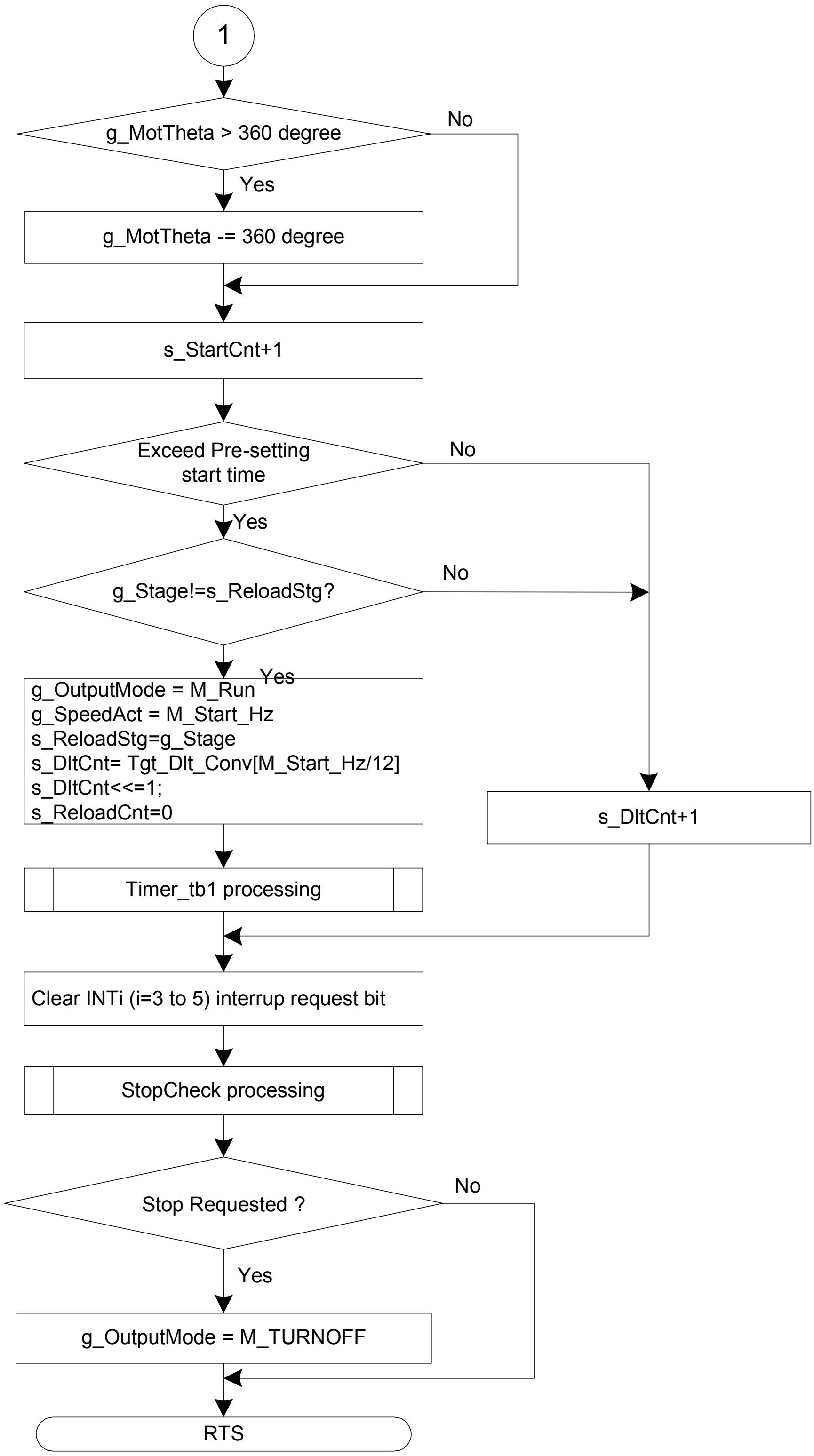


4.5 Bootstrap Processing

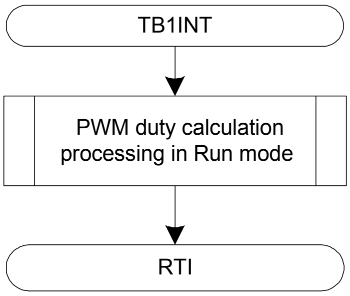


4.6Turn-on Processing

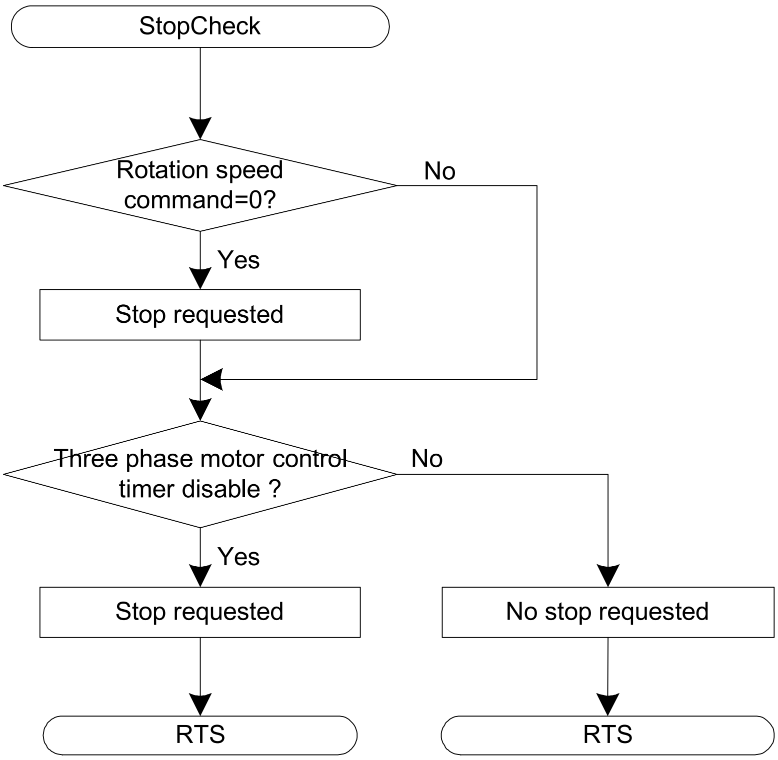



1
g_MotTheta > 360 degree
No
Yes
g_MotTheta -= 360 degree
s_StartCnt+1
Exceed Pre-setting
start time
No
Yes
g_Stage!=s_ReloadStg?
No
Yes
g_OutputMode = M_Run
g_SpeedAct = M_Start_Hz
s_ReloadStg=g_Stage
s_DltCnt= Tgt_Dlt_Conv[M_Start_Hz/12]
s_DltCnt<<=1;
s_ReloadCnt=0
s_DltCnt+1
Timer_tb1 processing
Clear INTi (i=3 to 5) interrupt request bit
StopCheck processing
Stop Requested ?
No
Yes
g_OutputMode = M_TURNOFF
RTS

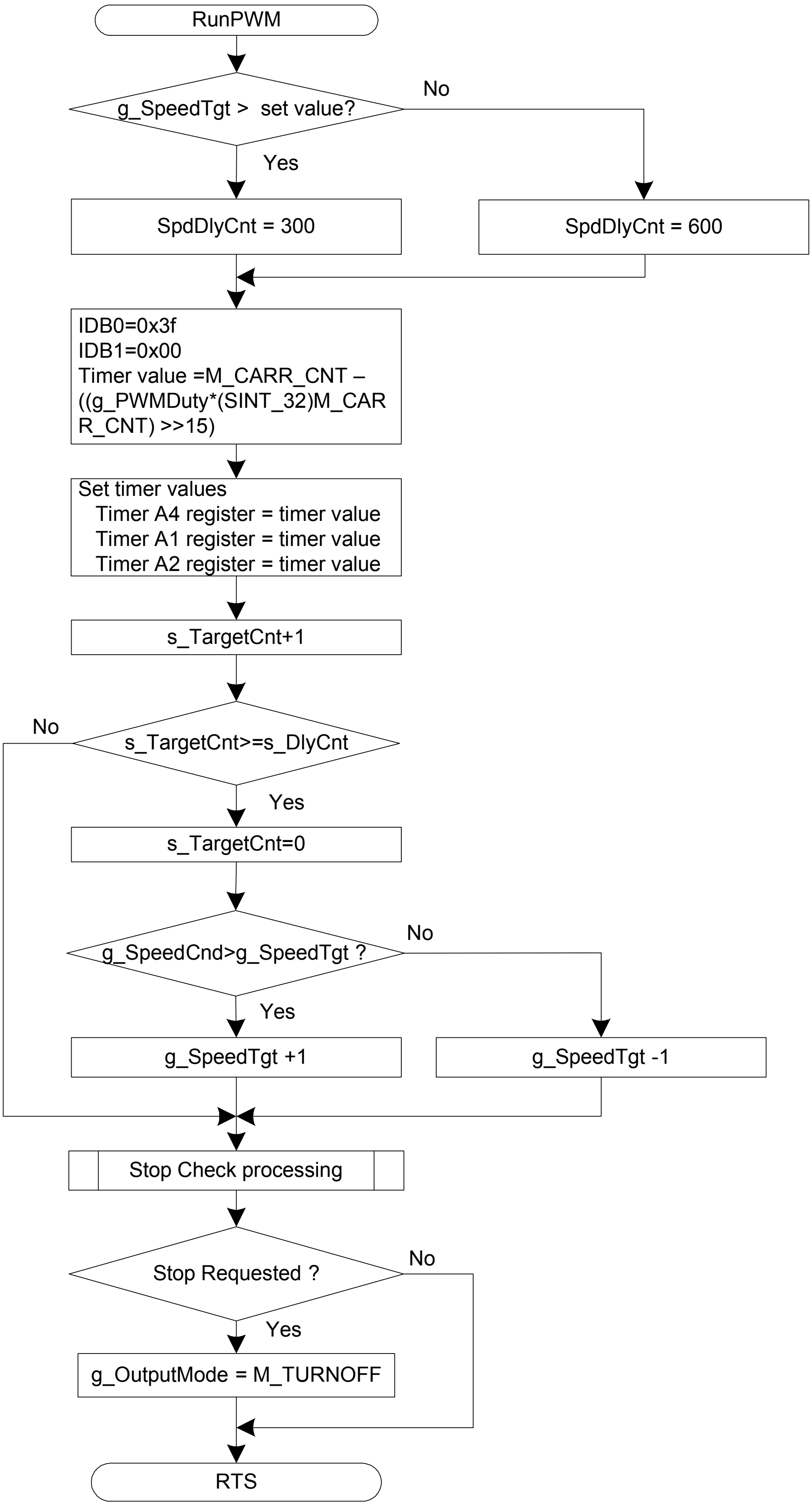
4.7 TB1 Interrupt Processing



4.8 Stop Check Processing



4.9 Run Processing



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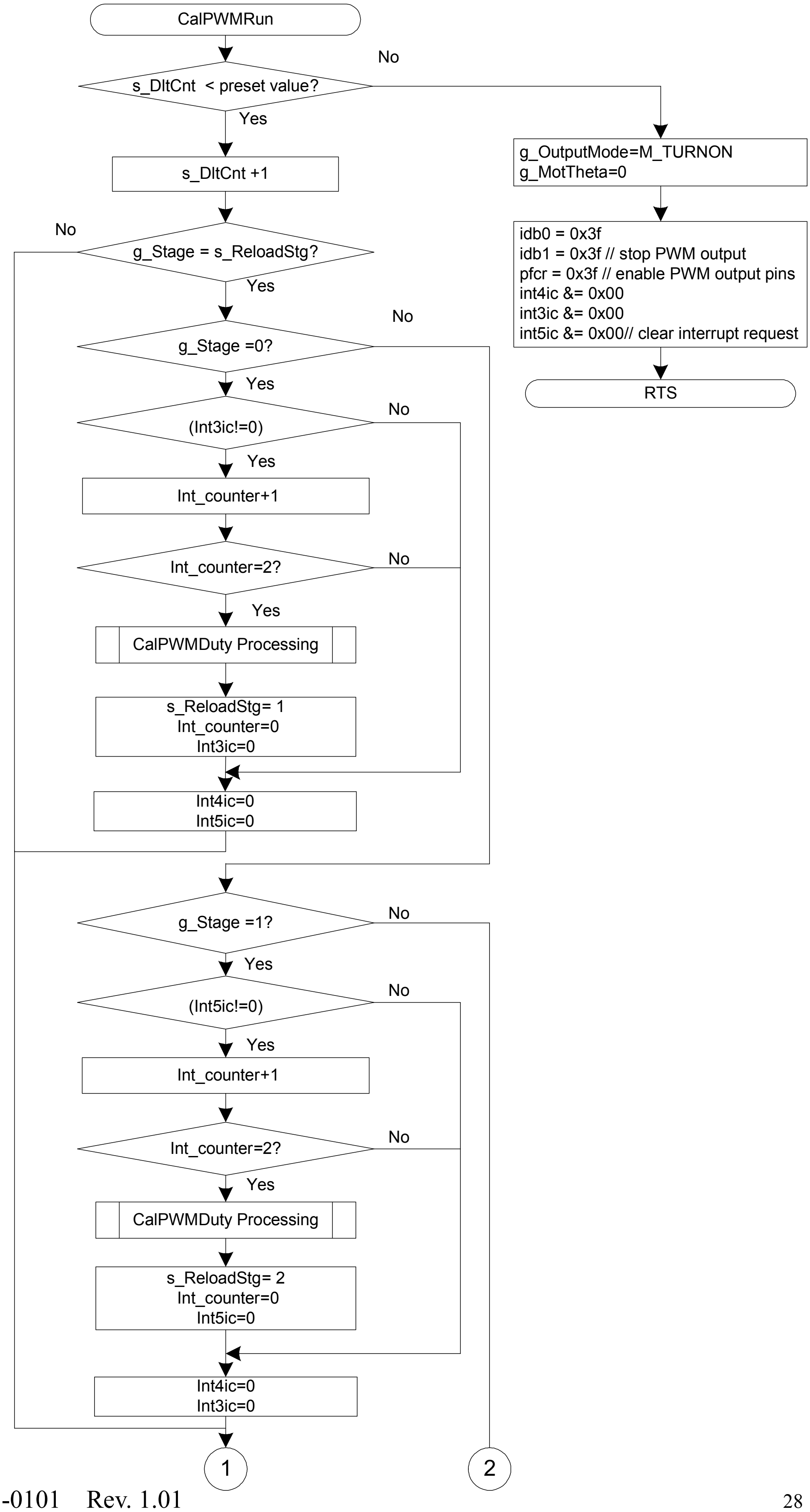
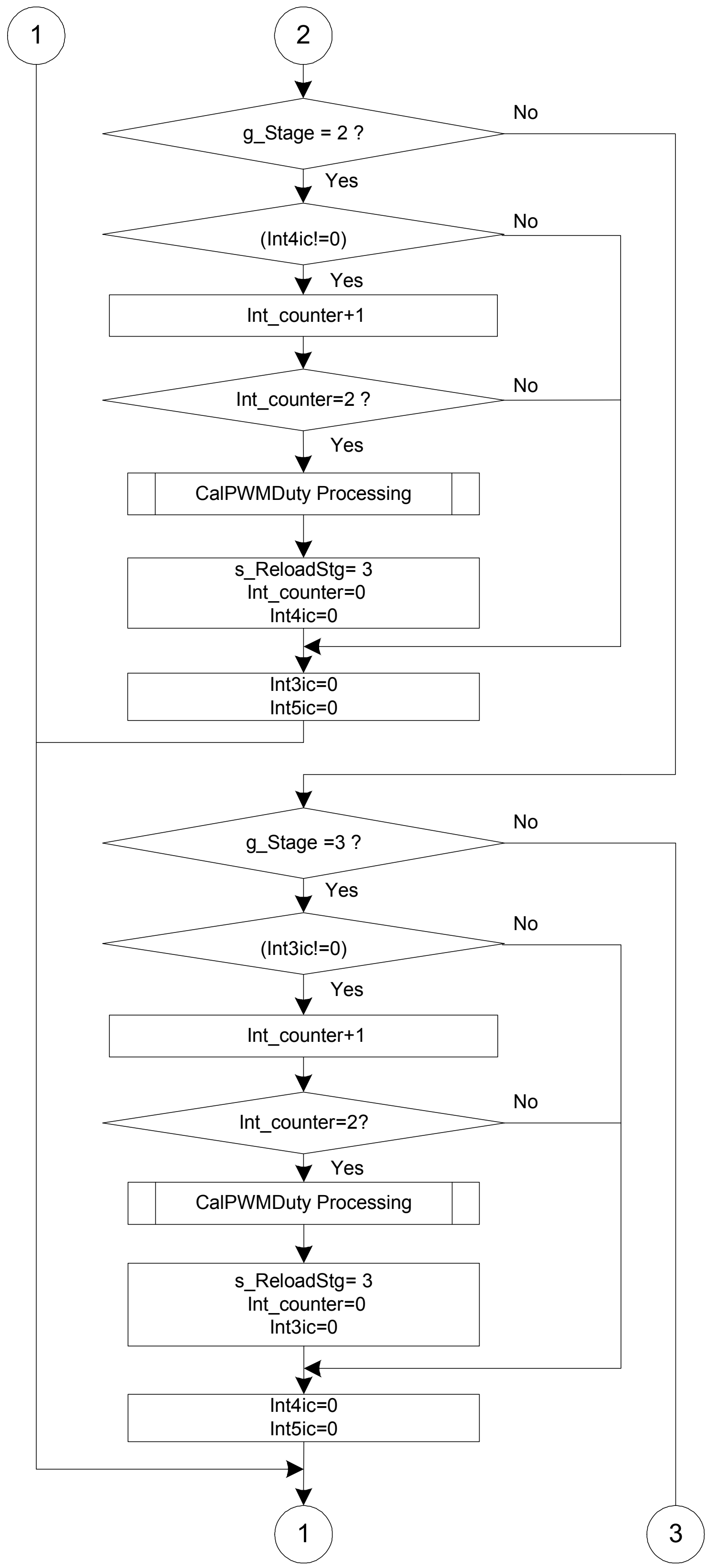
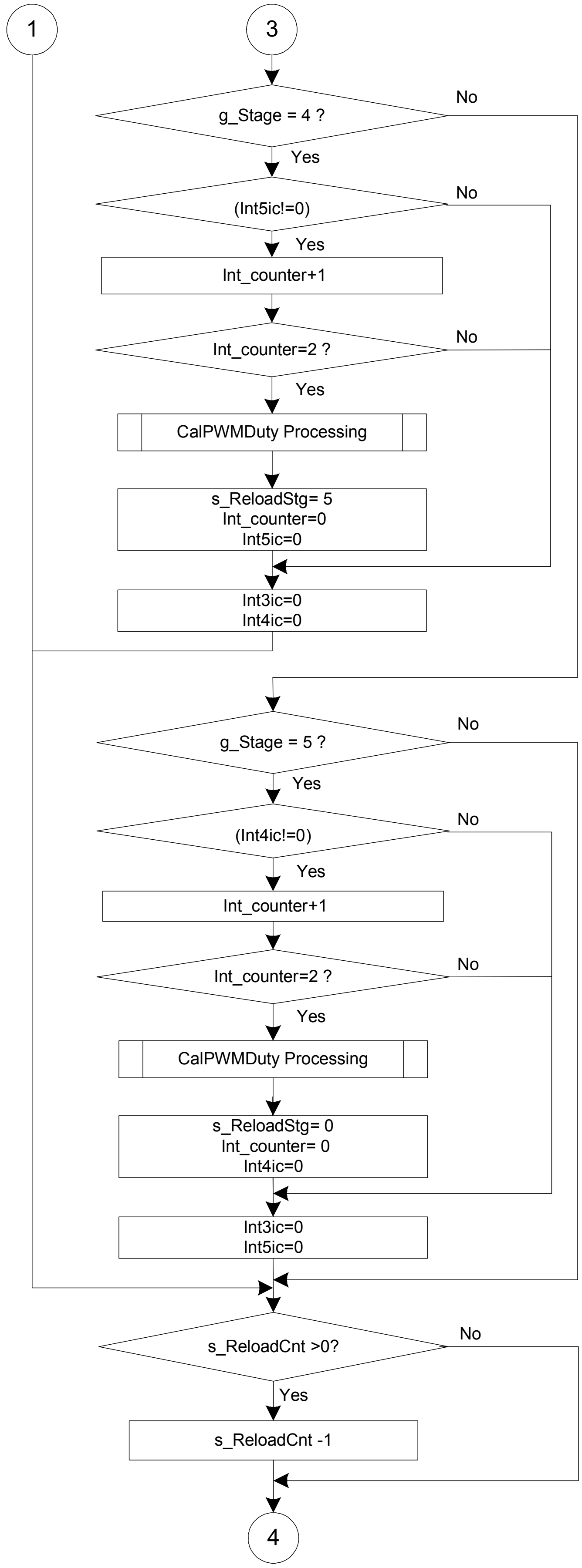
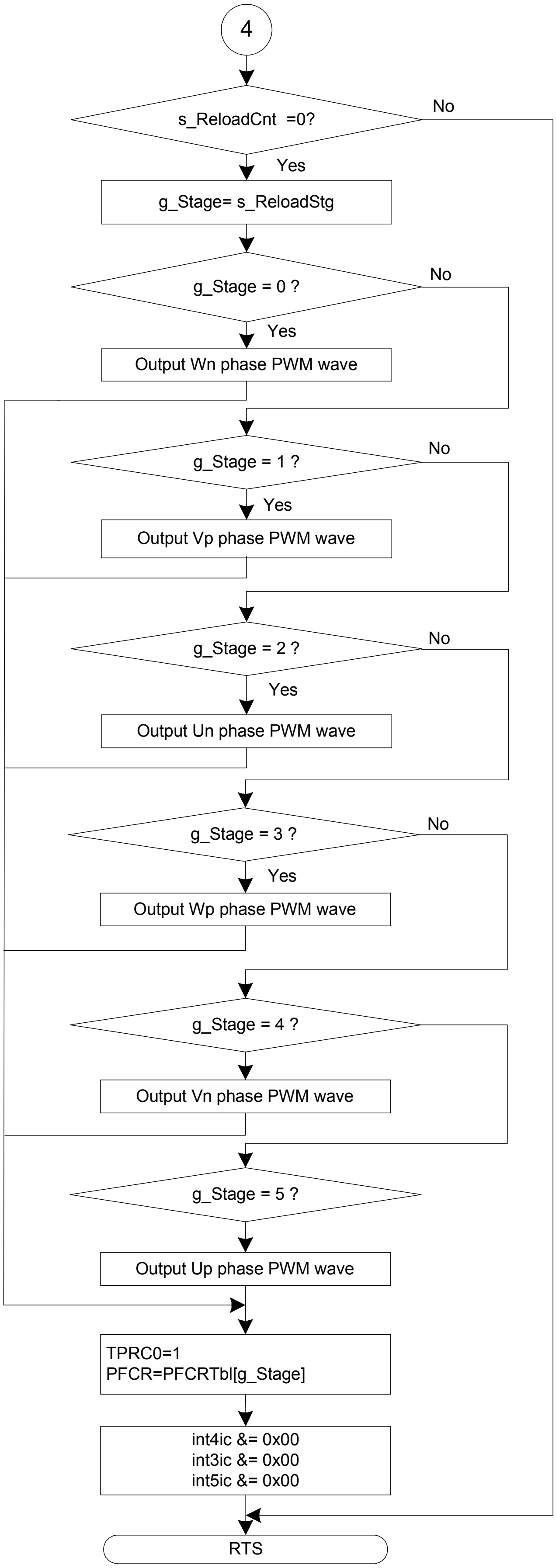
4.10 PWM Run Calculation Processing



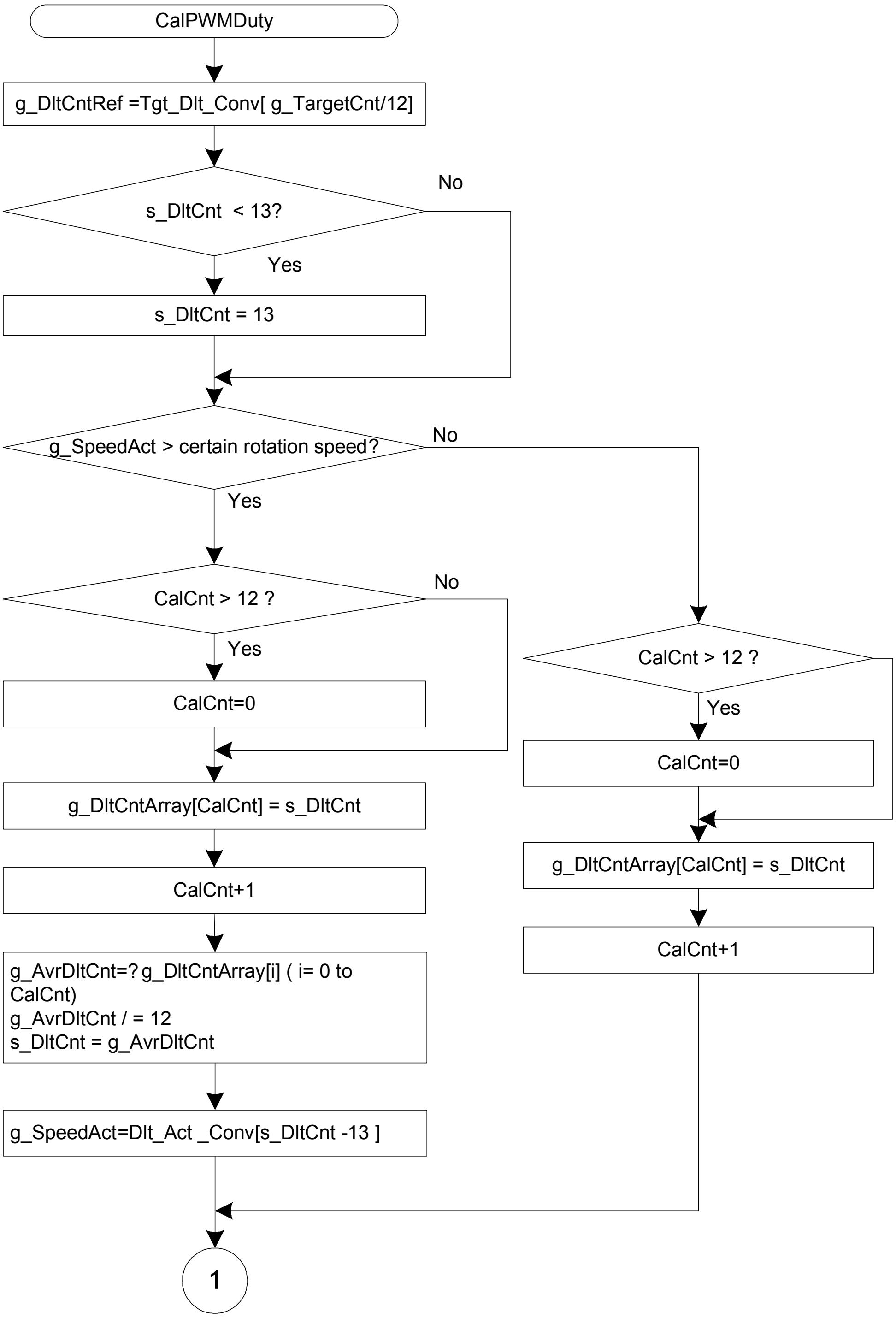

1
2
g_Stage = 2 ?
No
Yes
(Int4ic!=0)
No
Yes
Int_counter+1
Int_counter=2 ?
No
Yes
CalPWMDuty Processing
s_ReloadStg= 3
Int_counter=0
Int4ic=0
Int3ic=0
Int5ic=0
g_Stage =3 ?
No
Yes
(Int3ic!=0)
No
Yes
Int_counter+1
Int_counter=2?
No
Yes
CalPWMDuty Processing
s_ReloadStg= 3
Int_counter=0
Int3ic=0
Int4ic=0
Int5ic=0
1
3

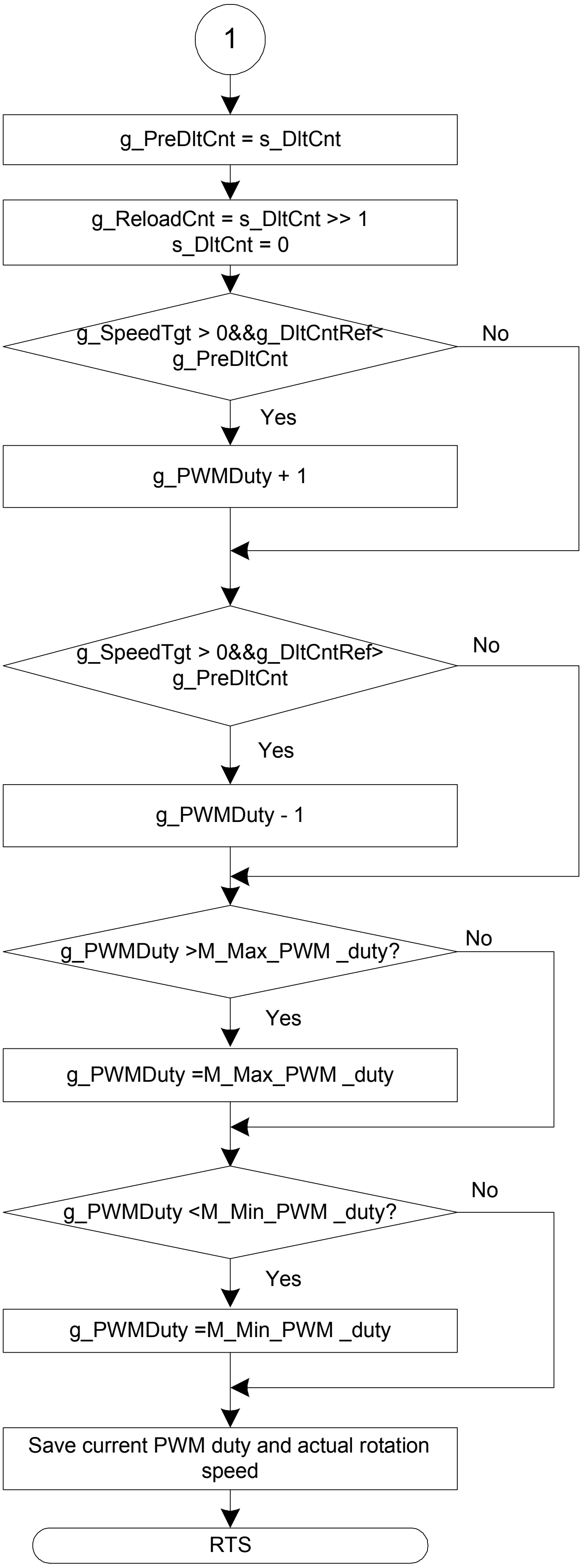

1
3
g_Stage = 4 ?
No
Yes
(Int5ic!=0)
No
Yes
Int_counter+1
Int_counter=2 ?
No
Yes
CalPWMDuty Processing
s_ReloadStg= 5
Int_counter=0
Int5ic=0
Int3ic=0
Int4ic=0
g_Stage = 5 ?
No
Yes
(Int4ic!=0)
No
Yes
Int_counter+1
Int_counter=2 ?
No
Yes
CalPWMDuty Processing
s_ReloadStg= 0
Int_counter= 0
Int4ic=0
Int3ic=0
Int5ic=0
s_ReloadCnt >0?
No
Yes
s_ReloadCnt -1
4



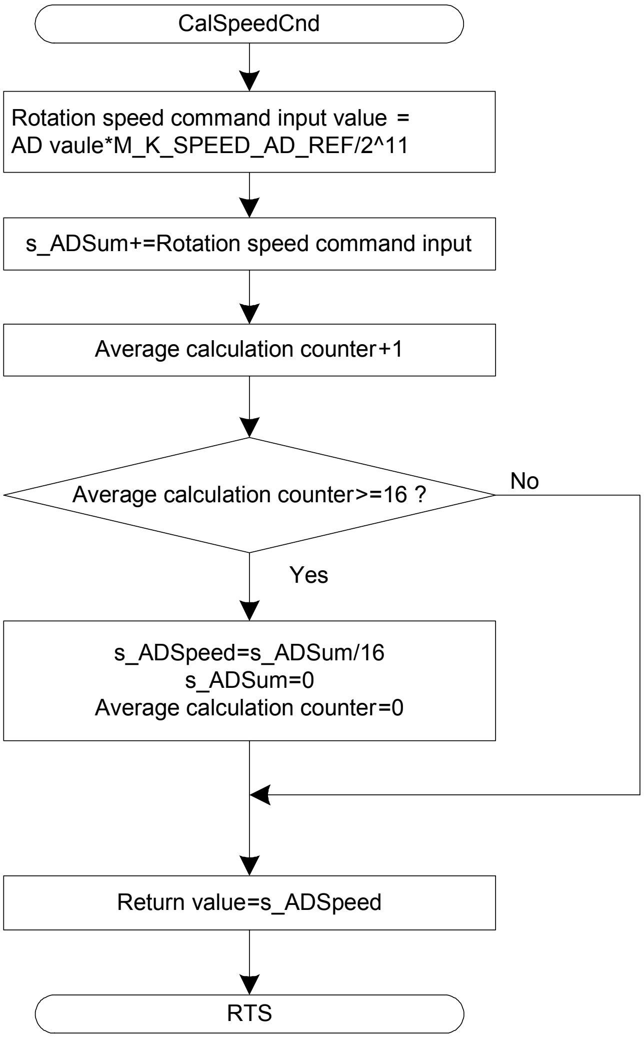
4
s_ReloadCnt =0?
No
Yes
g_Stage= s_ReloadStg
g_Stage = 0 ?
No
Yes
Output Wn phase PWM wave
g_Stage = 1 ?
No
Yes
Output Vp phase PWM wave
g_Stage = 2 ?
No
Yes
Output Un phase PWM wave
g_Stage = 3 ?
No
Yes
Output Wp phase PWM wave
g_Stage = 4 ?
Output Vn phase PWM wave
g_Stage = 5 ?
Output Up phase PWM wave
TPRC0=1
PFCR=PFCRTbl[g_Stage]
int4ic &= 0x00
int3ic &= 0x00
int5ic &= 0x00
RTS

4.11 PWM Duty Calculation Processing




1
g_PreDltCnt = s_DltCnt
g_ReloadCnt = s_DltCnt >> 1
s_DltCnt = 0
g_SpeedTgt > 0&&g_DltCntRef<
g_PreDltCnt
No
Yes
g_PWMDuty + 1
g_SpeedTgt > 0&&g_DltCntRef>
g_PreDltCnt
No
Yes
g_PWMDuty - 1
g_PWMDuty >M_Max_PWM _duty?
No
Yes
g_PWMDuty =M_Max_PWM _duty
g_PWMDuty <M_Min_PWM _duty?
No
Yes
g_PWMDuty =M_Min_PWM _duty
Save current PWM duty and actual rotation speed
RTS

4.12 Calculate Rotation Speed Command Processing



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