RX23T Inverter Kit – What enables you to use Float in your motion control algorithm?

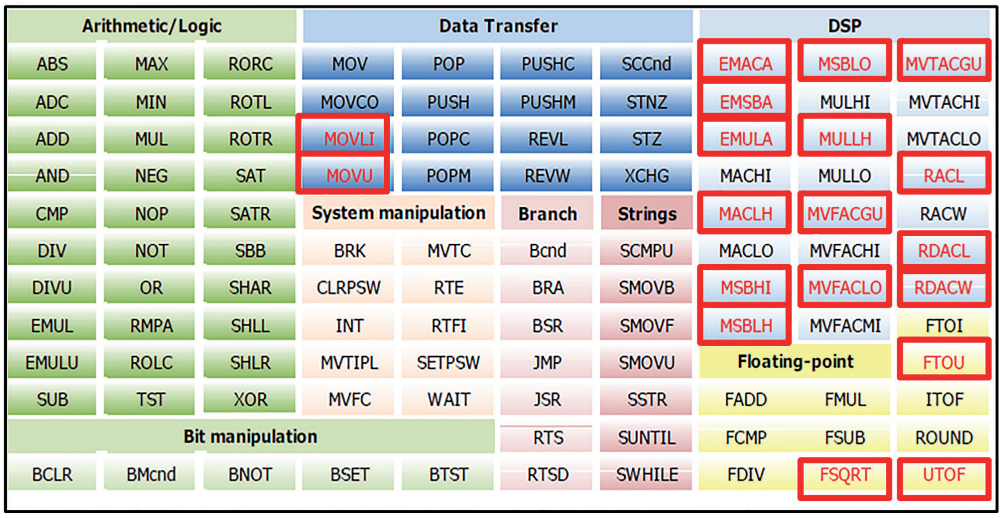
Introduction

The new microcontroller families RX23T and RX24T featuring the new RX v2 core are designed to ensure the best compromise in terms of performance and cost to address motion control. In case of the RX23T, the latest benchmarks are showing a performance of 80 DMIPs at 40 MHz. In case of the RX24T, the MCU reaches up to 160 DMIPs at 80 MHz. For both cores, according to EEMBC Certified Scores, the RX23T/24T deliver up to 4.25 CoreMark per MHz. For more details, please refer to the official website:
www.eembc.org/coremark/
These MCU's are designed to operate at 5 V to ensure the highest noise immunity and incorporate key hardware modules like the Floating Point Unit (FPU). The FPU is the main topic of this paper as it is becoming fundamental for software engineers to deliver state of the art software, easy to maintain and to test.

Why has Renesas implemented a Floating Point unit on the latest RX23T/RX24T families?

The current RX62T & RX63T have been extremely successful in the current generation of motor control solutions. These families already integrate Floating Point Unit. Renesas decided to improve the overall RX Core and the FPU was one component of it.
Please find below the instructions of the RX V2 Core included in "red" the new one added to the V1.

🟥 New instructions of the RX V2 Core



Arithmetic/Logic			Data Transfer				DSP		
ABS	MAX	RORC	MOV	POP	PUSHC	SCCnd	🟥 EMACA	🟥 MSBLO	🟥 MVTACGU
ADC	MIN	ROTL	MOVCO	PUSH	PUSHM	STNZ	🟥 EMSBA	MULHI	MVTACHI
ADD	MUL	ROTR	🟥 MOVLI	POPC	REVL	STZ	🟥 EMULA	🟥 MULLH	MVTACLO
AND	NEG	SAT	🟥 MOVU	POPM	REVW	XCHG	MACHI	MULLO	🟥 RACL
CMP	NOP	SATR	System manipulation		Branch	Strings	🟥 MACLH	🟥 MVFACGU	RACW
DIV	NOT	SBB	BRK	MVTC	Bcnd	SCMPU	MACLO	MVFACHI	🟥 RDACL
DIVU	OR	SHAR	CLRPSW	RTE	BRA	SMOVB	🟥 MSBHI	🟥 MVFACLO	🟥 RDACW
EMUL	RMPA	SHLL	INT	RTFI	BSR	SMOVF	🟥 MSBLH	MVFACMI	FTOI
EMULU	ROLC	SHLR	MVTIPL	SETPSW	JMP	SMOVU	Floating-point		🟥 FTOU
SUB	TST	XOR	MVFC	WAIT	JSR	SSTR	FADD	FMUL	ITOF
Bit manipulation					RTS	SUNTIL	FCMP	FSUB	ROUND
BCLR	BMcnd	BNOT	BSET	BTST	RTSD	SWHILE	FDIV	🟥 FSQRT	🟥 UTOF

Based on the three additional FPU instructions below and the fourteen DSP new instructions, the RX v2 core offers higher calculation accuracy by executing 32-bit multiply by a single instruction. Furthermore, the specific instructions to manage the accumulator and the rounding processing ensure high overall performance. The new RXv2 offers up to 2 DMIPs per MHz, compared to 1.65 DMIPs per MHz of the RX v1.

New RX v2 Instruction	Function
FSQRT	Floating point square root
FTOU	Floating point to integer conversion
UTOF	Integer to floating-point conversion

By comparing the implementation of a three shunts sensorless vector control algorithm on the same Microcontroller RX23T, the on-chip FPU module shows high benefits by decreasing the processing time by 27% and by reducing the CPU load by 28%.

RX23T			
CPU clock	40 MHz, V2 core		Perform. Diff.
Arithmetic used in software	Fixed	Float	
Control loop Timing	51 µs	40 µs	27%
Code size in Flash	26 KB	20 KB	30%
Code size in RAM	3 KB	2 KB	50%
CPU load @ 16 KHz PWM/Control loop	82%	64%	28%

The measurements above are done on the inverter kit software running on the RX23T kit called YROTATE-IT-RX23T kit. The software incorporates the following software blocks:

- Proportional-Integral Current Controller
- Proportional-Integral Speed Controller
- Clamped Pulse Width Modulation
- Clarke and Park Transformations
- Flux Phase estimator
- Speed estimation
- Three shunt current reading

The complete source code of the software used for the benchmarks and tests are fully available and royalty-free.
Additionally, in many motion control applications, the equipment is connected to sensors and filtering the signals and data coming from them is a fundamental tasks.
That's why Renesas performed some comparisons between the RX V1 and V2 versions, in various filtering operations.

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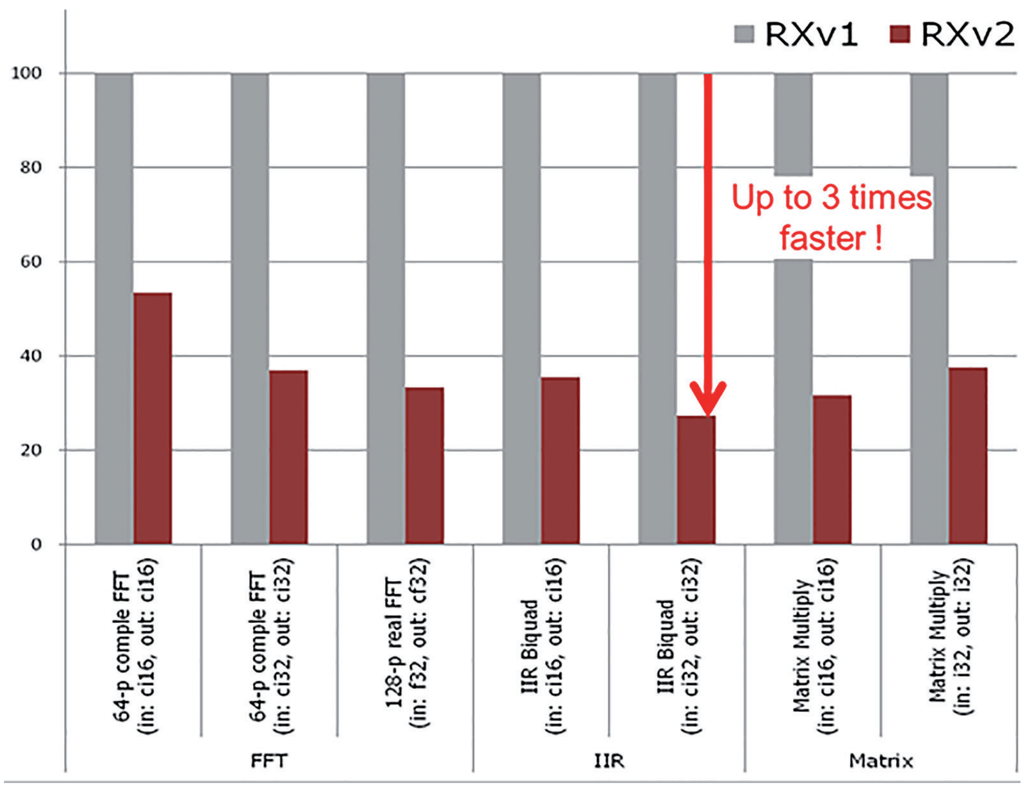


The complete material related to the RX23T kit available on the website: **www.renesas.eu/motorcontrol**

First, let's dive into the embedded software source code of the inverter. The constants used in the inverter algorithm are showing high resolution and accuracy. It means the overall control of the torque and speed is accurate. The development and the maintenance of the embedded software is becoming easier. Furthermore, the variables used in the firmware are directly representing the real units in Ampere, in Volt, in Hertz, in Weber and in Henry, etc. Using Float variables is a way to represent real numbers on a Microcontroller.

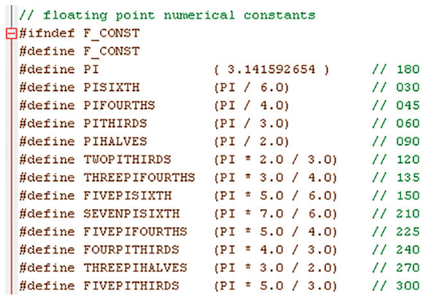
As you can observe above, for each filtering operations using Fast Fourier Transform (FFT), for the Infinite Impulse Response (IIR) and the Matrix multiplication, the newest core RX v2 is minimum two times faster. The graph is normalized compared to the RX V1 core, the data are relative to the RXv 1 core. There is no timing unit.

In case of the second order filter (IIR Biquad), the RX v2 core is three times faster than the RX v1 core thanks to the new instructions, at the same clock frequency.

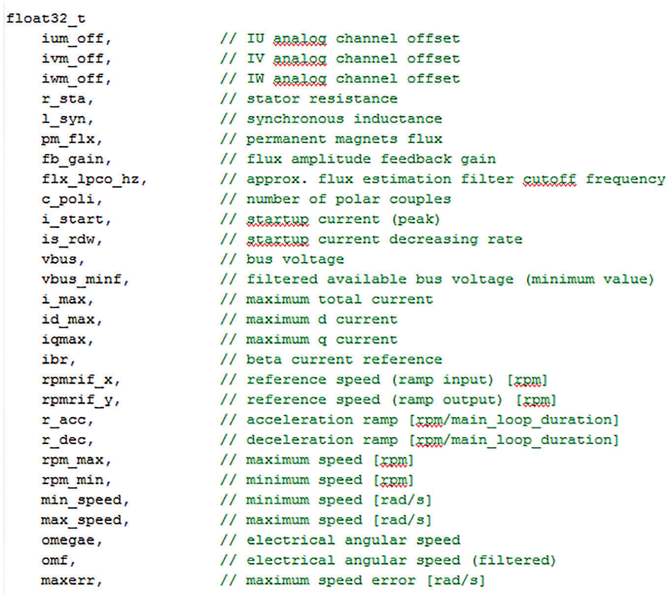
Up to now, it was presented the reasons to embed a Floating Point Unit module and the results in terms of performance, code size and overall code efficiency.

How can I move from fixed arithmetic to float?

The first step is to start by evaluating available 3-phase inverter reference platform driving already Permanent Magnet Motors. The kit based on RX23T (e.g. YROTATE-IT-RX23T) enables any developer to quickly experiment the usage of float variables.



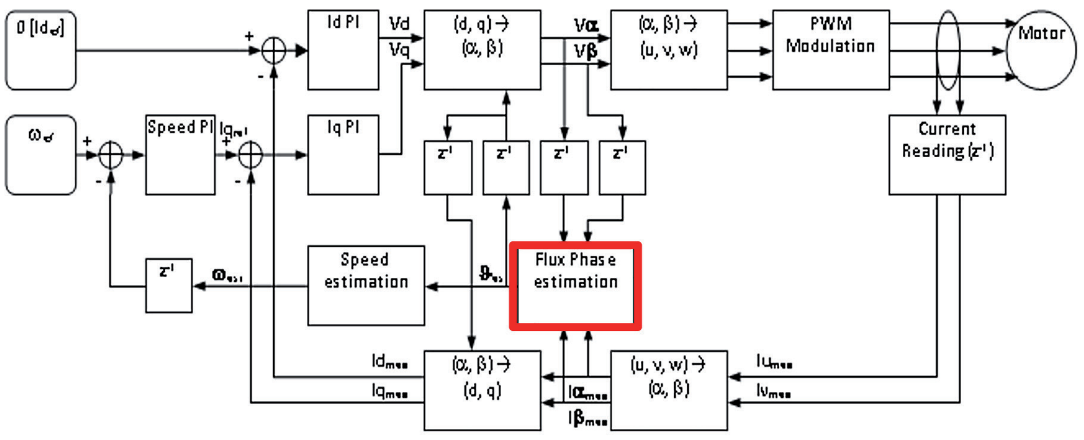
```
// floating point numerical constants
#ifndef F_CONST
#define F_CONST
#define PI              ( 3.141592654 )      // 180
#define PISIXTH         (PI / 6.0)           // 030
#define PIFOURTHS       (PI / 4.0)           // 045
#define PITHIRDS        (PI / 3.0)           // 060
#define PIHALVES        (PI / 2.0)           // 090
#define TWOPITHIRDS     (PI * 2.0 / 3.0)     // 120
#define THREEPIFOURTHS  (PI * 3.0 / 4.0)     // 135
#define FIVEPISIXTH     (PI * 5.0 / 6.0)     // 150
#define SEVENPISIXTH    (PI * 7.0 / 6.0)     // 210
#define FIVEPIFOURTHS   (PI * 5.0 / 4.0)     // 225
#define FOURPITHIRDS    (PI * 4.0 / 3.0)     // 240
#define THREEPIHALVES   (PI * 3.0 / 2.0)     // 270
#define FIVEPITHIRDS    (PI * 5.0 / 3.0)     // 300
```



```
float32_t
    ium_off,            // IU analog channel offset
    ivm_off,            // IV analog channel offset
    iwm_off,            // IW analog channel offset
    r_sta,              // stator resistance
    l_syn,              // synchronous inductance
    pm_flx,             // permanent magnets flux
    fb_gain,            // flux amplitude feedback gain
    flx_lpco_hz,        // approx. flux estimation filter cutoff frequency
    c_poli,             // number of polar couples
    i_start,            // startup current (peak)
    is_rdw,             // startup current decreasing rate
    vbus,               // bus voltage
    vbus_minf,          // filtered available bus voltage (minimum value)
    i_max,              // maximum total current
    id_max,             // maximum d current
    iqmax,              // maximum q current
    ibr,                // beta current reference
    rpmrif_x,           // reference speed (ramp input)  [rpm]
    rpmrif_y,           // reference speed (ramp output)  [rpm]
    r_acc,              // acceleration ramp [rpm/main_loop_duration]
    r_dec,              // deceleration ramp [rpm/main_loop_duration]
    rpm_max,            // maximum speed [rpm]
    rpm_min,            // minimum speed [rpm]
    min_speed,          // minimum speed [rad/s]
    max_speed,          // maximum speed [rad/s]
    omegae,             // electrical angular speed
    omf,                // electrical angular speed (filtered)
    maxerr,             // maximum speed error [rad/s]
```

All the internal representation of physical quantities of the system of the 3-phase inverter is very simple using floating point. There is no need to normalize the variables or scale them. Thanks to these the code is becoming easy to manage and read. The motor model can be easily worked out without scaling efforts on each intrinsic.

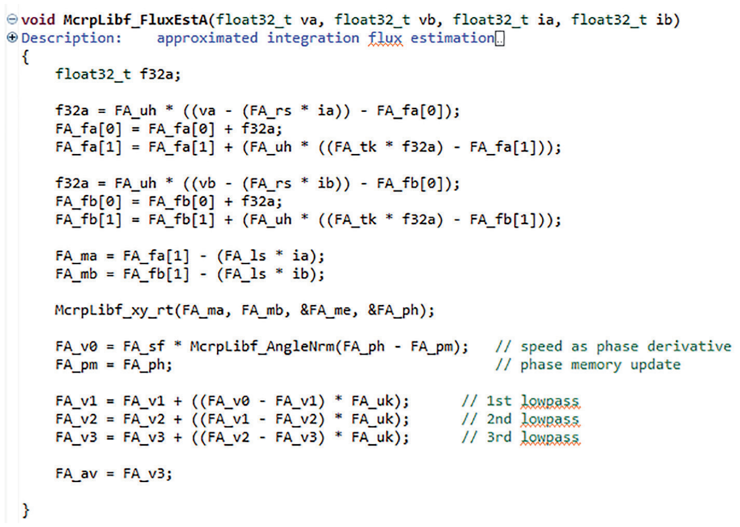
Furthermore, let's have a look at the "Flux Phase Estimation" block as shown on the next page.



The implementation of the Flux Phase estimation method is shown above The implementations of three major low pass filters are using only three lines of code and a few clock cycles.

Using the FPU will strongly decrease the risk of errors and variables overflow compared to a fixed arithmetic.

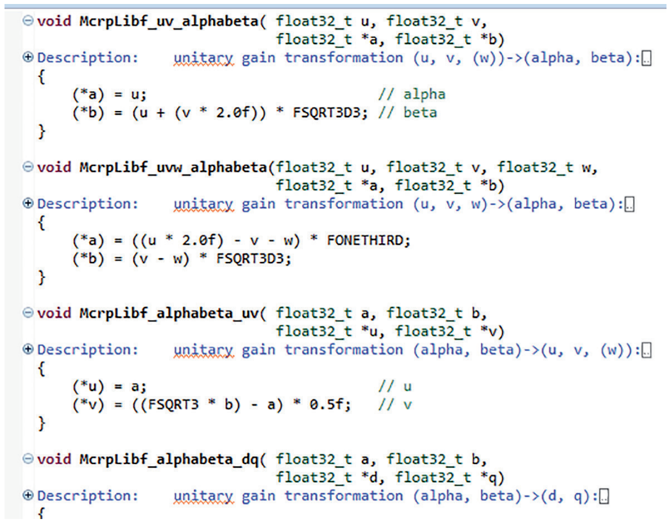
The development time and test procedure are also shorter.



```
⊖void McrpLibf_FluxEstA(float32_t va, float32_t vb, float32_t ia, float32_t ib)
⊕Description:    approximated integration flux estimation[]
 {
     float32_t f32a;

     f32a = FA_uh * ((va - (FA_rs * ia)) - FA_fa[0]);
     FA_fa[0] = FA_fa[0] + f32a;
     FA_fa[1] = FA_fa[1] + (FA_uh * ((FA_tk * f32a) - FA_fa[1]));

     f32a = FA_uh * ((vb - (FA_rs * ib)) - FA_fb[0]);
     FA_fb[0] = FA_fb[0] + f32a;
     FA_fb[1] = FA_fb[1] + (FA_uh * ((FA_tk * f32a) - FA_fb[1]));

     FA_ma = FA_fa[1] - (FA_ls * ia);
     FA_mb = FA_fb[1] - (FA_ls * ib);

     McrpLibf_xy_rt(FA_ma, FA_mb, &FA_me, &FA_ph);

     FA_v0 = FA_sf * McrpLibf_AngleNrm(FA_ph - FA_pm);   // speed as phase derivative
     FA_pm = FA_ph;                                       // phase memory update

     FA_v1 = FA_v1 + ((FA_v0 - FA_v1) * FA_uk);      // 1st lowpass
     FA_v2 = FA_v2 + ((FA_v1 - FA_v2) * FA_uk);      // 2nd lowpass
     FA_v3 = FA_v3 + ((FA_v2 - FA_v3) * FA_uk);      // 3rd lowpass

     FA_av = FA_v3;

 }
```

Finally the trigonometric functions are the real one using real value, no tables or else, so it ensures high accuracy. Please find below the software source code used for the Park and Clarke transformations. Each transformation is using maximum two lines of codes and no tables are used to manage the Cos and Sin. Compared to any implementation using the integer arithmetic, the Cos table is using 256 bytes, the Sin table also and the Arctangent.

Finally, the overall implementation is strongly reduced in terms of code size, the code is becoming easy to maintain. By using Simulink, or Scilab or any modelling tools, the output models is using Float which can be reused directly into the e^{2}studio project used by the RX23T inverter kit.



```
⊖void McrpLibf_uv_alphabeta( float32_t u, float32_t v,
                             float32_t *a, float32_t *b)
⊕Description:    unitary gain transformation (u, v, (w))->(alpha, beta):[]
 {
     (*a) = u;                               // alpha
     (*b) = (u + (v * 2.0f)) * FSQRT3D3; // beta
 }

⊖void McrpLibf_uvw_alphabeta(float32_t u, float32_t v, float32_t w,
                             float32_t *a, float32_t *b)
⊕Description:    unitary gain transformation (u, v, w)->(alpha, beta):[]
 {
     (*a) = ((u * 2.0f) - v - w) * FONETHIRD;
     (*b) = (v - w) * FSQRT3D3;
 }

⊖void McrpLibf_alphabeta_uv( float32_t a, float32_t b,
                             float32_t *u, float32_t *v)
⊕Description:    unitary gain transformation (alpha, beta)->(u, v, (w)):[]
 {
     (*u) = a;                               // u
     (*v) = ((FSQRT3 * b) - a) * 0.5f;   // v
 }

⊖void McrpLibf_alphabeta_dq( float32_t a, float32_t b,
                             float32_t *d, float32_t *q)
⊕Description:    unitary gain transformation (alpha, beta)->(d, q):[]
 {
```

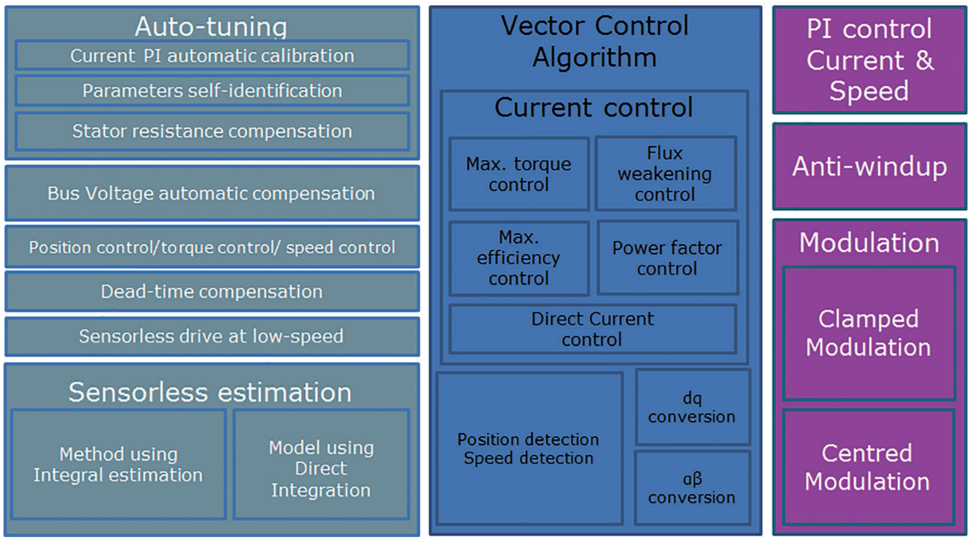
Which are the concrete FPU benefits for 3-phase inverter?

The FPU enables an efficient implementation of the sensorless vector control algorithm as the control loops and the transformations are executed very quickly, which speed-up the overall rotor position estimation.

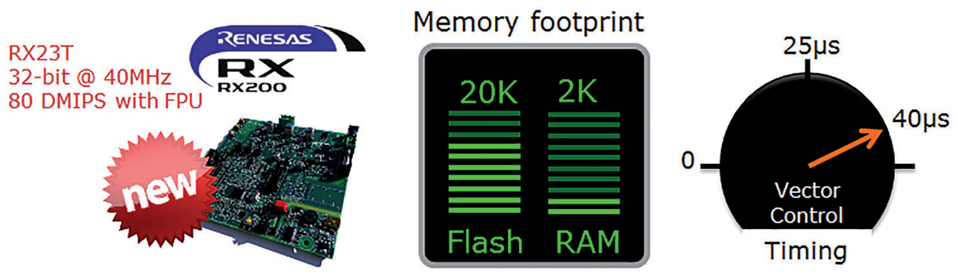
Finally, it guarantee high dynamics algorithm which can run at the same speed at the Pulse Width Modulation frequency. In case of the RX23T, the implementation ensure efficient control up to 22 KHz control frequency (the complete algorithm uses 40 µs).

It means that for each PWM cycles up to 22KHz, the control algorithm can react and adjust the torque and current under high load variations.

Within the RX23T kit, the complete software package is delivered including the following blocks.


Auto-tuning
Current PI automatic calibration
Parameters self-identification
Stator resistance compensation
Bus Voltage automatic compensation
Position control/torque control/ speed control
Dead-time compensation
Sensorless drive at low-speed
Sensorless estimation
Method using Integral estimation
Model using Direct Integration
Vector Control Algorithm
Current control
Max. torque control
Flux weakening control
Max. efficiency control
Power factor control
Direct Current control
Position detection Speed detection
dq conversion
αβ conversion
PI control Current & Speed
Anti-windup
Modulation
Clamped Modulation
Centred Modulation

By setting up the RX compiler optimization level to "Max", the performances below are reached.

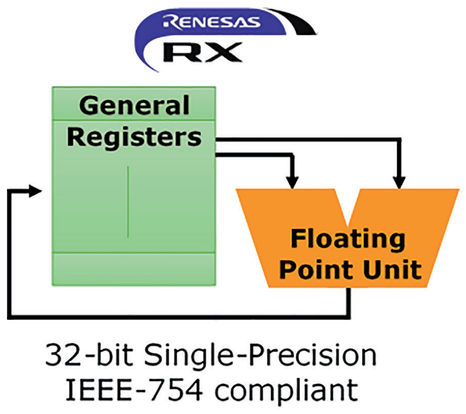


The resources used by the software running on the RX23T are very limited: 20 KB flash and 2 KB RAM, so it means, up to 108 KB free for the application on the RX23T with 128 KB flash.

Conclusion

This paper is describing in details how much the performance of the inverter algorithm are improved using the RX23T Floating Point Unit.

The overall code is reduced, the overall software implementations are executed much faster as no scaling or saturation occurred. Furthermore, it offers a higher accuracy than the integer implementation as the real physical units are used in the embedded software. Finally, the FPU guarantees a faster computation time for PI controllers and estimators. So, stop waiting and download the latest material on **www.renesas.eu/motorcontrol** to evaluate by yourself the source code delivered royalty-free.



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