Introduction

The STEVAL-IHM040V1 is a 3-phase permanent magnet brushless motor driver designed to drive the motor using either the six-step or field-oriented control (FOC) commutation technique. The board can operate from the AC mains from either 115 or 230 V AC nominal at 50/60 Hz or from a DC input voltage between 150 and 350 V DC. The board can supply a continuous output current of 0.5 A RMS to the motor.

The circuit consists of three main blocks, as shown in *Figure 2*, *Figure 3*, and *Figure 4*. The digital control block uses the STM32F100C8T6 microcontroller to implement the control algorithms and generates the control signals for the power stage. The main outputs of the control block are the signals GAH, GAL, GBH, GBL, GCH, and GCL that are the gate control signals for the power stage. The power stage, second block, is a 3-phase inverter bridge implemented using the STGIPN3H60 SLLIMM™-nano intelligent power module. The SLLIMM includes the 6 IGBTs, gate drivers and level shift required to interface the logic signals from the digital control to the motor terminals. The SLLIMM also provides a hardware overcurrent shutdown and a free op amp used to scale and bias the current sensing. The power supply block uses the VIPer®16L to convert the high voltage DC bus to a regulated 15 V supply that supplies the SLLIMM and analog circuitry on the board. The 15 V supply also supplies an L78L33 linear regulator that provides the 3.3 V logic supply for the microcontroller.

Two firmware control programs are available, one for six-step and one for FOC that run on the same hardware platform.
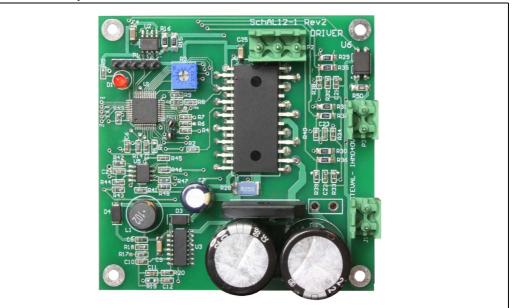
Figure 1.   PCB photo

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Figure 2.   Schematic sheet 1

Figure 3.   Schematic sheet 2
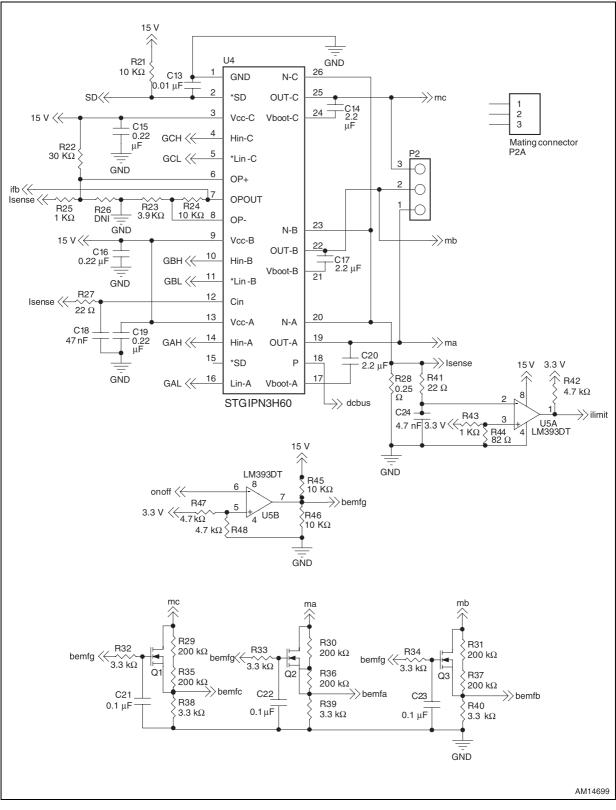
Figure 4.   Schematic sheet 3

Table 1. Bill of material

Quantity	Reference	Value/ generic part number	Package/ class	Manufacturer	Manufacturer ordering code	Supplier	Supplier ordering code
4	C1, C15, C16, C19	0.22 µF	603	Any		Any	
6	C2, C8, C11, C21, C22, C23	0.1 µF	603	Any		Any	
2	C3, C5	220 µF, 200V	Radial 18 mm dia., 7.5 mm LS	Panasonic	EEU-ED2D221	DigiKey®	P13522
1	C4	4.7 µF	1206	Any			
2	C6, C18	47 nF	603	Any		Any	
1	C7	100 µF, 35 V	8 mm dia., 3.5 mm LS	Panasonic	EEU-FC1V101	DigiKey	P10294
2	C9, C25	1.0 µF	1206	Any		Any	
2	C10, C13	0.01 µF	603	Any		Any	
1	C12	2.2 nF	603	Any		Any	
3	C14, C17, C20	2.2 µF	1206	Any		Any	
1	C24	4.7 nF	603	Any		Any	
1	D1	Red LED	Thru hole	ROHM Semiconductor	SLR-343VRT32	DigiKey	511-1256-1
1	D2	GBU604 bridge		Diodes®, Inc.	GBU604	DigiKey	GBU604DI
2	D3, D4	STTH1R06A	SMA	STMicroelectronics®	STTH1R06A	ST	
2	J1, P3	2 pos. ver. header 5.08 mm	2 pos. header	PHOENIX CONTACT	1758018	DigiKey	177-1128, 277-1128
2	J1A, P3A	DNI	2 pos. plug	PHOENIX CONTACT	1779987	DigiKey	277-5986
1	L1	1 mH inductor	Thru hole 5 mm LS	Würth	744-772-102	DigiKey	732-3783
1	P1	5 pos. 100 header	Thru hole	SULLINS CONNECTOR SOLUTIONS	PCE36SAAN	DigiKey	S1012E-36
1	P2	3 pos. header 5.08 mm	Thru hole	PHOENIX CONTACT	1758021	DigiKey	277-1129
1	P2A	DNI	3 pos. plug	PHOENIX CONTACT	1786417	DigiKey	277-5985

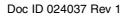**Table 1.   Bill of material (continued)**

Quan-tity	Reference	Value/ generic part number	Package/ class	Manufacturer	Manufacturer ordering code	Supplier	Supplier ordering code
3	Q1, Q2, Q3		SOT223	ST	STN1NK60Z	ST	
4	R2, R4, R6, R7	2.2 KΩ	603	Any		Any	
1	R3	2 kΩ pot	Thru hole	BOURNS®	3362P-1-202LF	DigiKey	3362P-202LF
1	R5	470 Ω	603	Any		Any	
1	R8	22 kΩ	603	Any		Any	
1	R9	7.5 kΩ	603	Any		Any	
2	R10, R12	470 kΩ	1206	Any		Any	
2	R11, R13	100 kΩ	2512	VISHAY®/DALE	CRCW2512100KJNEG	DigiKey	541-100KCCT
1	R14	8.2 kΩ	603	Any		Any	
2	R15, R16	100 Ω	1206	Any		Any	
1	R17	2.8 KΩ	1206	Any		Any	
7	R1, R18, R20, R21, R24, R45, R46	10 KΩ	603	Any		Any	
1	R19	DNI					
1	R22	30 KΩ	603	Any		Any	
1	R23	3.9 KΩ	603	Any		Any	
2	R25, R43	1 KΩ	603	Any		Any	
1	R26	DNI					
2	R27, R41	22 Ω	603	Any		Any	
1	R28	0.25 Ω	2512	VISHAY/DALE	WSL25122500FEA	DigiKey	WSLG-.25CT
6	R29, R30, R31, R35, R36, R37	200 kΩ	1206	Any		Any	
6	R32, R33, R34, R38, R39, R40	3.3 kΩ	603	Any		Any	
3	R42, R47, R48	4.7 kΩ	603	Any		Any	
1	R44	82 Ω	603	Any		Any	
1	R49	220 Ω	603	Any		Any	
1	R50	1 kΩ	1206	Any		Any	

Table 1. **Bill of material (continued)**

Quan-tity	Reference	Value/generic part number	Package/class	Manufacturer	Manufacturer ordering code	Supplier	Supplier ordering code
9	TP1, TP3, TP4, TP5, TP6, TP7, TP8, TP9, TP10		Via				
2	TP2, TP11		Thru hole	KOBICONN Industrial Partner	151-203-RC	MOUSER ELECTRON.	151-203-RC
1	U1		LQFP48	ST	STM32F100C8T6	ST	
1	U2		SO8	ST	L78L33	ST	
1	U3		SO16	ST	VIPer16	ST	
1	U4		STGIPN3H60	ST	STGIPN3H60	ST	
1	U5A		SO8	ST	LM393DT	ST	
1	U6	Opto-coupler	4-pin DIP	CEL	PS2561A-1_a	DigiKey	PS2561A-1-A
1	W1	Not installed					
1	Y1	8 Mhz ceramic resonator	3-pin SM	Murata	CSTCE8M00G55Z-RO	DigiKey	490-1219-1

1 Power supply section

Power enters the board on connector J1, as shown in *Figure 3*. The board may be powered from a single phase AC line at either 115 or 230 VAC nominal and either 50 or 60 Hz or from a DC supply between 150 and 350 volts.

When operating from 230 VAC, jumper W1 MUST be left open to disable the voltage doubler. If the doubler is enabled, it would generate a DC bus voltage that would destroy many components of the board. Operating from 230 VAC as a full wave rectified supply will generate a nominal DC bus voltage of 320 VDC, which is the correct value for driving 200 to 250 VAC rated motors. Since the SLLIMM module utilizes 600 V rated IGBTs, this class of motors is the most efficient to use with this PCB, and will deliver the most power output.

When operating from 115 VAC mains, wire jumper W1 can be soldered in to utilize the voltage doubler function and also generate a 320 VDC nominal bus. For operation with lower voltage motors, W1 can be left off to generate a nominal 160 VDC bus.

The high voltage bus supplies the input power to the VIPer16L which is configured as a buck type non-isolated switch mode converter. The VIPer16L provides the regulation, control, and gate drive along with the high voltage MOSFET high side switch. The 15 V output is sampled via D4, C8, and the attenuation and filtering circuit consisting of R17, R18, and C10. The duty cycle of the bus voltage applied to inductor L1 is modulated so as to regulate the output. D3 is a freewheeling diode to maintain current flow in L1 during the PWM off time and C7 is the main output filter capacitor. As previously described, U2 is a linear regulator that generates the 3.3 V regulated supply needed to operate the STM32™. Resistors R15 and R16 are connected between the 15 V supply and the input to the 3.3 V regulator. These resistors serve to "move out" some of the power dissipation from the linear regulator by dropping its input voltage. This allows U2 to run cooler.

2 STM32 based controller section

The STM32 provides all of the controller data processing functions. Two example firmware programs are available to run on the board, one to operate the motor in six-step mode and one to operate the motor in field oriented control. The default program loaded in the board is the six-step firmware.

The input signals to the STM32 are:

ifb-> This analog signal comes from the op amp in the SLLIMM module and is a biased and scaled replica of the DC bus current. The signal is biased such that the voltage at *ifb* is approximately ½ of the full scale voltage for the ADC when the current in the sense resistor is zero. The gain, set by resistors R23 and R24 (sheet 3), is adjusted so that the peak to peak signal remains within the full scale range of the ADC when operating at maximum rated current. When operating in six-step mode, this signal is synchronously sampled using the 12 bit ADC of the STM32 during the on time of the PWM signal. The converted value is used to calculate the average motor current over one full cycle and is used by the overload function. When operating in FOC mode, this signal is separated and converted by the program into accurate current feedback for each of the three motor phases.

bussense-> This analog signal is an attenuated replica of the DC bus voltage. When operating in FOC mode, accurate bus voltage information is required to scale the applied voltage value which feeds the sensorless rotor position observer.

potentiometer-> This analog signal is read at PA2 of the STM32 and provides the speed command.

bemfa-> This analog signal is derived from the motor phase A terminal voltage via the MOSFET based active clamping circuit. When operating in six-step mode, this signal is monitored by the ADC to determine the zero crossings of the BEMF of the floating phase. This signal is not used in FOC mode.

bemfb-> see *bemfa*

bemfc-> see *bemfa*

limit-> This is a digital signal which goes low whenever the motor current exceeds a fixed hardware set threshold. This signal triggers the STM32 Timer1's external trigger based cycle by cycle current control. The active edge of this signal will cause the active high side transistor in the bridge to be turned off for the remainder of the PWM cycle. The transistor will turn back on at the beginning of the next cycle. This input and the cycle by cycle current limit are used only in the six-step operating mode.

RX-> This digital signal is available at PB7 of the STM32 which is also the RX input of the USART. This connection, and the optocoupler that drives it, are provided for future expansion and are not used by the example software.

The STM32 provides the following output signals:

onoff->   This signal controls the operating mode of the active MOSFET based BEMF interface circuit. When this output is low, the output of comparator U5B is high, applying gate voltage to the MOSFETs and causing the circuit to operate as a pure active clamp. This is the proper state for six-step mode operation when sampling BEMF during off time. When the output is high, gating voltage is removed from the MOSFETs and the circuits work as pure attenuators. This is the proper state for six-step mode operation when sampling during on time. The on time sampling capability is provided for future expansion as the example six-step program samples only during off time. FOC mode does not use this signal.

led->   This signal drives the single LED display from PA11 of the STM32. The LED is normally on solidly when the drive is ready to run or running and will flash repeatedly in the event of a fault condition. The only fault condition current being reported is an overcurrent trip. In this case, the LED will flash twice, repeatedly, with a long pause in between.

GAH->   This logic signal drives the SLLIMM intelligent power module. This signal is positive logic and will be high whenever the high side transistor for phase A should be on.

GAL->   This logic signal drives the SLLIMM intelligent power module. This signal is negative logic and will be low whenever the low side transistor for phase A should be on. The STM32 manages the required dead time between the high and low transistor gating using the dead time function of the advanced timer.

GBH->   see GAH

GBL->   see GAL

GCH->   see GAH

GCL->   see GAL

3 STGIPN3H60 based 3-phase inverter bridge

The schematic of the inverter bridge and the analog circuitry is shown in *Figure 4*. The 15 volt supply is supplied to the STGIPN3H60 intelligent power module on pins Vcc-A, Vcc-B, and Vcc-C. Local power supply bypass capacitors are provided at each of the three pins.

The high voltage power supply, *dcbus*, is connected to pin P of the IPM. As described in *Introduction* and in *Section 1: Power supply section*, the voltage can be between 150 and 350 V DC. Internally, the IPM distributes the *dcbus* to the collector of the high side IGBT for all three phases.

The emitters of the three low side IGBTs are connected to pins N-A, N-B, and N-C and are tied together externally and then returned to ground through current sensing resistor R28. The resistor value is 0.25 Ω and thus generates a signal of 0.25 V per Ampere of motor current. This *Isense* signal is applied to the input of comparator U5A and compared to a fixed threshold of 0.25 V. When the voltage across R28 exceeds the 0.25 V threshold, the comparator takes the *ilimit* signal low. When operating with the evaluation software in six-step mode, this triggers the current limit function in the STM32 and sets up a cycle by cycle current limit of 1.0 Ampere.

This *Isense* signal is also applied to the *Cin* input of the IPM. The *Cin* signal is compared internally against a fixed 0.5 V reference which will trigger the internal smart shutdown function whenever *Isense* exceeds 0.5 V, which occurs when the current reaches 2.0 Amperes. This functions as a backup to the current limit described above which should prevent this condition from occurring. The smart shutdown function will immediately turn off all of the inverter transistors and will also activate an internal MOSFET which will pull the signal at the SD pin of the IPM down to the guaranteed turn off level of the input. This SD signal is connected back to the Timer1 BRK input of the STM32 via a resistive attenuator and a small low pass filter. The attenuation is required due to a possible voltage level mismatch between the guaranteed low level to which the IPM will pull the SD and the low level input threshold of STM32 BRK input. Adding the attenuator guarantees that the signal will be recognized. When this BRK signal is recognized by the STM32, internal hardware will immediately place all of the transistor control signals in the off state (low for high gates and high for low gates) and will also interrupt the processor.

The six logic inputs of the IPM are internally pulled down or up as appropriate to turn off the output. This is important to be sure that the output devices are off during power up or if the STM32 is reset. Whenever the STM32 is reset, the output pins will go into a high impedance state. After reset, the pins are assigned to GPIO configured as inputs, which are high impedance. The pins will remain in the high impedance state until the initialization section of the control program runs and gives control to Timer1. Without the proper pull-up and pull-down, the bridge state would be undetermined and could be unsafe or uncontrolled.

The SLLIMM module also provides an uncommitted op amp which is used to bias and amplify the *Isense* signal so that it is scaled to better match the allowable input range of the ADC in the STM32. The op amp circuit is configured as a non-inverting amplifier with positive bias. The input signal (*Isense*) is taken at R25 and the output (*ifb*) is taken from pin 7 (*opout*). The voltage across the sense resistor is normally of a positive polarity since this is actually DC bus current and a positive bus current represents power flowing from the bus to the motor. If, however, the motor is operated in a regenerative quadrant, power flow and thus the polarity of the *Isense* signal will be negative. Since the ADC of the STM32 can only convert positive voltages in the range of 0 to 3.3 volts, the op amp output is biased so that an input of zero gives an output of 1.44 volts nominal.

The program carefully measures this offset before the inverter bridge is enabled (when current is known to be zero) and uses the value to correct each reading. The effective overall gain of the circuit is 3.47 volts per volt which, combined with the sense resistor value of 0.25 Ω (volts per Ampere) gives the effective sensitivity of 0.8675 volts per amp. This determines the full scale positive current (3.3 V at ADC) to be 2.14 Ampere. Full scale in the negative direction is somewhat less (since the offset is not exactly at half scale) but it is assumed that regenerative currents will not be as large.
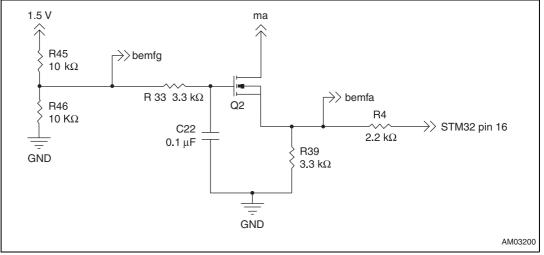
4 BEMF sensing circuit

The zero crossing of the BEMF of the unenergized phase is used in the six-step commutation technique to set the appropriate commutation time between steps. In this implementation the motor terminal voltage is measured by the ADC and the software determines when the zero crossing has occurred. The BEMF sensing is not used by the FOC software. The BEMF sensing circuit is identical for all there phases so only phase A will be described. The circuit is designed to allow sensing of the BEMF during either the on time or off time of the PWM cycle. Only sensing during the off time is implemented in the example program, but sensing during the on time could be added to allow the motor to be operated with PWM duty cycles up to 100%.

To get the best performance and lock on to the BEMF at low speeds, it is best to sense the motor terminal voltage during the off time without any attenuation. However, since the motor terminal voltage can go as high as several hundred volts, the voltage to the microcontroller must be clamped so that it remains within the allowable safe range, usually limited to the microcontroller supply voltage. The interface circuit needs to provide the unattenuated motor terminal voltage to the input pin, when the voltage is in the range between ground and V_{DD}, and clamp the voltage when the motor terminal voltage is outside of the allowable safe range. Figure 5 shows the equivalent circuit for the active clamp circuit used for sensing during off time. The circuit basically operates in two modes, as a fully on switch with Q2 fully on when the motor terminal voltage is low and as a source follower, limiting the source voltage, when the motor terminal voltage is above the allowable limit.

Figure 5. Active clamp circuit for BEMF sensing during off time

In Figure 5, the drain of Q2 is connected to motor terminal and the source as the BEMF input to the ADC of the STM32. Resistors R45 and R46 bias the gate voltage of Q2 to approximately 7.5 V. Q2 is an STD1NK60 that has a specified gate threshold voltage of 3 V and a typical *Rdson* of 8 Ω When the drain voltage is near zero, Q2 is fully turned on and the drain and source voltages are essentially equal. As the motor terminal voltage and drain of Q2 rise, the source voltage will follow at essentially the same voltage since the on resistance of Q2 is much less than R39. The voltage at the source will continue rise and follow the drain voltage until the source voltage reaches a point equal to the gate voltage (7.5 V) minus the gate threshold voltage (3 V). At this point Q2 becomes a source follower with the source following the fixed bias voltage at the gate less the gate threshold voltage. As the drain

voltage continues to rise, the source voltage will be clamped at approximately 4.5 V. Resistor R4 works with the internal protection diodes of the STM32 to limit the current and clamp the voltage at the input. The series resistance of R4 is well below the specified maximum series resistance for the ADC input (10 kΩ). The circuit provides a clamp for positive voltages, but does not prevent the *bemfa* signal from going negative. However, the freewheeling diodes in the power bridge clamp the motor terminal to one diode drop below ground. With a small negative voltage on the motor terminal, resistor R4 and the internal camp diodes limit the voltage at the input of the STM32.

The part designations in *Figure 5* match the part designations for the clamp circuit for phase A shown on sheet 3 of the full schematic. The additional circuitry in the full schematic is used for sensing during on time and to switch between on time and off time sensing. Comparator U5B is essentially an inverting buffer to shift the level of the control single, *onoff*, from the microcontroller. When sensing during off time the output of comparator U5B is off and the gates are biased at 7.5 V, as discussed above. To change to sensing during on time, the output of U5B is on and the gate bias is 0 so Q1, Q2, and Q3 are all off. The equivalent circuit for BEMF sensing during on time is shown in *Figure 6*.
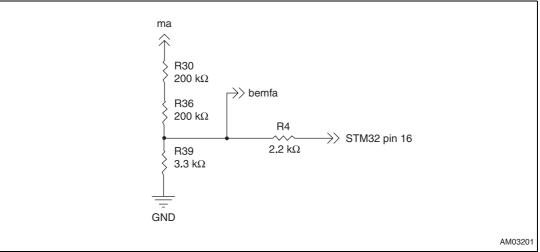
Figure 6.   Back EMF sensing circuit during on time

When Q2 is off, resistors R30, R36, and R39 form a resistive attenuator with a factor of 122:1, as shown in *Figure 6*. Even with 403 volts at the motor terminal, the output would be only 3.3 volts. When sampling during on time, the BEMF is compared against a threshold equivalent to one half of the DC bus instead of near zero. On time sampling is desirable in some cases, such as if we are required to run the duty cycle all the way up to 100%. Since, by definition, there is no off time when we are operating at 100%, off time sampling cannot be done. At lower duty cycles (and presumably lower motor speeds) off time sampling is preferred since the full signal strength of the BEMF is preserved. If we try to start the motor while using on time sampling, the signal strength is severely attenuated so that, all other things being equal, the motor must be ramped up to a much higher speed before we can lock on to the rotor position. An optimal strategy is usually to operate with off time sampling during start up and at lower duty cycles and then do a mode switch to on time sampling at higher duty cycles. Using the on time sampling is not implemented in the example software.

5 Additional references and resources

- Gerber files (zip file - see: www.st.com/internet/evalboard/product/255604.jsp).
- STEVAL-IHM040V1 firmware - see: www.st.com/internet/evalboard/product/255604.jsp
- STM32 PMSM FOC SDK v3.2 Motor Control Firmware Library see: www.st.com/internet/com/SOFTWARE_RESOURCES/SW_COMPONENT/FIRMWARE/stm32_pmsm_foc_motorcontrol_fwlib.zip
- ST Motor Control Workbench GUI see: www.st.com/internet/com/SOFTWARE_RESOURCES/TOOL/CONFIGURATION_UTILITY/motorcontrol_workbench.zip

Appendix A Startup procedure for STEVAL-IHM040V1 using the STM32 PMSM FOC SDK v3.2

1. Obtain and install the "IAR Embedded Workbench®" integrated development tool and C compiler for the STM32. A trial version called the "KickStart" version is available free of charge at the IAR web site.

2. Obtain a copy of the STM32 FOC SDK V3.2 (from www.st.com) and place a copy of the working directory in a convenient location on your computers hard drive. The installation process for the SDK will also install the configuration workbench program and the user documentation files.

3. Change the debugger connection from JTAG to SWD in the project options.

4. In the user project workspace, at the top, pick STM32100B-EVAL from the prop-down at the top.

5. Open the "STEVAL-IHM040V1 FOC SDK workbench settings" (from www.st.com/internet/evalboard/product/255604.jsp) file with the workbench program.

6. Go to options and change the "output path" setting so that it points to the "System & Drive Params" folder of your working directory. Change the settings as appropriate for your motor.

7. With the workbench program, generate the design files.

8. Edit main.c to "uncomment" the line: #define DEMOMODE

9. If you prefer different run and stop times, edit main.c to change the lines:
#define RUN_DURATION_SEC 5
#define STOP_DURATION_SEC 3.

10. Press F8, pick STM32100B-EVAL.

11. Click make.

12. Transfer the program to the target and run.

Appendix B Startup procedure for STEVAL-IHM040V1 using the STEVAL-IHM040V1 six-step program

1. Obtain and install the "IAR Embedded Workbench" integrated development tool and C compiler for the STM32. A trial version called the "KickStart" version is available free of charge at the IAR web site.

2. Obtain a copy of the STEVAL-IHM040V1 "SLLIMM 6 step program" (from www.st.com/internet/evalboard/product/255604.jsp#FIRMWARE) and place a copy of the working directory in a convenient location on your computers hard drive. The user documentation file for the program is also available on the ST web site.

3. Change the debugger connection from JTAG to SWD in the project options.

4. Open the project file using the "IAR Embedded Workbench".

5. Per the software documentation, change the user settable parameters as appropriate for your system.

6. Press F7, to rebuild the program.

7. Transfer the program to the target and run.

Revision history

Table 2.   Document revision history

Date	Revision	Changes
25-Jan-2013	1	Initial release.

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