Lappeenranta University of Technology
LUT School of Energy Systems
Degree Program in Electrical Engineering

Master’s Thesis

Kimmo Tirri

STANDARDIZED ELECTRICAL TESTS FOR ELECTRICAL EQUIPMENT IN ROAD VEHICLES CASE: VISEDO OY POWERMASTER M-FRAME

Examiners:	Professor Pertti Silventoinen Tero Järveläinen M.Sc. (Tech.)
Supervisor:	Tero Järveläinen M.Sc. (Tech.)

ABSTRACT

Lappeenranta University of Technology
LUT School of Energy Systems
Degree Program in Electrical Engineering

Kimmo Tirri

Standardized electrical tests for electrical equipment in road vehicles Case: Visedo Oy PowerMASTER M-frame

Master's Thesis

2016

59 pages, 25 figures, 6 tables, and 1 appendice.

Examiners: Professor Pertti Silventoinen
Tero Järveläinen M.Sc. (Tech.)

Keywords: automotive, power electronics, standard, ISO 16750

Electrical road vehicles were common at the begin of the 20th century but internal combustion engines took a victory from electrical motors in road vehicles. The acknowledgement of the environment, and the price and the availability of the crude oil are reasons for the comeback of the electrical vehicles. Advancement in industrial technology and political atmosphere in EU as the directive 20–20–20, which consists of reducing fossil emission, increasing renewable energy and increasing the energy efficiency, have made the electrification popular again.

In this thesis tests based on standard ISO 16750–2 electrical loads for electrical equipment in road vehicles are made for Visedo Oy's PowerMASTER M-frame power electronics device. This device is designed for mainly drive trains in mobile work machines and marine vessels but can be used in other application in its power range which also includes road vehicles. The functionality of the device is tested with preliminary tests which act as a framework for the tests based on standards.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
LUT School of Energy Systems
Sähkötekniikan koulutusohjelma

Kimmo Tirri

Standardien mukaiset sähköiset testit ajoneuvoihin sijoitetuille sähkölaitteille Case: Visedo Oy PowerMASTER M-frame

Diplomityö

2016

59 sivua, 25 kuvaa, 6 taulukkoa ja 1 liite.

Tarkastajat: Professori Pertti Silventoinen
DI Tero Järveläinen

Hakusanat: ajoneuvo, tehoelektroniikka, standardi, ISO 16750
Keywords: automotive, power electronics, standard, ISO 16750

Sähköautot olivat vielä 1900-luvun alussa yleisiä, kunnes polttomoottorin kehitys vei voiton sähkömoottoreista. Huoli ympäristöstä sekä raaka-aineiden saatavuudesta ja hinnasta ovat olleet syitä, joiden takia ajoneuvojen sähköistäminen on alkanut uudestaan. Tämän ovat myös mahdollistaneet teollinen kehitys ja poliittinen ilmapiiri, johon kuuluu muun muassa EU:n 20–20–20 päätös alentaa päästöjä, panostaa uusiutuviin energialähteisiin ja parantaa energiatehokkuutta.

Työssä valmisteltiin standardin, ISO 16750–2 sähköiset kuormat ajoneuvoihin tarkoitetuille sähkölaitteille, mukaisesti testit Visedo Oy:n PowerMASTER M-frame tehoelektroniikan laitteelle. Kyseinen laite on suunniteltu työkoneiden ja laivojen voimansiirtoa varten, mutta sitä voidaan käyttää myös muissa sen teholuokan laitteissa, kuten ajoneuvoissa. Työssä myös varmistetaan laitteen toiminnallisuus standardin mukaisia testejä varten preliminaarisilla testeillä, jotka toimivat kehyksenä standardoituja testejä varten.

ACKNOWLEDGEMENT

This thesis was done for Visedo Oy and I would like to thank the company for the opportunity. I want to thank for M.Sc. (Tech.) Tero Järveläinen for being the supervisor and an examiner of the thesis and for giving guidance and advices. Thanks to D.Sc. (Tech.) Risto Tiainen for ideas and help in preliminary tests. Also thanks to all in Visedo Oy whom I have worked with.

I want to give special thank for professor Pertti Silventoinen for being an examiner of the thesis, and giving ideas to the thesis and keeping the thesis on track.

Thanks for my parents Oili and Kalervo for supporting me through the studies. Special thanks to all my friends and for the countless sauna evenings. Hell yeah!

Last but not leasts I want to thank Silva for the support and being part of my life.

Lappeenranta, May 16, 2016

Kimmo Tirri

CONTENTS

APPENDICES

NOMENCLARUTE

Roman symbols

C	Capacitor
I	Current
L	Phase
n	Integer
R	Resistance
S	Switch
t	Time
U	Voltage

Abbreviations

A,B,C	Voltage, phases of grid side
AC	Alternating current
AFE	Active front end
ASIC	Application-specific integrated circuit
CAN	Controller area network, communication
CEN	European general standards organization
CENELEC	European electric standards organization
CPU	Central processing unit
CSI	Current source inverter
DC	Direct current
DIN	German general standards organization
PM	Device under the test
EMC	Electro magnetic compatibly
EMI	Electro magnetic interference
EU	European Union
EV	Electrical vehicle
FPGA	Field-programmable gate array
GTO	Gate turn-off thyristor
HEV	Hybrid electrical vehicle
ICE	Internal combustion engine
IEC	International electric standards organization
IGBT	Insulated-gate bipolar transistor
IGCT	Integrated gate-commutated thyristor

IO	Input/output, communication
ISO	International general standards organization
HVDC	High voltage direct current
LVDS	Low voltage differential signalling
MOSFET	Metal-oxide-semiconductor field-effect transistor
PCB	Printed circuit board
PM	PowerMASTER M-frame
PT100	Platinium thermometer, 100 Ω at 0°C
PWM	Pulse width modulation
RMS	Root mean square
RS-485	Recommended standard 485, communication
RT	Room temperature
SFS	Finnish general standards organization
U,V,W	Phases of motor side
VSD	Variable-speed drive
VSI	Voltage source inverter

Subscripts

1,2,3	Phases
1,2,3,4,5,6	Number of switch
act	Actual
DC+	DC-link voltage, plus side
f	Fall time
i	Internal resistance
LL	RMS value of line to line AC-voltage
min	Minimum
nom	Nominal
P	Primary side of a VSD
r	Rise time
S	Secondary side of a VSD
S	Supply voltage

1 INTRODUCTION

Testing is an important part of the product development. As developing a product based on standards does not only make it safe to use but also it allows the customer know that the product meets certain requirements. If the product is part of a larger system, it means that customer can use the product and not to worry about compatibility issues [1, 2, 3]. That is, if the customer has designed its own system within the standards.

Standards are guidelines, not mandatory unless a standard is made to a law [1, 2]. Standards were introduced in an effective way at the 19th century when the industrialization begun which meant mass production. This production needed subcontracting and specialization over borders and that meant every part of the same design needed to be exactly the same. [3]

The standards are divided in three levels: international, regional and national. For example national standards, DIN and SFS use 15 % and 8 % of their own standards. Rest of their standards are based on European standards CEN or CENELEC, or international ISO or IEC standards. [3, 4]

In this thesis the second part of the standard ISO 16750 is presented for testing Visedo Oy's PowerMASTER M-frame. That standard describes electrical tests for electrical equipment for road vehicles. Before the tests based on any standard can be done, the functionality of the PM must be tested first.

This functionality is tested with preliminary tests. These tests are for ensuring that the PM operates as designed. The preliminary test results are used to compare results of the test based on standards.

1.1 The big picture

A hundred years ago, in the early 20th century, electrical vehicles (EV) were more common than the vehicles that used internal combustion engines (ICE) [5, 6, 7]. The introduction of the electrical ignition and cheaper price of ICE vehicles turned the tide to the decline of EV for a century [5, 6, 7]. Now, the EVs are making a comeback along the side with hybrid electrical vehicles (HEV), and there are couple of reasons to that.

In the year 2008 the price of the crude oil peaked after it had risen in a year to more than double of its price from the year 2007 [8, 9]. A year after the oil consumption decreased but then the consumption begun to increase again, as the price of the crude oil decreased [8, 9, 10]. In the year 2014 Asia consumed little less than half of the world's oil and the whole world had increased its oil consumption, with Europe being an exception [10].

The European Union proposed the famous 20–20–20 in the year 2007 which came reality in the form of a directive in the year 2009 in the EU countries. This 20–20–20 stands for three targets: the amount of greenhouse gasses is decreased by 20 % to the level of it was in 1990, energy efficiency is increased by 20 % and 20 % of the energy production must be on based renewable energy sources. In addition to this, the vehicle fuel consumption should be based on 10 % of biofuels. All of these targets meant to be achieved at the latest in the year 2020. [11]

There will come a day when the last drop of oil will be drilled. This is done by either exhausting the last oil source or when the expenses of drilling the oil losses to the money getting out of it. People has already waken to the fact that environment suffers from the actions that we cause by polluting it. Although completely transferring to using EV or HEV vehicles will not solve every problem caused to environment, it is a step forward to change it back to being healthy again.

1.2 Electrically operated vehicles

An EVs can be operated purely with electricity or it can also use an ICE along side with electrical motor. In the latter case the vehicle is called an HEV.

An EV has an energy storage system which is recharged from the grid network or when braking. The stored energy is then used by an electrical motor or motors to create torque to move the vehicle forward. There is more than this, a converter to produce a DC-voltage for the energy system from the grid, an inverter to produce an AC-voltage to a electrical motor and a control to use correct value of the current and the frequency to be fed to the electrical motor. The electrical drive train also acts as a generator when braking or going downhill.

An HEV means that there is an ICE and an electrical motor in the vehicle propulsion. There are three types of HEVs and these are called a series hybrid, a parallel hybrid and a combination of both. In the series hybrid, the ICE is connected to a generator which creates energy for the electrical motor or motors [7, 12]. In this case, the ICE operates independently ideally at its nominal operation point. The parallel hybrid means that the ICE is connected to the wheels through an electrical motor that can act as a generator when braking or moving downhill, and when accelerating the electrical motor helps the ICE [7, 12]. When a series and a parallel hybrid are combined, it means that the ICE is connected to a generator and to an electrical motor [7, 12]. This allows to operate the vehicle in both ways as series or parallel hybrid. Like in EV, the same power electronics exist with their control and energy storage system with exception that not all HEVs have the capability to connect to grid to load their energy storage systems.

The energy storage systems are constantly shaping to have a better energy in a volume[13, 14]. That means decreasing the size, increasing the energy capacity or doing both. This allows a larger operational range for the EVs which enables to drive further without recharging the energy storage system.

The electrical motors are more efficient compared to ICEs [15]. When the efficiency of the whole energy chain is investigated, the efficiency is not so black and white. We are not living in ideal world nor in a world where the electricity magically just comes out from the plug in the wall. For example burning coal in plant does not have efficiency of 100 %, electricity transfers in the grid with losses and semiconductor devices do not have ideal switches. But even so, EVs are more energy efficient compared to ICE in the urban environment, mainly because the EV takes an advantage of storing the energy during braking [15].

The power electronics are evolving and the usage of those are more and more in common everyday life [16]. Not only in the shape of the EVs and the HEVs but also in an industrial applications for example a pump that uses a throttle to control the fluid speed. This means that the pump system is running at the full speed for whole time. If the pump system is replaced with a controlled pump, then energy is saved. The reason to that is due the fact that the pump is not needed to run at the full speed for the whole time but the speed can be controlled.

2 CONVERTERS AND INVERTERS

Electrical motors do not just operate in steady grid voltage of 230 V and grid frequency of 50 Hz. Electrical motors need different voltages and frequencies in order to achieve different torques and speeds. To operate an electrical motor a voltage conversion is needed which means first conversion from AC to DC and then to DC to AC [17, 18, 19].

For an active voltage conversion in converters and in inverters switches are needed. These switches are semiconductor devices that generally nowadays are either power metal-oxide-semiconductor field-effect transistors (MOSFET) or insulated-gate bipolar transistors (IGBT), diodes, thyristors, integrated gate-commutated thyristors (IGCT) or gate turn-off thyristor (GTO) [17, 18, 19]. Although diodes and thyristors are not switches but those can be used in passive converters.

For two of inverter types current source inverter (CSI) and voltage source inverter (VSI), the latter is more popular of these two in low and medium voltage inverters. One reason is that a large inductor is needed in CSI for storing the energy. [19, 20, 21]

When a converter and an inverter are combined, the result is a variable speed drive (VSD). Picture of an ideal variable-speed drive is presented in Figure 1.

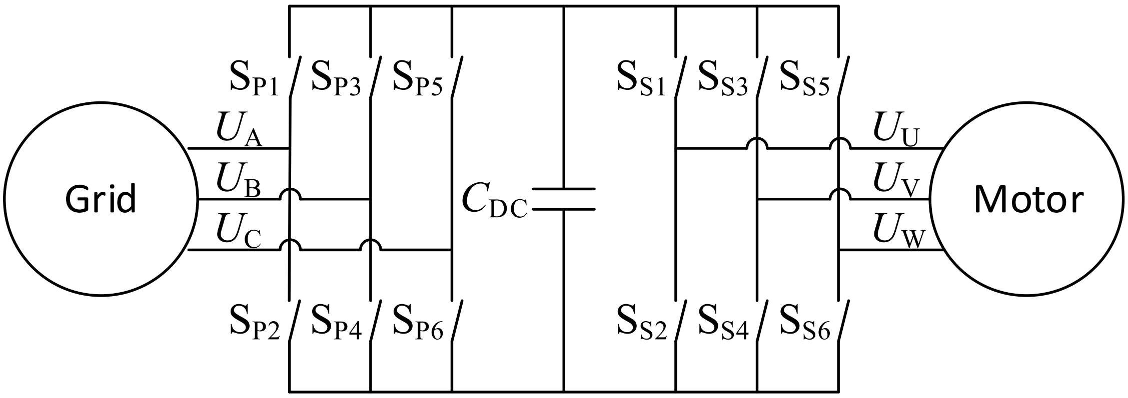

Figure 1. Figure of a VSD where is an AFE and an inverter with VSI topology. VSI which means that there is a capacitor in the DC-link. [19, 22]

2.1 Converters

Converters change AC-voltage to DC-voltage with an amplitude depending, on the topology, switch control and if the DC-voltage is boosted or lowered. An ideal VSI converter is presented in Figure 2.

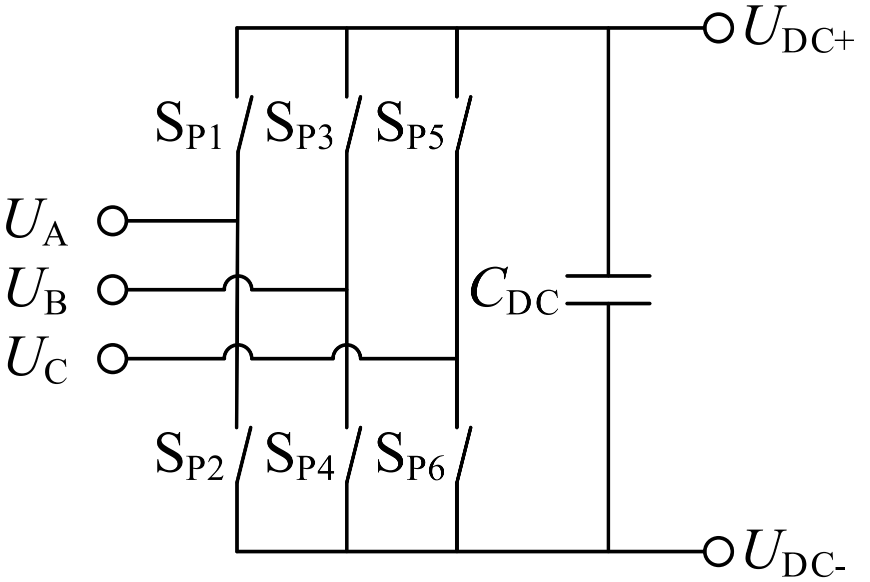

Figure 2. Three phase ideal converter with six ideal switches [19, 22]. The converter changes AC-voltage to DC-voltage.

The simplest way to construct a converter is to use semiconductor devices called diodes which are passive components. When using diodes or thyristors the converter is called a rectifier as the power can only flow to one direction. Other semiconductor devices need a some form of a control which generally done with a pulse width modulation (PWM) [17, 18]. The main purpose of the converter is to produce a correct DC-link voltage to be used for an inverter in the motor side. This is done either using the voltage from the grid or from a generator.

Converter that uses switches is also known as an active front end (AFE) which is a device that acts as a bidirectional power conversion. That enables power flow back to the grid in a situation when the electrical motor is braking. Other purpose of the AFE is to work as an active filter to improve power quality since it is controlled. [22, 23, 24, 25]

2.2 Inverters

Inverters are for motor control. The purpose of inverters is to generate voltage and frequency to drive the electrical motor from the DC-link voltage. The frequency of the voltage impacts on the speed of the motor and current to the torque the motor is producing. The basic concept of VSI inverters is presented in Figure 3 which includes a DC-link capacitor and six switches.

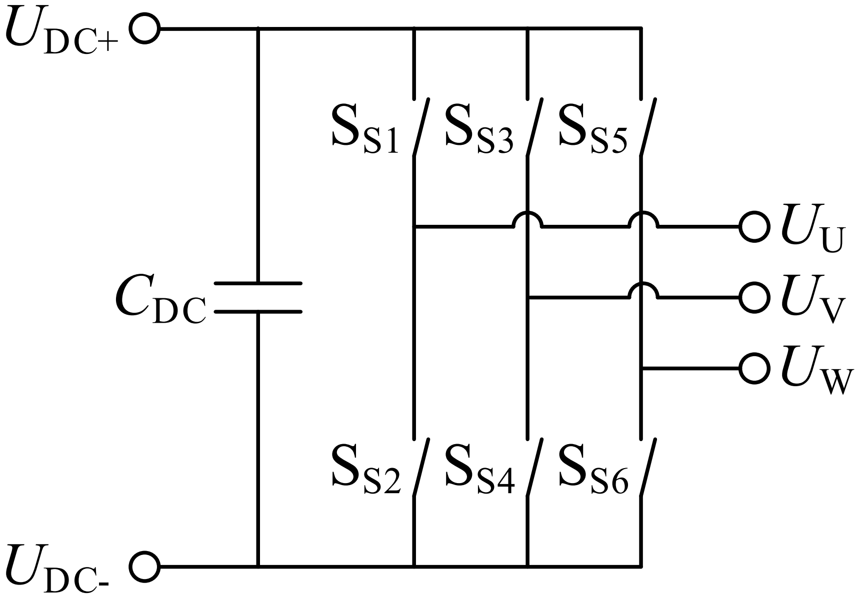

Figure 3. Three phase ideal VSI with six ideal switches [19, 22]. Inverter does the opposite to converter and that is DC-voltage to AC-voltage.

Inverter has to always use active switches to create AC-voltage. If controlled correctly, inverter can act as a converter when the motor is braking, feeding energy to the DC-link.

2.3 PowerMASTER M-frame

The PM is a power electronics device that can operate as an inverter, a converter or an AFE. The device is water cooled medium-voltage semiconductor device, single device designed for powers up to 300 kW and mainly for drive drains in work machines and marine vessels, but can be used in any application its power range [26]. The PM has own control program called PowerUSER where references and parameters can be changed according to the application and the operation of the PM. A picture of the PM is presented in Figure 4.

Figure 4. Visedo Oy's PowerMASTER M-frame. The device has connections for DC-link, three phase AC-voltage connection, cooling liquid connections, AMPSEAL 35-pin connector and a maintenance port.

The PM can be used in other application than mentioned early, only limit is the power. The different environments presents different challenges to the design of the device. Whereas in industrial applications the device is placed in a rather steady environment, compared to the changing environment in automotive applications.

The cooling of a power electronic device must be done right because in higher powers the device also produces more heat than in lower powers. The compactness also effects to the ability of the device to dissipate heat because there is less room for free and forced convection. The compactness and the amount of electrical power are the reasons that the PM is liquid cooled. The PM can operate with coolant temperature of 75 °C and the coolant flow of minimum of ten litres per minute [26].

2.3.1 Industrial applications

Industrial environments are mechanically steadier than automotive because the device is placed for example in racks or cabinets which might be bolted to the ground. The ambient temperature is steady if the device is placed inside a building. The exposure to different chemicals is narrower compared to the automotive since devices are placed in closed environments.

The electrical stress can be constant but in large industrial complexes that might produce a problem. That is because multiple devices with multiple switches exists, and so the grid harmonics may also exists. That cause problems to other electrical devices that are connected to the grid of the industrial complex. Filtering prevents and minimizes this phenomena which is done in passive filtering, active filtering or combination of both.

2.3.2 Automotive applications

An applications for automotive industry faces a constantly changing environment. The cause for this is that road vehicles are used in and kept at the mercy of the nature. Driving in cold and dry climate or hot and moist have a different effect to all equipment on board the vehicle, which also means to the electrical equipment.

The condition of the road causes mechanical stress to the parts of the vehicle. It can be constant vibration due the road or from the ruggedness of the tires. Also bumps and holes on the road causes sudden forces to devices on board.

The location of the device might vary but generally the power electronics are not placed inside the passenger compartment. This effects to chemicals and compounds that the device might encounter.

The EMC and the EMI problems are effecting only to the vehicle and its devices during the drive. The vehicle itself acts like a Faraday cage, preventing problems with EMI but causing possible EMC inside the vehicle. The EMC problems might be conducted to the grid when an EV or an HEV is connected to the grid for a battery recharge.

3 ISO 16750

The ISO 16750 is aimed for electrical equipment in vehicles that operate on the roads. The purpose of the ISO 16750 is to simulate situations and conditions of which the device under the test (DUT) might encounter during its life cycle. These includes: where the vehicle is driven, in what climate it is driven, type of the vehicle, operation modes of the vehicle, life cycle of the device and the supply voltage. [27]

The standard ISO 16750 consists of five parts. These parts are: part one - General, part two - Electrical loads, part three - Mechanical loads, part four - Climatic loads and part five - Chemical loads. [27]

In the part one, the general test conditions are given, which are room temperature (RT) of (23 ± 5) °C and relative humidity between 25 % and 75 %. These also includes mounting location for example engine compartment or passenger compartment. How the device is connected, the supply voltage of the device and the functionality mode of the device are described in the part one. As are functionality statuses which are presented in Table 2. [27]

Table 2. Functionality statuses for the DUT during the tests [27].

Class	Description
A	The DUT performs as designed during and after the test.
B	The DUT performs as designed during but one or more functions can exceed the tolerance limit. The DUT returns to normal operation after the test. The memory functions must remain in class A.
C	One or more functions of the DUT can be out of operation but return automatically to normal operation after the test.
D	One or more functions of the DUT can be out of operation and The DUT does not return automatically to normal operation after the test. The DUT needs a reset to return normal operation.
E	One or more functions of the DUT can be out of operation and the DUT needs repairing or the whole DUT needs to be replaced.

3.1 ISO 16750–2 Electrical loads

In this thesis the focus is on the part two - electrical loads of the standard ISO 16750 excluding the EMC test. The tests are described in this section. These tests include two tests from ISO 16750-4 Climatic loads, as last two tests needs to be done after damp heat cyclic test described ISO 16750-4.

Unless otherwise specified, the general conditions are applied which are RT of (23 ± 5) °C and relative humidity between 25 % and 75 %. The maximum temperature t_{max} is defined as 105 °C [28]. The tolerances for the tests are, for voltages ± 0.2 V, for resistances ±10 %, and for the frequency and the time ± 5 %, unless stated otherwise. The general test setups for DC-voltage and AC-voltage are presented in Figures 5 and 6.

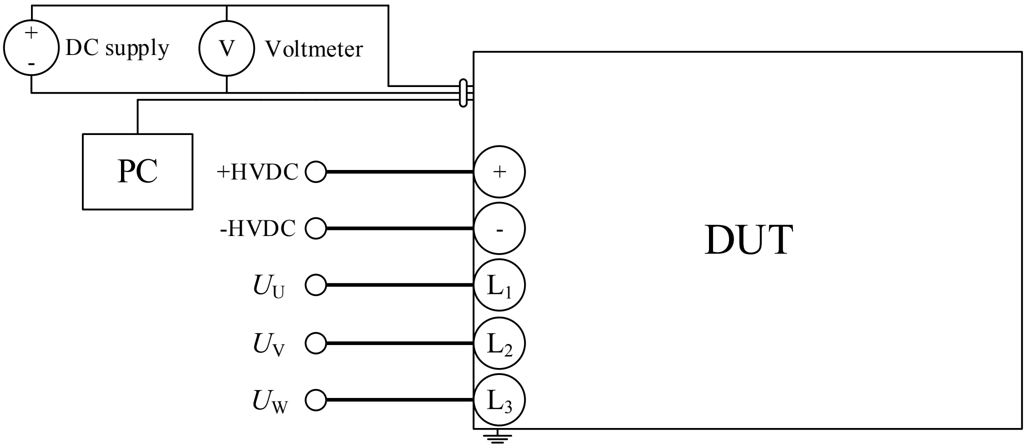

Figure 5. The general test setup with DC-voltage supply.

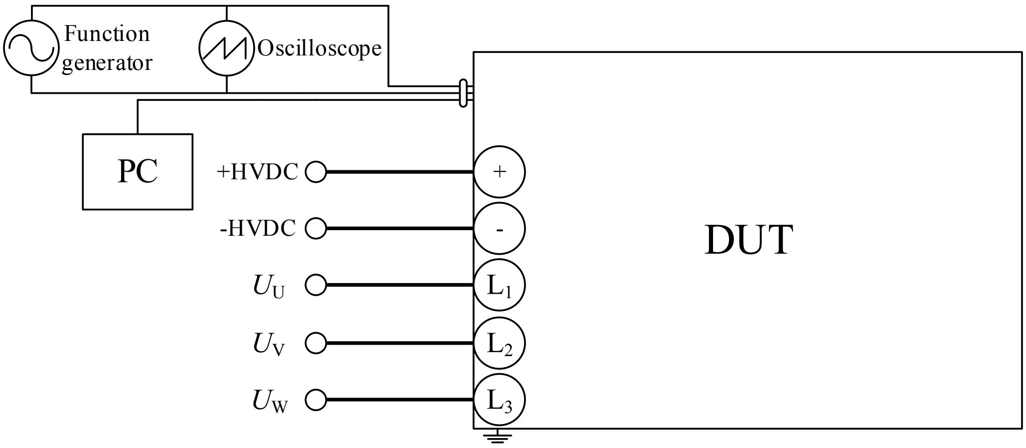

Figure 6. The general test setup for AC-voltage as supply voltage.

The tests are to simulate a real vehicle events and failures that can occur during the vehicle operation. These are for example start up of the vehicle, failure in battery connection while it is recharged or wrongly connected battery.

Devices that are part of the vehicle's voltage supply system are alternator, regulator and battery. The alternator is a generator that is connected to the battery via voltage regulation. The regulator is a device that makes a voltage transfer from the alternator's AC-voltage to DC-voltage for the battery and devices of the vehicle.

3.2 Direct current supply voltage

The PM is tested with minimum and maximum supply voltages. The minimum U_S being 10 V and the maximum 32 V [29]. The PM is run as in normal operation and class A must be attained [29]. The test uses the general test setup for DC-voltage presented in Figure 5.

3.3 Overvoltage

The PM is heated to $t = t_{\text{max}} - 20\,°C$ which is 85 °C [29]. For 60 min supply voltage U_S is set to 36 V [29]. The PM is run as in normal operation without high voltage connections.

If the generator regulator fails, the supply voltage will rise above nominal values as in the test [29]. Class A must be attained. The test setup is presented in Figure 7.

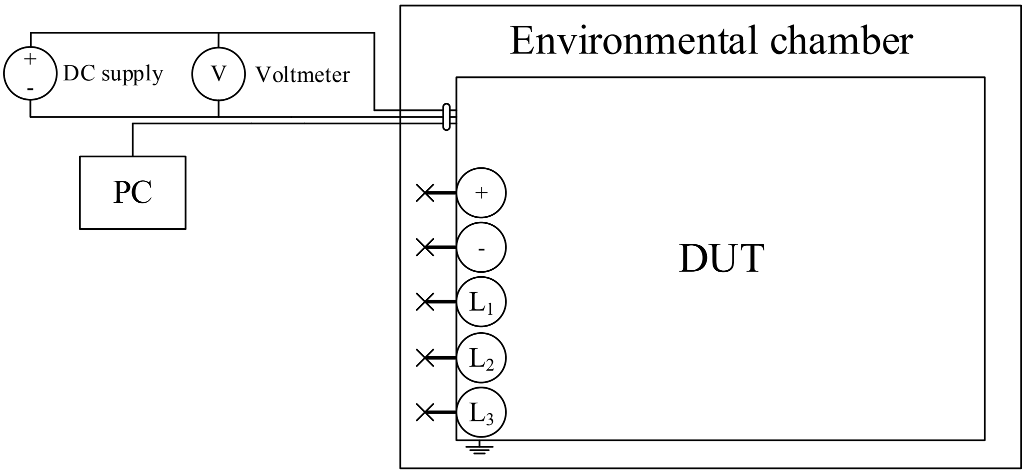

Figure 7. The test setup for DC supply voltage. The high voltage connections are disconnected.

3.4 Superimposed alternating voltage

The PM is supplied with AC-voltage of 10 V AC-component with DC offset of 27 V, maximum voltage being 32 V. The AC-component is set to start from 50 Hz and is risen to 25 kHz in 60 s, and back down to 50 Hz in 60 s. The total time of one sweep is 120 s and the total amount of sweeps done in this test is five. The internal resistance of the power supply must be within the range of 50 mΩ-100 mΩ. [29]

The purpose of the test is to test the PM's ability to withstand residual AC-voltage in the DC-supply [29]. Class A must be attained. The test setup is the general test setup for AC-voltage presented in Figure 5.

The AC-voltage in the supply voltage is caused by the regulator not working as designed. That means the regulator does not correctly regulate the voltage to DC-voltage.

3.5 Slow decrease and increase of supply voltage

The U_S is set to 10 V. Then the voltage is decreased to 0 V with linear rate of (0.5±0.1) V/min or steps size of 25 mV or less.

If an electronic device is left on in the vehicle while engine is not running, the battery will exhaust. The battery starts from the state where it is not much of the charge to start from. Class A must be attained at 10 V and class D for lower values. A stricter functionality class C can be used instead of class D. The test setup is general test setup for DC-voltage which is presented in Figure 5.

3.6 Momentary drop in supply voltage

The test voltage of 10 V U_S is set to U_S. The voltage is dropped to 9 V in 10 ms or less and back up in same 10 ms or less. The total dwell time is 100 ms. [29]

When a conventional fuse is melted in another circuit which the power supply supplies, it causes a voltage drop for the rest of the systems. This test is for simulating this situation [29]. Class B must be attained. The test setup is presented in Figure 8.

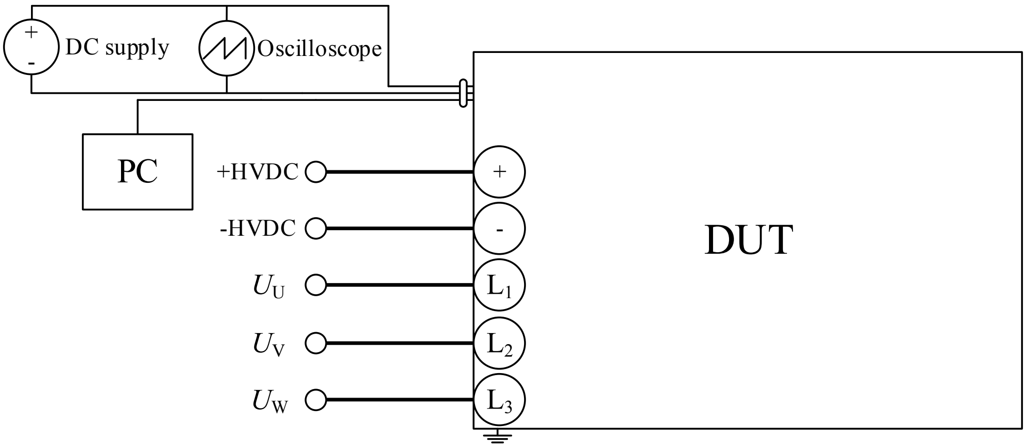

Figure 8. The test setup for DC supply voltage. The PM is operated as in normal operation.

3.7 Reset behaviour at voltage drop

The test is done starting from $U_{\text{S,min}}$ of 10 V and the voltage is lowered according to

$$U_{\text{S}} = (20 - n) \times 0.05 \times U_{\text{S,min}} \tag{1}$$

In the equation (1), *n* starts from 1 and goes up to 20 with steps of one. The voltage is held down for five seconds and it is brought back to $U_{\text{S,min}}$ for at least ten seconds [29]. During that time functionality of the PM is checked.

This tests the behaviour if the PM during a different voltage drops [29]. Class C must be attained during the test. The test setup is general test setup for DC-voltage which as presented in Figure 5.

3.8 Starting profile (Cranking impulse)

Cranking is term for ICE start up operation where the start motor is turned on with solenoid. Cranking impulse is what is seen in the supply voltage during that time. The starting profile voltage waveform is presented in Figure 9.

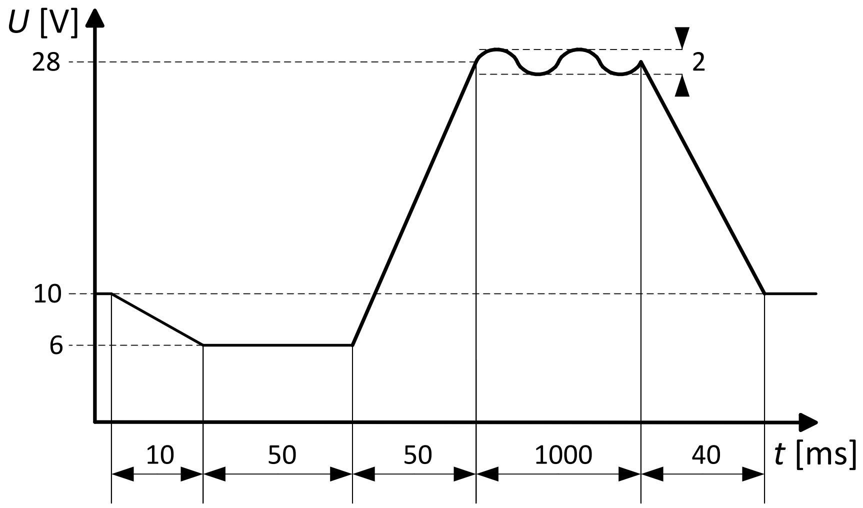

Figure 9. The supply voltage profile for starting profile test. The frequency during the voltage of 28 V is 2 Hz. This test is run ten times with a pause of 1–2 s in between. [29]

This test presents a situation what happens during cranking and after it. Pause of 1–2 s is recommended in the total of ten cycles. The frequency during the voltage of 28 V is 2 Hz. Class B must be attained during the test. The test setup is the general test setup for AC-voltage presented in Figure 6. [29]

3.9 Load dump

The internal resistance R_i of load dump has to be 1–8 Ω [29]. The internal resistance can be calculated with the equation

$$R_\mathrm{i} = \frac{10 \times U_\mathrm{nom} \times N_\mathrm{act}}{0.8 \times I_\mathrm{rated} \times 12000\,\mathrm{min}^{-1}} \tag{2}$$

In the equation (2) U_nom is the voltage of alternator, I_rated is the current of the alternator at speed of 6000 min^{-1} and N_act is actual alternator speed per minute. [29]

The test waveform and the parameters are presented in Figure 10.

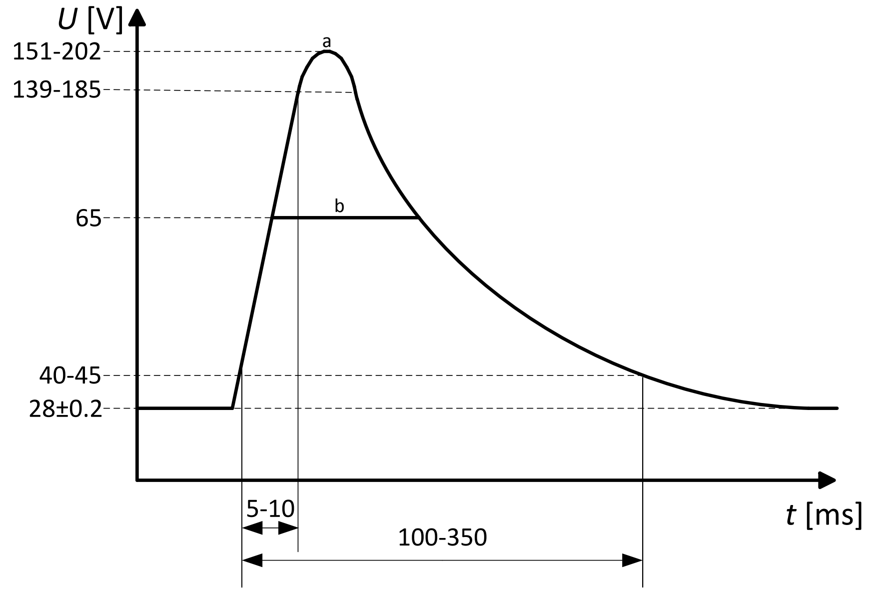

Figure 10. Test pulse for load dump test. The curve a is with non-centralized load dump and curve b is with the centralized load dump. [29]

The rise time, at the time of 5–10 ms, voltages are defined by equation

$$U_{\text{rise}} = pct * (U_{\text{max}} - U_{\text{s}}) + U_{\text{s}} \tag{3}$$

Where in the equation (3), *pct* is 10 % for lower value or 90 % for upper value, U_{max} is 151 V or 202 V, and U_{s} is 28 V.

Class B must be attained during the test [29]. The test setup is the general test setup for AC-voltage presented in Figure 6 [29].

This test simulates a phenomena when battery is disconnected from the alternator. This causes a voltage spike to the rest of the systems that are connected to battery and alternator.

3.10 Reversed voltage

Test is done with U_{S} of 28 V with reversed polarity. The reversed polarity is kept for (60±6) s. Class A must be attained after fuses have been replaced. The test setup uses the general test setup for AC-voltage presented in Figure 5. [29]

The test ensures that the PM is still operational if the supply voltage is accidentally connected in opposite polarity.

3.11 Ground reference and supply offset

Every output and input are connected to their right loads and networks. The supply voltage U_S is set to 28 V. An offset voltage of (1.0±0.1) V is set to every ground/supply line separately in sequence. The PM must also be tested with reversed offset voltage. [29]

This test mimics a situation where multiple power supplies are present, like signal ground and supply voltage ground [29]. The functionality of the PM is tested after every offset voltage is applied. Class A must be attained during the test, and there cannot be any malfunctions or latch ups. The test setup is the general test setup for DC-voltage presented in Figure 5.

3.12 Open circuit test

The PM is connected as in normal operation and a contact is opened for (10±1) s. The open circuit resistance must be at least 10 MΩ. The functionality is observed during the interruption. Every relevant connection must be tested. [29]

Test simulates a situation when there is an interruption in the signal circuit [29]. Class C must be attained during the test [29]. The test setup is the general test setup for DC-voltage presented in Figure 5. The 10 MΩ ensures that a connection is disconnected since carrying even 1 mA current over 10 MΩ would need a voltage of 10 kV. Because $U = R \times I$. Even a higher voltage is needed to carry more current.

3.13 Signal circuits

Every relevant input and output is connected to voltage of 32 V for (60±6) s. Other connections can be open. This test is done to connected supply voltage and ground terminals with outputs active and inactive, to disconnected supply voltage, and to disconnected ground terminals. [29]

This test's purpose is to ensure the case when supply voltage is accidentally connected to wrong input or output. Class C must be attained during the test. The test setup is the general test setup for DC-voltage presented in Figure 5.

3.14 Load circuits

The PM is supplied with U_S of 28 V and load circuits must be in operation. If fuses are used the test duration can be found in ISO 8820 (operating time rating) with the upper tolerance 10 %. If other than fuses are used, the test duration will be agreed between manufacturer and user. The load circuits must be operational. [29]

Every electronically protected outputs must withstand the currents by corresponding protection and attain the class C. With fuses class E is acceptable and fuses can be replaced. Every unprotected outputs must attain class E and the device must meet the requirements flammability of UL94-V0. [29]

The test uses the general test setup for DC-voltage presented in Figure 5.

3.15 Damp heat cyclic test

This test is done prior to tests withstand voltage and insulation resistance. The temperature and humidity curves are presented in Figures 11 and 12.

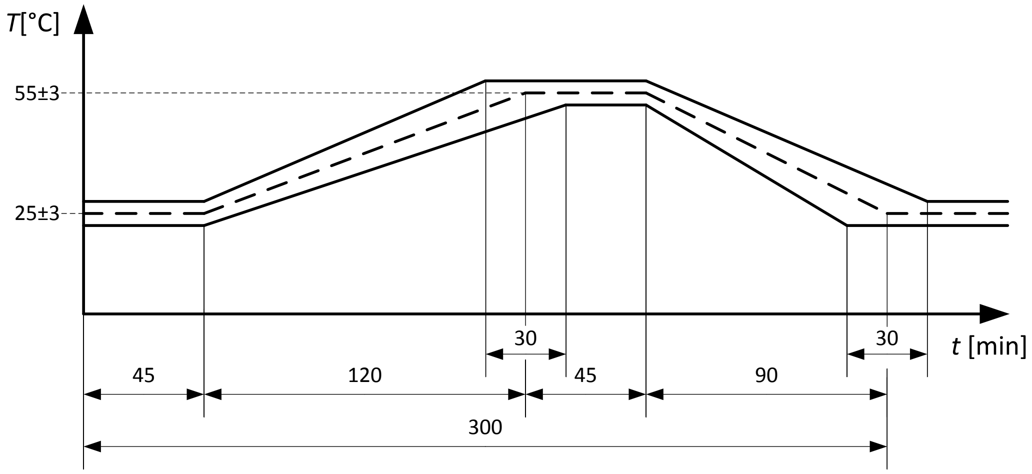

Figure 11. The temperature curve used in damp heat cyclic test. The test is performed before the tests withstand voltage and insulation resistance. One cycle lasts 300 minutes. [28]

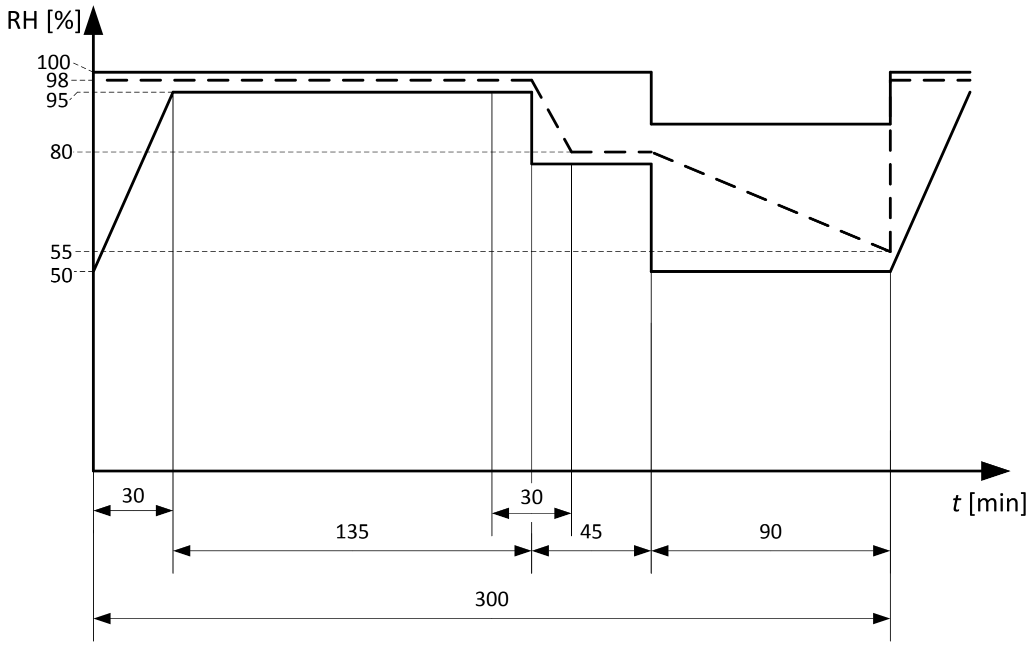

Figure 12. The humidity curve used in damp heat cyclic test. The test is performed before the tests withstand voltage and insulation resistance. One cycle lasts 300 minutes. [28]

One cycle lasts 300 minutes and the cycle performed to the PM in total of six times. At the maximum temperature (55±3) °C the supply voltage U_S is set to (28±0.2) V and the PM is run as in normal operation. [28]

3.16 Withstand voltage

This test is performed after the damp heat cyclic test. The PM is kept in RT for 30 min after the damp heat cyclic test. [29]

A test AC-voltage of 500 V RMS and frequency of (55±5) Hz is applied for 60 s to between terminals with galvanic isolation, terminals and housing with conductive surface with galvanic isolation, and terminals and an electrode wrapped around the housing in case of plastic housing. [29]

The test verifies the PM's ability to withstand the dielectric voltage capability with galvanic isolation. This test is done to systems and equipment that contain inductive elements or is connected to inductive load. Class C must be attained during the test and no dielectric breakdown nor a flashover can occur. [29]

Dielectric breakdown means that the insulating material has become conductive. Flashover on the other hand stands for insulating material becomes temporarily conductive that an arc of electricity passes through the insulator.

3.17 Insulation resistance

This test is performed after the damp heat cyclic test. The PM is kept in RT for 30 min after the damp heat cyclic test. [29]

An DC-voltage of 500 V is applied for 60 s to between terminals with galvanic isolation, terminals and housing with conductive surface with galvanic isolation, and terminals and an electrode wrapped around the housing in case of plastic housing. [29]

The test verifies that the minimum ohmic resistance is met to avoid current between galvanic isolated circuits and conductive parts in the PM [29]. The insulation resistance must be greater than $10\,\mathrm{M\Omega}$.

The test checks that galvanically isolated circuits are still isolated from each other. As the DC-current should not be transferred between galvanically isolated circuits.

4 PRELIMINARY TESTS FOR POWERMASTER M-FRAME

The control of the PM can be done with two Controller area networks (CAN), five user IOs or encoder. Other connections of the PM are three external PT100, two syncs for master/slave, power on, two stops signals, 5 V output, HV loop, two RS485, LVDS, resolver, ground connections and supply voltage connection.

The general functionality needs to be tested first. This is done to verify that the PM is working as intended. These tests shows parameters and signal values which can be observed and compared during the tests based on standards.

4.1 Power on and stop test

The first thing to test is that the PM powers up and that it operates in the supply voltage area as specified. The testing that software is correctly downloaded to the PM must also be done. This also includes that the voltage limits for the power on and the stop signals are correct. Testing with a supply voltage higher than 5.5 V and lower than 36.7 V as those are the overvoltage and undervoltage limits specified in hardware.

The overvoltages and undervoltages are checked in surge protector. The surge protector uses threshold voltages for overvoltages and undervoltages where the voltage is checked with voltage divider from the supply voltage.

The stop signals are for manually stopping the PM. These acts as an emergency switches in a case when the user needs to shutdown the PM.

The power on has to be connected to the supply voltage. This signal is for a surge protector to open the supply voltage line to the rest of the device. A voltage from CPU power on is connected to power on comparator. The reason for this is that the CPU would do its on going calculations before it is shutdown.

In order to get the PM to working condition it needs a bootloader downloaded to the flash. After that the software can be downloaded to the FPGA.

4.2 Current measurements and overcurrent trigger test

When a current travels in a conductor it creates a circulating magnetic field according to ampère's law. The strength of the circulating magnetic field is a proportion to the current. This magnetic field changes the path of the charge carries in hall effect sensor, creating a voltage difference in it [30, 31]. This voltage can be measured through voltage comparators to analog to digital converter to microprocessor, field-programmable gate array (FPGA) or application-specific integrated circuit (ASIC).

The current measurement is tested by supplying current through a hall sensor called LEM which is a device that measures current from a wire that is pulled through the LEM loop. To get higher current measurement than the supply voltage can provide, the wire be pulled through the LEM multiple times. The current passed through the LEM is multiple to the current that passed in the wire. That way there is no need for HV connection for this test. The LEM uses hall effect to measure the current.

A conformation that the PM triggers at the event of overcurrent if a current that is high enough is passed through the LEM. This and the measurements are tested in every phase. The currents and triggers points are also measured to both direction of the current. It is possible to simulate the overcurrent by providing a voltage directly to the measurement in the printed circuit board (PCB).

4.3 The DC-link voltage measurement and overvoltage trigger tests

A voltage is measured from the DC-link. The voltage measurement and overvoltage trigger levels are investigated. This is done by either providing high voltage to the DC-link. If this is not possible a voltage can be applied directly to the PCB where the voltage measurement is done.

The DC-link voltage is monitored via serie resistors through an operation amplifier to a analog to digital transform. The corresponding voltage at 1182 V is 3.3 V at input of the operation amplifier. The DC-link overvoltage is dimensioned to trigger above 1067 V and untrigger below 1037 with a push-pull output comparator.

4.4 The enclosure voltage measurement test

An enclosure is a shield that covers the electronics and the connections inside the PM. The purpose of the enclosure is to protect inner parts from dust, water, tools or human parts, and to shield from the EMI and protected emitting the EMI.

In case of a high voltage is somehow connected to the enclosure, meaning that the enclosure is not shielding from electricity as it designed to. Then this measurement indicates that and triggers the PM to shutdown the switching process. The enclosure voltage measurement is tested by supplying voltage to DC-link or directly to measurement on the PCB. The enclosure voltage is a voltage from DC-link through 12 $\mathrm{M}\omega$ of resistance to the enclosure of the PM.

The enclosure voltage is monitored through an operation amplifier to an analog to digital transform. The corresponding enclosure voltage at 1203 V is 3.3 V at input of the operation amplifier. The enclosure voltage does not have a hardware trigger as phase currents and the DC-link voltage do.

4.5 The short circuit trigger event

The short circuit means that a non-intended connection is added in parallel which adds a new path for a current to flow. The total resistance of the circuit after it is shorted is at maximum the smaller resistance of the two. The higher current caused by short circuit can destroy components and connections before the point of the shorted circuit. The components before the surge stopper current measurement are dimensioned to withstand a current of 5 A.

The short circuit is tested with connecting a load from the surge stopper current measurement to the ground. In this case the load is Aim-TTi LD300 DC electric load. The short circuit current should be at 5 A.

4.6 IGBT and external PT100 temperature measurement test

The initial temperature test is done in RT, checking that measurements show correct value in that temperature. This is done by placing the PM inside an environmental chamber near the RT. Also the thermal resistance is calculated from the results.

The external PT100s and the PM is heated and cooled in a environmental chamber to check that IGBT temperature and external PT100 measurements are correct. The IGBTs have their own PT100 for the temperature measurement.

4.7 Auxiliary voltage output tests

The PM has 5 V output for auxiliary devices. These are tested in a way that they produce the correct voltage and that those are protected from overloads. The current limit is designed to be in the range of 200–400 mA.

The test is performed with 5 V output is connected to a load via a current measurement. For 5 V, the 200 mA is reached when the load is 25 Ω and 400 mA with load of 12.5 Ω.

4.8 The communication tests

The sync link is for operation when two or more same type devices are connected in parallel. In that way those can provide an additive to the power to one device can produce. By syncing the devices means that they are run with same control that their voltages and currents are in same phase enabling the parallel drive.

All the five user IO channels are tested as digital inputs and outputs. Every channel with exception to the fifth channel, is tested and analog inputs. The fifth channel does not have hardware support for the analog measurement.

The test is done so that every operation mode of the specific user IO pin is tested. This is done by setting one of user IO pins as an input and one as an output.

The CAN communication is tested with baud rates of 100 kbit/s, 250 kbit/s, 500 kbit/s and 1000 kbit/s. The test is performed with J1939 V2 protocol. The PM is started and stopped with the CAN by switching a bit in P-CAN view program. The correct value is observed with different communication port, in this case PDP with PowerUSER. Bus errors are observed with P-CAN view.

4.9 The resolver test

The purpose of the test is to verify that the PM is capable to run an electrical motor and to test that the PM can run it in a closed loop with a resolver. The motor used is PowerDRUM XXSE synchronous reluctance assisted permanent magnet electric drive with nominal values: 500 V, 190 Hz, 1900 RPM, 110 A, 89 kW and cos ϕ of 0.99. The test script is presented in Appendix 1.

The resolver is tested with the voltage ramp test starting from 0 RPM with 10 Nm as a load or from 60 RPM with 461 Nm as a load with step of 5 RPM. One step lasts for 15 s and the test ended at 1900 RPM. The sample time is set to 10 Hz.

As the load increases the higher the current is that the PM provides to the motor. During the test, the IGBT and motor temperatures are observed, especially with torque of 461 Nm as higher the torque the more does the system heat up. The load side values are also measured to have a reference to the values of the PM.

The PM can measure the angle of rotor in the electrical motor or generator with a resolver. The resolver operates in pairs and those are referred as a sine and a cosine since those are in an angle of $\frac{\pi}{2}$ apart from each other. The reason why resolver uses a pair is that one part gets same value of the angle twice per rotation. For example at zero and π the sine gets the value of zero but the cosine gets values of one and minus one.

5 PRELIMINARY TEST RESULTS

The results of the preliminary tests to the PM are presented in this section. These tests indicates that the PM is ready for tests based on standards and to become a device that can be mass produced. The voltage source for supply or other connection was provided by Aim TTi CPX400DP unless otherwise stated.

5.1 Power up and stop test

The power on was observed in schematics and couple of changes must be made in order to make power on operational. The power on is presented in Figure 13.

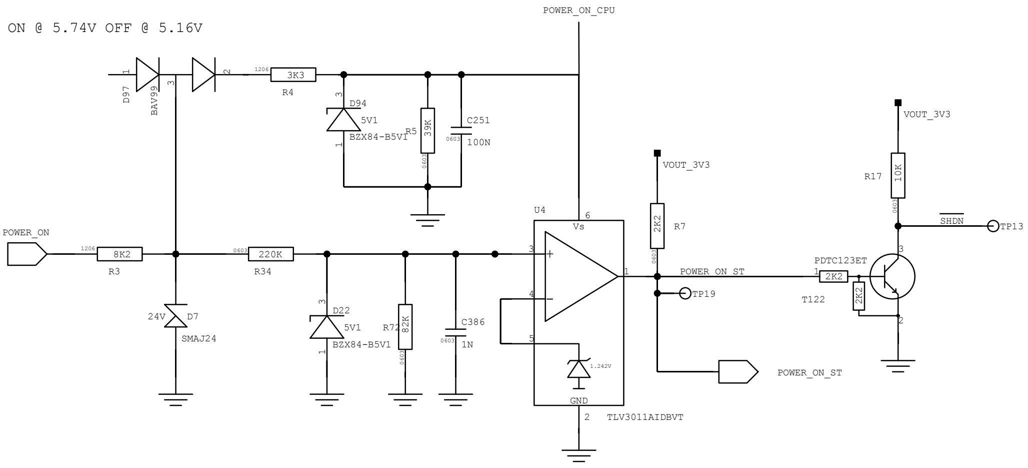

Figure 13. Power on circuit with voltage comparator.

The comparator output should be connected to comparator's supply voltage with larger pull-up resistor than 2.2 kΩ. During the power on the transistor's T122 pin three is connected to ground via pin two. This also means that $\overline{\text{SHDN}}$ signal is also connected to the ground. As the shutdown signal is also connected to surge protector, the voltage of that pin goes under 2.2 V, the surge protector shuts down. In order to prevent that from happening, the transistor T122 is removed and pins one and three are connected. Also the resistor R17 is removed due limiting the voltage provided for $\overline{\text{SHDN}}$.

The bootloader was successfully downloaded with CAN to the flash after a modification to the PCB. The inverted CAN enable signal was connected to flash inverted write protect. It means that when the flash were tried to be updated with CAN, it also prevented downloading software to the flash. The flash inverted write protect was disconnected from the inverted CAN enable and connected to 3.3 V voltage.

In the temporarily fixed version the CPU shuts down when the voltage supply is disconnected. In order that not to happen a new version of the power on has to be designed. In this version the power on and shutdown are measured with Agilent U1242B and those event occurs for power on at around 6.00 V and shutdown at around 5.85 V. The shutdown at high voltage happens at 32.6 V. Inspection of the schematic revealed that the overvoltage of the surge protector is 36.7 V but it is then limited to 33.1 V later in the supply voltage circuit.

For the updated version a totally different power on schematic is proposed. This has to be tested again with the fixed power on. The overvoltage needs to be set higher after the surge protector circuit.

5.2 Current measurements and overcurrent trigger test

Currents were measured by supplying a current through LEMs with a voltage supply Aim TTi QPX600DP. A wire with cross section of 0.75 mm^2 was pulled through LEMs by 20 times.

The initial observation with the current measurements in PowerUSER showed a third lower current as it should have been. This is due the change from 400 LEMs to 600 LEMs. This gain was corrected in software before the test was proceeded.

The power source was used against a current limits of 10 A, 20 A and 30 A. The currents were observed with PowerUSER and the results are presented in Table 3.

Table 3. Phase currents. Measured by pulling a wire 20 times through each LEM and the power supply used against the current limit. The current from the power supply is multiplied by 20 in the table for readability reasons.

Supply current [A]	L_1 Current [A]	L_2 Current [A]	L_3 Current [A]
600	593	596	597
400	398	399	399
200	200	198	198
-200	-199	-198	-200
-400	-398	-399	-400
-600	-593	-595	-597

The overcurrent hardware triggers were tested with connecting a voltage supply Aim TTi

CPX400DP to comparators inputs. The voltages presented were observed from the supply voltage. In the overcurrent measurement, another comparator observes a voltage higher than 3.176 V and another lower than 0.167 V as these voltage limits stand for currents of 750 A and -750 A. The hardware triggers occured at 0.19 V and 3.20 V. Also noted that when a LEM is disconnected from the PCB the current measurement shows 811 A which also causes overcurrent trigger event. These trigger events also stopped the modulation.

5.3 The voltage measurements and overvoltage trigger tests

The DC-link and the enclosure voltage were tested by supplying a voltage from the voltage supply to the DC-link contacts. The DC-link voltage and the enclosure voltage were observed from PowerUSER and the results are presented in Table 4.

Table 4. The DC-link voltage and the enclosure voltage. The voltage from the supply voltage is connected to the DC-link contacts.

Supply voltage [V]	DC-link voltage [V]	Enclsoure voltage [V]
40.0	39.8	20.6
80.0	79.8	41.1

The DC-link voltage measurement is capped at 1182 V with hardware. The maximum DC-link voltage transfers to voltage of 3.3 V in the voltage in measurement on the PCB. Addition to this, the overvoltage triggers at DC-link voltage of 1067 V. To test higher voltages measurements than the voltage supply was able to provide, the voltage is supplied directly to measurement on the PCB. The results of this measurement is presented in Table 5.

Table 5. The DC-link voltage and the enclosure voltage. The voltage from the voltage supply Aim TTi CPX400DP is connected to the DC-link and enclosure voltage measurements. The maximum supply voltage is 3300 mV in both measurements.

Supply voltage [mV]	DC-link voltage [V]	Enclsoure voltage [V]
825	296	300
1650	592	601
2475	886	902
3300	1181	1202

The DC-link voltage hardware trigger event occured when a voltage of 2960 mV was applied to PCB measurement which corresponds to the DC-link voltage of 1060 V. This ended the modulation. The enclosure voltage does not have trigger event in hardware but it can be produced with software.

5.4 The short circuit trigger event

The DC load Aim-TTi LD300 was connected from output of current sensing resistor in the power surge stopper and to the ground. The current of the DC load was increased until the hardware trigger event occurred.

The measured current in the DC load was 3.91 A at the event of the trigger. Adding the current consumed without the DC load, 0.35 A, the short circuit current is 4.26 A. The short circuit protection current falls short from the designed current which is 5 A.

5.5 Stop signals test

The stop signals were tested in RT. With both signals the shutdown occurred at 2.22 V and start was prevented until stop signals at least had a voltage of 3.45 V.

Both signals were tested separately, meaning that other signal was connected to supply voltage. Also the test yielded the same results when both signals were together connected to the test voltage.

5.6 IGBT and external PT100 temperature measurement tests

The test is proceeded by first setting the PM in RT and measuring the temperature produced by the PM itself without high voltage or cooling connections. RT, high and low temperatures are used to test PT100 measurements in the IGBTs and external temperature measurements. Also the DC-link voltage, the enclosure voltage and the phase currents are observed. The start and the stop are tested with different voltages in high and low temperature. Stop signal voltage levels are also checked at high and low temperatures. The values were observed and saved to a file from PowerUSER.

The environment chamber used was Climats 1192H40/3. It could provide the minimum temperature of -27.5°C and the high temperature used was 105°C. The PM is placed on the bottom of the environmental chamber, next to its own temperature measurement. The external PT100 measurements are placed on the top of the PM.

During the tests IGBT and external temperatures, DC-link voltage, enclosure voltage and phase currents are measured. The reason for other than temperature measurements are observed is that there might be effects to measurements by the temperature change. Temperatures are observed as those should show the value close to the environmental chamber temperature.

5.6.1 Temperature test in RT

The PM was placed in the 20 °C for a time until the temperature was stabilized in the temperature measurements of the PM. There was no supply voltage during the stabilizing period except when the temperatures were checked. This was done by applying supply voltage to the PM and checking the temperatures. The supply voltage was shutdown right after the temperatures were measured.

The temperature was checked once in a 15 minutes. If there was no temperature change larger than ±0.1 °C, the PM was ready for the test. When the temperature was stabilized the voltage supply was connected with voltage of 24 V and the modulation was turned on. The results of this test is presented in Figure 14.

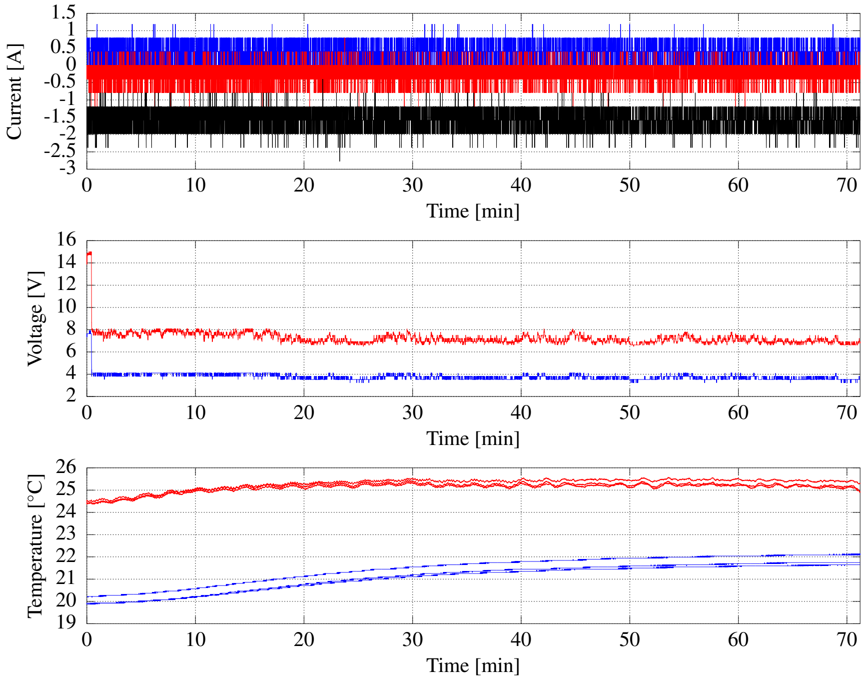

Figure 14. The results of power on in 20 °C. In the uppermost figure three phase currents are shown. In the middle figure is seen DC-voltage as red trace and enclosure voltage as blue trace. In the lowest figure the temperature measurements are presented. The IGBTs temperatures are the blue traces and external PT100 measurements are shown as red traces.

The DC-link offset decreases by 0.5 V. Also in enclosure voltage a decreasement of 0.2 V is seen. A difference of 4.5 ° is visible in between of IGBT temperetures and external PT100 measurements at the begin of the test. The IGBTs heat up during idle state approximately 1.8°C.

The fluctuation of the external measurement is a result of the environmental chamber trying to keep its temperature at the 20 °C. The device consumes at idle run state with modulation on a current of 450 mA. The voltage used was 24 V, this leads to power of 10.8 W which is turned to heat of 1.8°C. This gives the thermal resistance of the PM 0.167 °C/W without liquid cooling.

5.6.2 Temperature test in low temperature

The PM was placed in the environmental chamber with the supply voltage of 24 V and the temperature is set to -40 °C for getting as low as possible. The environmental chamber could reach the minimum temperature of -27.5 °C. the PM is operated as in idle state but modulating during the whole test. The results of this test are presented in Figure 15 with the start temperature of 12.8 °C measured at the environmental chamber temperature measurement with Agilent U1242A.

When the temperature has been stabilized, the stop signal voltage levels are investigates. Also the PM is started at stopped ten times in each voltage level of 10 V, 24 V and 32 V.

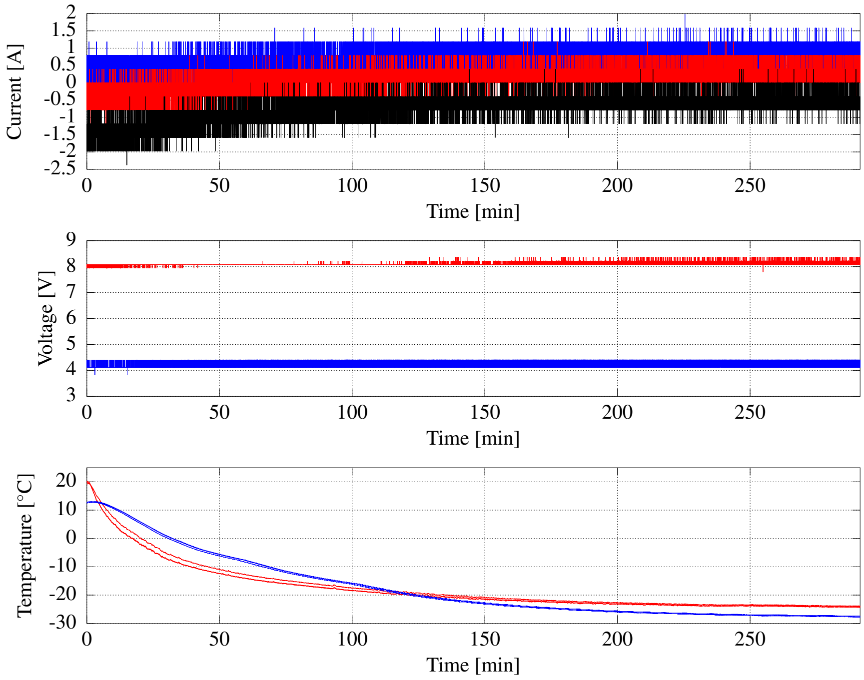

Figure 15. The results of low temperature test. In the uppermost figure three phase currents are shown. In the middle figure is seen DC-voltage as red trace and enclosure voltage as blue trace. In the lowest figure the temperature measurements are presented. The IGBTs temperatures are the blue traces and external PT100 measurements are shown as red traces.

The end temperatures for IGBTs are -27.6 °C and for external PT100 -24.2 °C. The DC-link voltage measurement increases by 0.2 V. Also every phase current measurement increases by 1 A compared to the begin of the test.

The start and stop test done on the voltage levels as described before. The PM started and stopped without any issues. For stop signals are the PM does not start under 3.55 V and shut downs for stop 1 2.18 V and stop 2 2.22 V. Stops were tested supply voltage being 24 V.

5.6.3 Temperature test in high temperature

This test was conducted in succession to the RT test, the supply voltage being 24 V. The temperature was set to 105 °C. The modulation was kept on during the test except for the time during the DC-link voltage was 15 V and enclosure voltage 8 V. During that time the PM was triggered to high temperature. The IGBT temperature trigger level was set to 120 °C. The limit was risen as soon as it was noticed. The test results are presented Figure 16.

The same voltage levels tests were done as in low temperature test which start and stop ten times with voltage levels of 10 V, 24 V and 32 V. The stop signal voltage levels were also tested.

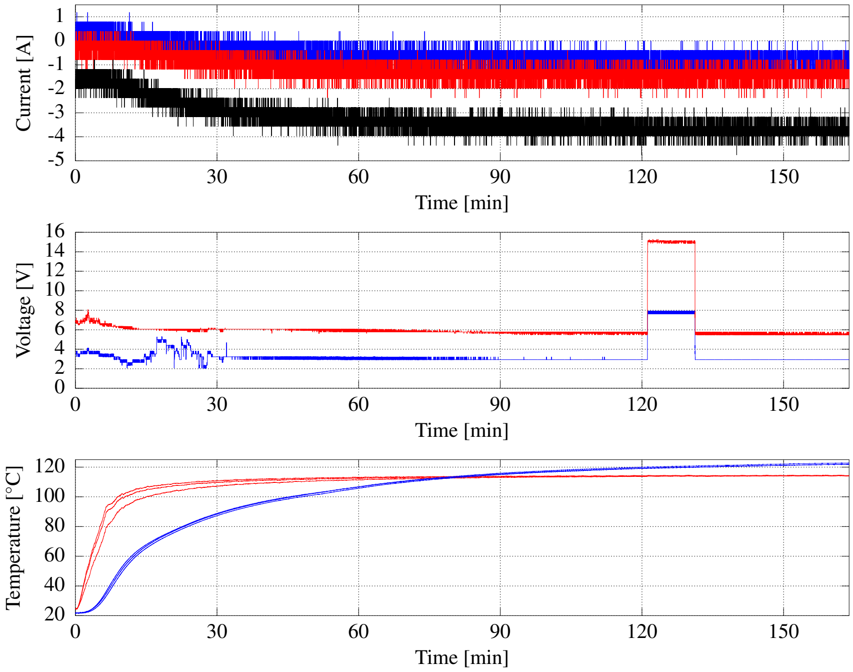

Figure 16. The results of high temperature test. In the uppermost figure three phase currents are shown. In the middle figure is seen DC-voltage as red trace and enclosure voltage as blue trace. In the lowest figure the temperature measurements are presented. The IGBTs temperatures are the blue traces and external PT100 measurements are shown as red traces.

The end temperatures for IGBTs are 122.2 °C and for external PT100 114.1 °C. Both voltage measurements experience a fluctuation at the begin of the test. The current and voltage measurements shifted to opposite direction when comparing to the low temperature test. The DC-link voltage settles at 6 V, 2 V lower than in RT. The enclosure voltage lowers by 1 V from RT test voltage level. The phase current measurements decreases by

1.25 A from the initial value, except for the one which decreases by 2 A. Also noted that the PM used more current than in RT. This current increased from 450 mA to 500 mA.

The start and stop test done on the voltage levels as described before. The PM started and stopped without any issues. For stop signal 1 the PM does not start under 3.50 V and for stop signal 2 the PM does not start under 3.45 V. The shutdown voltage for stop 1 2.29 V and stop 2 2.25 V. Stops were tested supply voltage being 24 V.

5.7 Auxiliary voltage output tests

The test was performed with metal film resistors, connected from 5 V output to the ground. The Agilent U1242B was connected in series with the resistor. Voltage over the resistor was also measured with the same multimeter. The results of auxiliary voltage output test is presented in Figure 17. The voltage measured from the output to the ground was 4.97 V.

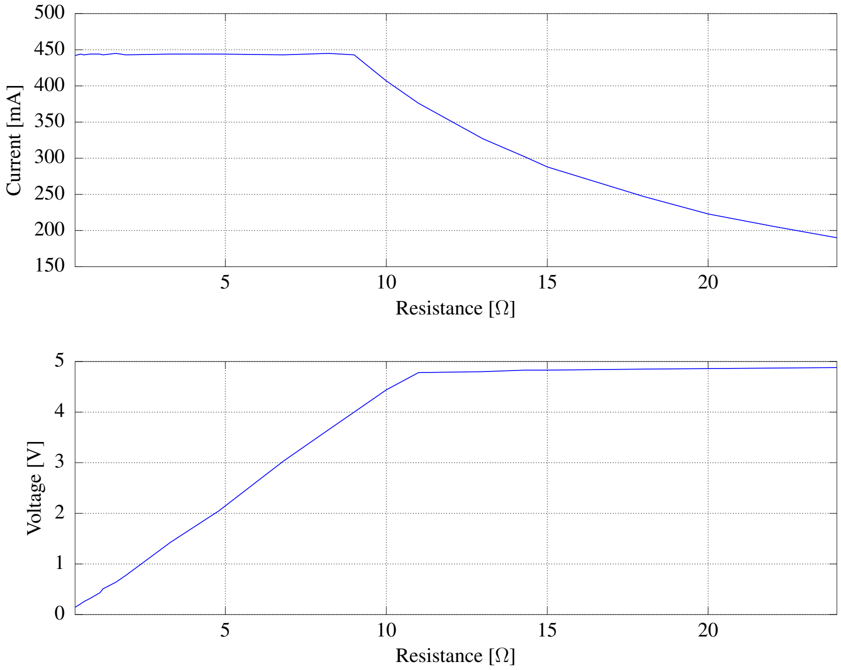

Figure 17. The upper figure shows the measured current. In the lower figure is presented the voltage over the load. The current is limited to 450 mA.

The voltage begins to be limited after the current reaches 400 mA. The current limit is seen as the constant current at 450 mA. The voltage keeps dropping in respect to the load but the current stays the same.

5.8 The user IO test

For analog input test, every input was connected to a test voltage, except for IO5 as it does not have an analog input capabilities. The test voltages and user IO read values are presented in the Table 6. The difference between the user IOs voltages were insignificant to the results. This is the reason why only one user IO voltage is presented in the Table 6. The digital values were switched and observed in PowerUSER as was the analog input.

Table 6. Analog input IO test results. Only one IO voltage is presented. The reason for this is that the IO measurement were similiar to each other to make an impact to the results.

Supply voltage [V]	IO voltage [V]
0.00	0.00
0.10	0.10
0.50	0.51
1.00	1.01
5.00	5.00
10.0	10.0
15.0	15.0
20.0	20.0
25.0	25.0
30.0	30.0
32.0	32.0

Digital inputs and outputs were tested by connecting IO1 and IO2 together, and IO3 and IO4 together. After IO3 and IO4 test was concluded, IO4 was disconnected and, IO3 and IO5 were connected together. Test was proceeded by switching other of the user IOs to write and other to read state. The write was switched to boolean TRUE and results were observed in the other IO if the state was switched to TRUE. It was also tested that the boolean FALSE was correctly switched by switching the write IO to boolean FALSE. This was done after it had been switched to TRUE as the initial state of the user IO is FALSE. These procedures were repeated until every user IO combination was tested. The digital user IOs correctly changed values and read them.

5.9 The CAN communication test

The test was done by switching the enable signal with P-CAN view to boolean TRUE and then back to FALSE. The enable signals was observed in PowerUSER software. Also the bus errors were observed during the test. The test was done with baud rates of 100 kbits/s, 250 kbits/s, 500 kbits/s and 1000 kbits/s with both CAN channels.

The enable signal switched TRUE and FALSE correctly with every baud rate and with both channels, and without bus errors. Terminator of 120Ω was used in between the CAN high and low signals.

5.10 The resolver test

The resolver test was done as described in previous section. The ramp size of 5 RPM is used and the maximum speed is 1900 RPM. There are in total of four tests with loads of -10 Nm, 10 Nm, -461 Nm and 461 Nm. The resolver speed measurements and torques from the load and the motor are saved to a file with a script done with Ruby presented in Appendix 1. The motor speed direction is the opposite to the load torque direction.

The important part of the test is to observe the ripple of the speed from the motor resolver speed. It is presented by reducing motor resolver speed from the motor reference speed. The spiking in the resolver speed measurement is not result of the switching the speed reference.

5.10.1 Motor resolver speed measurements with load of 10 Nm

The motor and load resolver speed measurements with the load of 10 Nm are presented in Figures 18 and 19. The speed ramp begins at 5 RPM and it is opposed to the sign of the load torque.

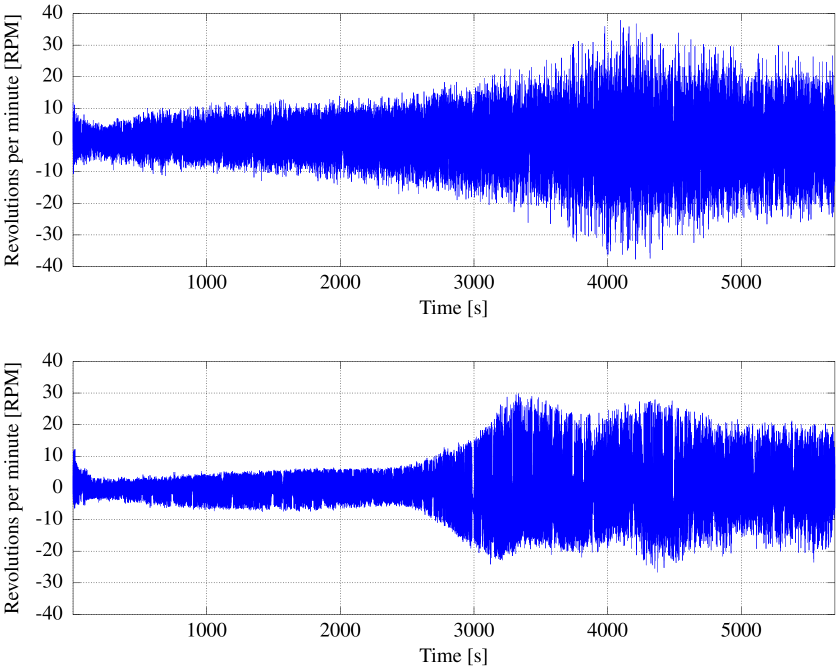

Figure 18. The motor and load speed with respect to motor reference speed for positive motor speed with -10 Nm load. Upper figure is for the motor side and lower figure for load side resolver speed measurement. The motor has speed reference of 5 RPM at the time of 0 s. Ramp time is 15 s with ramp of 5 RPM.

The resolver speed ripple rises as the speed increases and has the highest value of almost ±40 RPM during the time of 3900–4400 s. At this time zone the time stands for motor reference speed of 1300–1470 RPM. After that the motor speed ripple settles to ±25 RPM. At the highest point of motor speed ripple, the ripple is 3 % of the motor resolver speed.

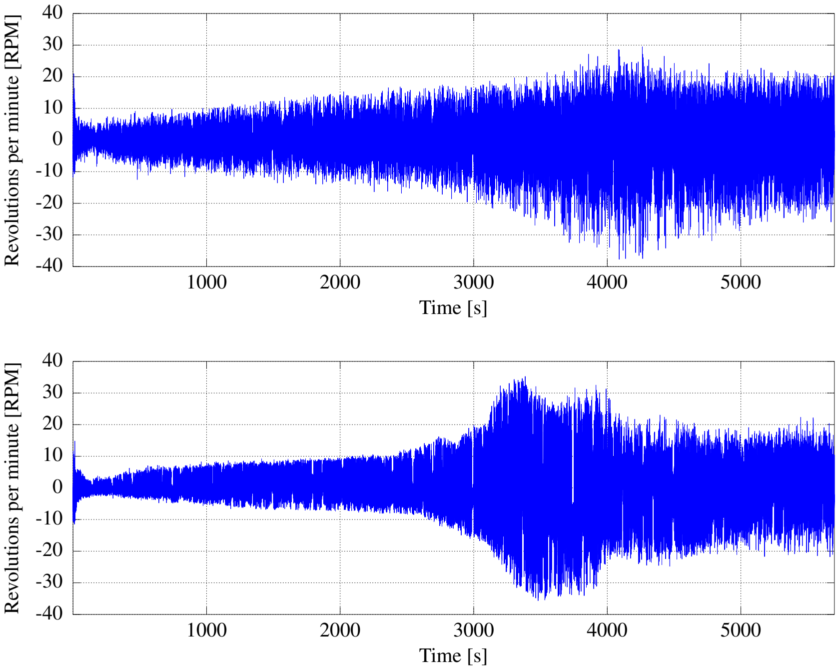

Figure 19. The motor and load speed with respect to motor reference speed for negative motor speed with 10 Nm load. Upper figure is for the motor side and lower figure for load side resolver speed measurement. The motor has speed reference of -5 RPM at the time of 0 s. Ramp time is 15 s with ramp of -5 RPM.

The same point for the motor speed ripple is the highest as with the positive motor speed reference at 3900–4400 s (1300–1470 RPM). In this case the ripple is not symmetrical, the ripple being +30 RPM and -40 RPM.

5.10.2 Torque measurements with load of 10 Nm

The motor and load torque measurements with the load of 10 Nm are presented in Figures 20 and 21. The speed ramp begins at 5 RPM and it is opposed to the sign of the load torque.

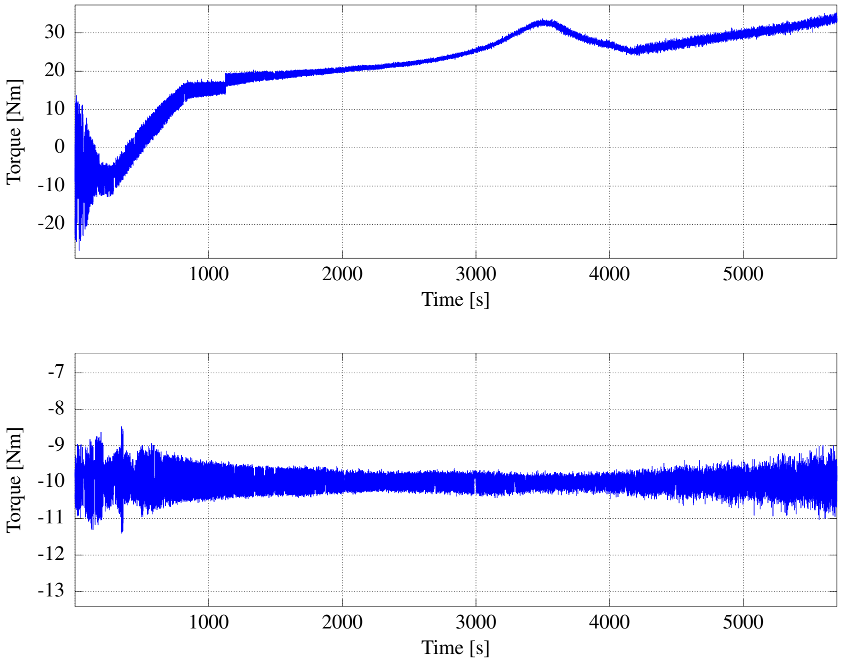

Figure 20. The motor and load torques for positive motor speed with -10 Nm load. Upper figure is for the motor side and lower figure for load side torque measurement. The motor has speed reference of 5 RPM at the time of 0 s. Ramp time is 15 s with ramp of 5 RPM.

The motor torque rises steadily after 800 s which is at the motor reference speed of 270 RPM if the local maximum at 3500 s is not taken to account. That local maximum is at motor reference speed 1170 RPM. At the begin of the test, 0–120 s, the motor torque is not steady. This is due the fact that motor has too slow speed reference. The speed reference at that time is 40 RPM. Also the motor torque the control uses is same sign torque as the load until 520 s which is at motor reference speed of 175 RPM.

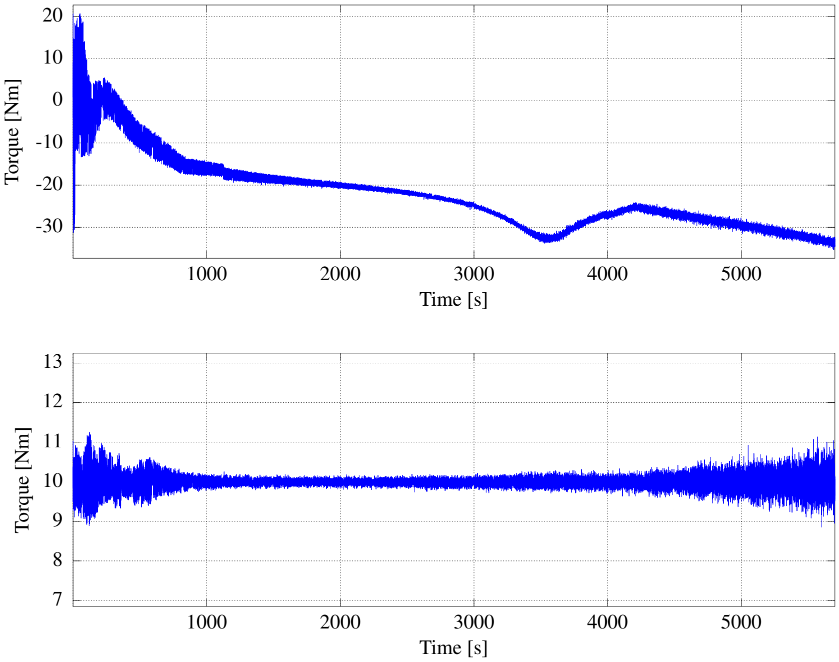

Figure 21. The motor and load torques for negative motor speed with 10 Nm load. Upper figure is for the motor side and lower figure for load side torque measurement. The motor has speed reference of -5 RPM at the time of 0 s. Ramp time is 15 s with ramp of -5 RPM.

The motor torque is almost identical to the motor torque in positive motor speed reference if the figure is mirrored in respect to x-axis. The same local maximum at 3500 s (1170 RPM) but sign of motor and load torques being the same until at 300 s (100 RPM). The torque ripple stabilizes at the same time as in positive motor resolver speed at 120 s (40 RPM).

5.10.3 Motor resolver speed measurements with load of 461 Nm

The motor and load resolver speed measurements with the load of 461 Nm are presented in Figures 22 and 23. The speed ramp begins at 60 RPM and it is opposed to the sign of the load torque.

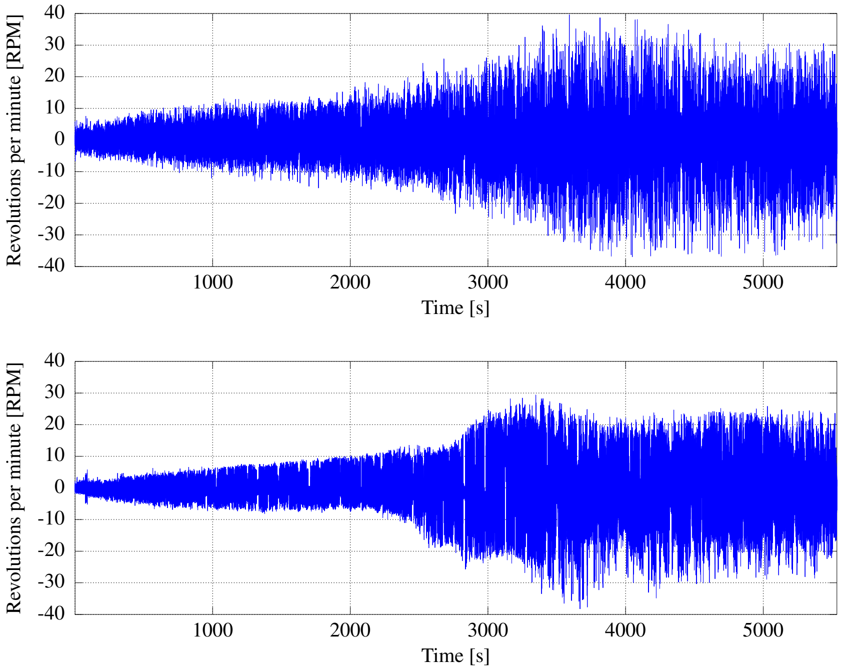

Figure 22. The motor and load speed with respect to motor reference speed for positive motor speed with -461 Nm load. Upper figure is for the motor side and lower figure for load side resolver speed measurement. The motor has speed reference of 60 RPM at the time of 0 s. Ramp time is 15 s with ramp of 5 RPM.

The motor resolver speed ripple is at the highest during 3600–4400 s (1200–1470 RPM) which is almost ±40 RPM. At 1200 RPM the ripple is 3.3 % of the motor resolver speed.

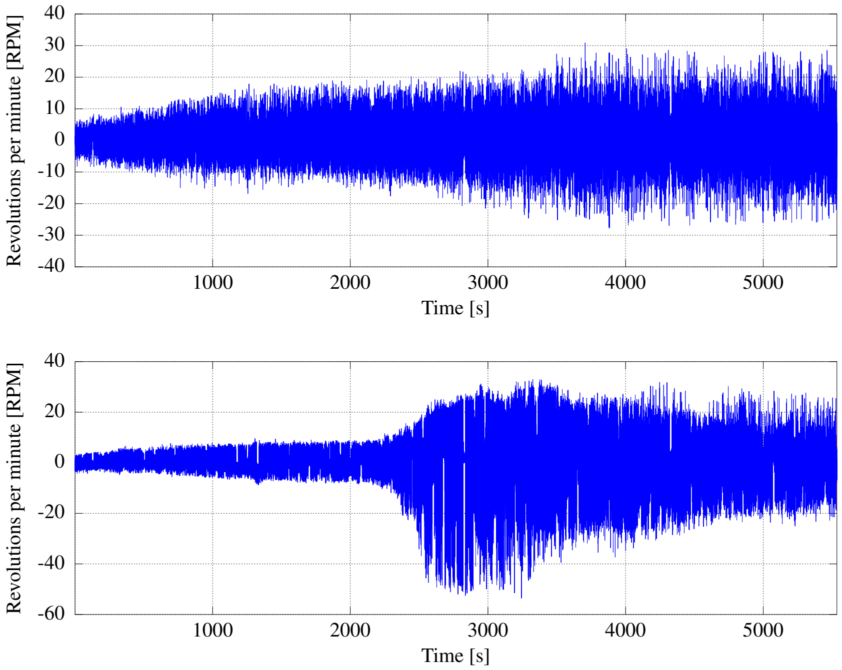

Figure 23. The motor and load speed with respect to motor reference speed for negative motor speed with 461 Nm load. Upper figure is for the motor side and lower figure for load side resolver speed measurement. The motor has speed reference of -60 RPM at the time of 0 s. Ramp time is 15 s with ramp of -5 RPM.

The motor resolver speed measurement ripple with positive load is more stable and linear than in the previous tests. At the near 4000 s (1330 RPM) there is no ±40 ripple but only ±25 RPM ripple. But still that ripple is at 3500 s (1170 RPM) is 2.1 % of the motor speed reference.

5.10.4 Torque measurements with load of 461 Nm

The motor and load torque measurements with the load of 461 Nm are presented in Figures 24 and 25. The speed ramp begins at 60 RPM and it is opposed to the sign of the load torque.

If an absolute value of the negative torque is taken, the waveform would look identical to test with the positive torque. In that case there would be a slight offset approximately 5 Nm to each other and larger jump in the value of the torque at the time of 900 s (300 RPM).

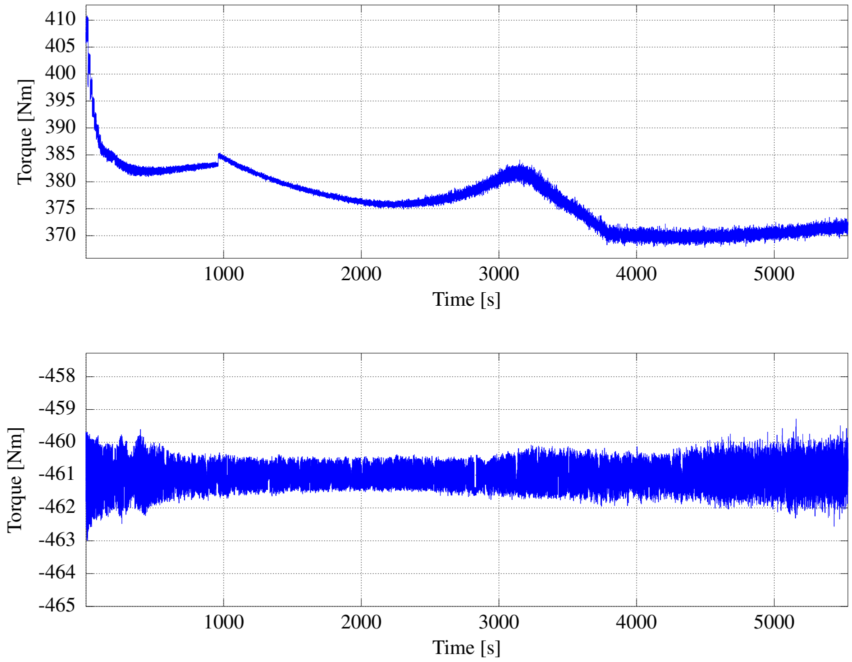

Figure 24. The motor and load torques for positive motor speed with -461 Nm load. Upper figure is for the motor side and lower figure for load side torque measurement. The motor has speed reference of 60 RPM at the time of 0 s. Ramp time is 15 s with ramp of 5 RPM.

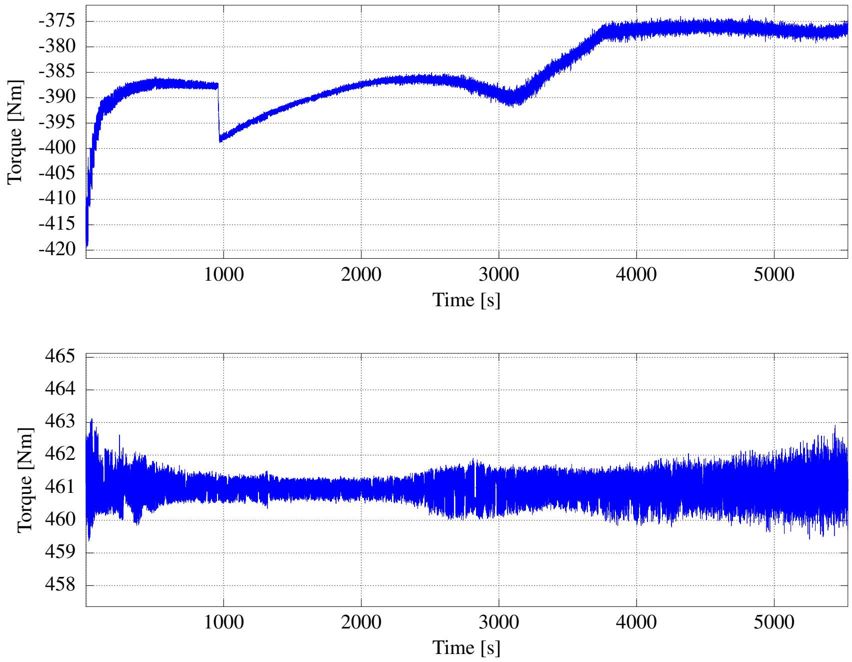

Figure 25. The motor and load torques for negative motor speed with 461 Nm load. Upper figure is for the motor side and lower figure for load side torque measurement. The motor has speed reference of -60 RPM at the time of 0 s. Ramp time is 15 s with ramp of -5 RPM.

6 DISCUSSION

The tests based on standard ISO 16750–2 are not presented. This is because there were changes in the hardware, and it is not efficient to do the tests based on standards with this version. Reason for this is, as those tests would be needed to done again with the fixed version.

6.1 The preliminary tests

The power on circuit had its problems. It needed multiple fixes in order to get it in working order and to start up and shutdown at 6 V. A new and more simpler circuit is done for the fixed version. The new circuit lessens the amount of the components and it allows the CPU do its calculations before a shutdown, as the circuit used in the testing did not.

The stop signals behaviour were correct in the RT. There was insignificant difference in low and high temperatures to stop signal voltage levels.

The measurements for the phase currents, and for DC-link and the enclosure voltage were done. For the phase currents a software change was needed as the LEMs that detect a phase current were changed. The hardware triggers operated as designed in phase overcurrents and DC-link overvoltage, and these triggers ended the modulation. Although the real phase overcurrents and DC-link overvoltage was not used, the trigger events were simulated by providing a voltage directly to the measurements in the PCB.

The short circuit current trigger is slightly lower than initially designed. The initial designed value was 5 A but in the measurements revealed it to be 4.26 A. However, this does not effect to the operation of the PM as it does not require that much current in normal operation.

The IGBT temperatures showed the correct temperature in RT and in low temperatures. The external PT100 measurements showed an offset of 5 °C higher than the IGBT temperatures or the environmental chamber temperature. At the high temperature test the IGBT temperatures are higher than the external PT100 measurements even though the software was not changed in between the tests. The excess of the supply current does not alone explain the behaviour of the IGBT temperature in this case. As the power only increased by 1.2 W. The effect of the high temperature needs to be investigated further. It is not efficient that the PM is shutdown as there is still room to heat up. The errors in voltage and current measurements due low or high temperatures are visible but not a reason to do a change in software or hardware.

The user IO analog inputs were tested in its whole measurement range from 0 V to 32 V. The difference at the maximum from supplied to measured voltage is 0.01 V. The difference is insignificant at voltages higher than 1 V as it is less than 1 % of the measured and supplied voltage. This error might also be from the supply voltage as it was not confirmed with a multimeter. The digital read and write for every user IO was tested. One of the user IOs was writing a digital value successfully while other was reading the digital value correctly.

The CAN bus with J1939 V2 protocol was tested by switching the enable signal TRUE and FALSE. This was done with CAN bus baud rate speeds of 100 kbits/s, 250 kbits/s, 500 kbits/s and 1000 kbits/s. There were no bus errors nor did the enable signal fail to switch states.

The resolver needs a better algorithm based to resolver tests. The ripple of the resolver is at the highest 3.3 % of the reference speed.

The sync link needs to be tested as soon as the software support for it has been accomplished.

6.2 Future Work

After the new version of the PM is manufactured, and the power on and flash bootloader are tested. After that the tests based on standard ISO 16750–2 can be done. Second thing to do is to perform the rests of the tests described in the standard ISO 16750. These tests include chemical, mechanical and climatic tests. There also exist other standards that the PM needs to fulfil. These standards are for example IEC 61800 which includes tests for safety and for EMC in adjustable speed electrical power drive systems.

7 CONCLUSIONS

The goal of the thesis was met in describing preliminary tests and performing the tests as these were to ensure the functionality of the PM. These tests produced data to be compare when tests based on standards are done. The tests based on standard ISO 16750–2 were described but not conducted in the time frame of the thesis.

The preliminary tests were done to ensure that the PM can do what it is designed to do. With exception the sync link test as the software support was not ready in time of this thesis. The preliminary tests produced data for fixing two hardware problems: power on circuitry and disconnecting CAN enable from the flash write. The hardware fixes of the PM has to be done before standardized tests.

The tests based on standard ISO 16750–2 were prepared but due the time limits of the thesis, these tests were not performed. These tests will be done as the whole ISO 16750 which are chemical, mechanical and climatic tests for electrical equipment in road vehicles. Other standards that the PM needs to pass are for example tests described in IEC 61800, tests for adjustable speed electrical power drive systems.

The standards confirm that the PM can be operated safely and it meets the requirements that are set by today’s industry. The PM can be used any application that is in its power range but it is mainly designed for drive drains for mobile work machines and marine vessels. These applications are today mostly still operated with fossil fuels but the electrification of these is inevitable.

Fossil fuels will some day be depleted, an alternative way to produce a force to propel road vehicles, work machines and marine vessels has to done. This has already begun due political shift to the cleaner environment. Technological advancement in power electronics and in energy storage have made the electrification possible and cost-effective. There is still a long way until the mankind is able to end the usage of fossil fuels, but that day is ahead of us.

REFERENCES

[1] International Electrotechnical Commissionn. You & The IEC - Your perspective, 2016. [online]. Available: http://www.iec.ch/perspectives/. [Accessed: January 8, 2016].

[2] The International Organization for Standardization. Standards, 2016. [online]. Available: http://www.iso.org/iso/home/standards.htm. [Accessed: January 8, 2016].

[3] Suomen standarditoimistoliitto SFS RY. *Standardit ja standardisointi*. 8th edition, 2013. ISBN 978-952-242-166-1.

[4] Deutsches Institut für Normung. DIN and our partners, 2016. [online]. Available: http://www.din.de/en/din-and-our-partners. [Accessed: January 8, 2016].

[5] S. D'Agostino. The electric car. *IEEE Potentials*.

[6] M. Guarnieri. Looking Back to Electric Cars. *HISTory of ELectro-technology CONference (HISTELCON), 2012 Third IEEE.*

[7] E. Hesla. Electric Propulsion [History]. *IEEE Industry applications magazine, July 2009.*

[8] SignalTrend Inc. Historical Oil Prices, 2015. [online]. Available: http://www.forecast-chart.com/chart-crude-oil.html. [Accessed: February 25, 2016].

[9] Nasdaq. Nasdaq, price of crude oil, 2016. [online]. Available: http://www.nasdaq.com/markets/crude-oil.aspx?timeframe=10y. [Accessed: February 24, 2016].

[10] Enerdata. Global energy statistical yearbook 2015, 2015. [online]. Available: https://yearbook.enerdata.net/. [Accessed: February 24, 2016].

[11] European Parliament. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*.

[12] P. Mindl Z. Ĉeȓovsкŕ. Hybrid Electric Cars, Combustion Engine driven cars and their Impact on Environment. *Power Electronics, Electrical Drives, Automation and Motion, 2008.*

[13] M. S. Whittingham. History, Evolution, and Future Status of Energy Storage. *Proceedings of the IEEE, vol. 100, May 13th, 2012.*

[14] J. Dixon. Energy storage for electric vehicles. *Industrial Technology (ICIT), 2010 IEEE International Conference on 14-17 March 2010.*

[15] F.G. Rieck H.C. Righolt. Energy chain and efficiency in urban traffic for ICE and EV. *EVS27 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium.*

[16] B. K. Bose. Global Energy Scenario and Impact of Power Electronics in 21st Century. *IEEE Transactions on industrial electronics, vol. 60 no. 7, July 2013.*

[17] B. K. Bose. Power Electronics and Motor Drives Recent Progress and Perspective. *IEEE Transactions on Industrial Electronics, vol. 56, no. 2, February 2009.*

[18] B. K. Bose. Power Electronics - Historical Perspective and My Experience. *IEEE Industry Applications magazine, Mar | Apr 2014.*

[19] N. Mohan, T. M. Underland, and W. P. Robbins. *Power Electronics - Converters, Applications and Design.* John Wiley & Sons, Inc, 3rd edition, 2003. ISBN 0-471-42908-2.

[20] W. Wu, J. Ji, F. Blaabjerg. Aalborg Inverter-A New Type of ”Buck in Buck, Boost in Boost” Grid-Tied Inverter. *IEEE Transactions on power electronics, vol. 30, no. 9, September 2015.*

[21] M. Salo, H. Tuusa. A Vector-Controlled PWM Current-Source-Inverter-Fed Induction Motor Drive With a New Stator Current Control Method. *IEEE Transactions on industrial electronics, vol. 52, no. 2, April 2005.*

[22] M. Chomat, L. Schreier, J. Bendl. Control of active front-end rectifier under unbalanced voltage supply and dc-link pulsations. *2011 IEEE International Electric Machines & Drives Conference (IEMDC).*

[23] A. Ndokaj, A. Di Napoli. Active Front End in Precence of Voltage Notches. *Clean Electrical Power (ICCEP), 2015 International Conference.*

[24] C.-C. Hou, P.-T Cheng. Experimental Verification of the Active Front-End Converters Dynamic Model and Control Designs. *IEEE Transactions on power electronics, vol. 26, no. 4, April 2011.*

[25] S. Leng, I.-Y. Chung, W. Liu, D. Carters. Reconfigurable Active Front-End of Adjustable Speed Drives for Power Quality Improvement. *Power & Energy Society General Meeting, 2009. PES ’09. IEEE.*

[26] Visedo Oy. PowerMASTER M-frame Liquid cooled heavy duty inverter, 2016. [online]. Available: http://www.visedo.com/sites/default/files/downloads/visedo_powermaster_m-frame_datasheet_r1215.pdf. [Accessed: January 12, 2016].

[27] The International Organization for Standardization. ISO 16750-1 Road vehicles - Environmental conditions and testing for electrical equipment and electronic equipment - General, 2006.

[28] The International Organization for Standardization. ISO 16750-4 Road vehicles - Environmental conditions and testing for electrical equipment and electronic equipment - Climatic loads, 2010.

[29] The International Organization for Standardization. ISO 16750-2 Road vehicles - Environmental conditions and testing for electrical equipment and electronic equipment - Electrical loads, 2010.

[30] R. Murayama W. Sriratana. Application of Hall Effect Sensor: A Study on the Influences of Sensor Placement. *Industrial Electronics (ISIE), 2013 IEEE International Symposium*.

[31] LEM. Isolated current and voltage transducers. [online]. Available: http://www.lem.com/images/stories/files/Products/1-3_applications/CH24101.pdf. [Accessed: March 21, 2016].

Appendix 1. Resolver test script

Resolver script main

```
require 'rubygems'
require 'vise_script'
require 'vise_script_utils'
require 'date'
require './Resolver-speed-ramp-test-methods.rb'
include ViseScript

begin
  ramp_time = 15;     # Ramp time in seconds
  meas_step = 10;     # Sample speed in hertz
  n_max = 1.0;      # Maximum speed, can be negative
  step_size = n_max/380;  # The size of the step
  load_ref_T = 461    # Load torque, automatically changes the according to sign of
      ↪ n_max

  client = ClientFactory.build;
  pdp_drive = client.get_device_by_name("Visedo Generic PDP Serial R");
  pdp_drive.connect.wait;
  pdp_drive_load = client.get_device_by_name("Visedo Generic PDP Serial M");
  pdp_drive_load.connect.wait;

  speed_measure_resolver(ramp_time, meas_step, step_size, n_max, pdp_drive,
      ↪ pdp_drive_load, load_ref_T)

  # If something interrupts the script, this is performed
  ensure
    pdp_drive.set_dataobject([10100, 1], false).wait; # Run command off, motor
    pdp_drive_load.set_dataobject([2000, 3], false).wait; # Enable off, load
    pdp_drive_load.set_dataobject([2000, 1], false).wait; # Run command off, load
end # Script end
```

Resolver script methods

```
# Speed ramp and save file based on the date and time
def speed_measure_resolver(ramp_time, meas_step, step_size, n_max, pdp_drive,
    ↪ pdp_drive_load, load_ref_T)
  n, n_ref, schedule, scheduler, file, start_time = speed_measure_resolver_init(
      ↪ step_size, n_max, load_ref_T, pdp_drive, pdp_drive_load);

  n.times do |time|
    schedule.append(time*ramp_time) do
      pdp_drive.set_dataobject([10100, 4], n_ref).wait; # speed reference
      puts "####################################################";
      puts "Running with speed reference #{1900*pdp_drive.get_dataobject([10100, 4])}
          ↪ RPM. Encoder speed #{(1900*pdp_drive.get_dataobject([7001, 1005])).round(0)
          ↪ } RPM."
      puts "Motor temperatures: R side #{pdp_drive.get_dataobject([8001, 1]).round(1)}
          ↪ and M side #{pdp_drive_load.get_dataobject([8001, 1]).round(1)}.";
      puts "Inverters junction temperature: R side #{pdp_drive.get_dataobject([8002,
          ↪ 10071]).round(1)}, #{pdp_drive.get_dataobject([8002, 10072]).round(1)} and
          ↪ #{pdp_drive.get_dataobject([8002, 10073]).round(1)}, and M side #{
          ↪ pdp_drive_load.get_dataobject([2000, 130]).round(1)}.\n";
      n_ref = n_ref + n_max/n;
    end
  end
  (n*meas_step*ramp_time).times do |time|     # number of measurements
```

(continues)

Appendix 1. (continued)

```ruby
    schedule.append(time/meas_step.to_f) do   # time between measurements
      file.write "#{pdp_drive.get_dataobject([10100, 4])}, #{pdp_drive.get_dataobject([10002, 13])}, #{pdp_drive.get_dataobject([10002, 16])}, #{pdp_drive_load.get_dataobject([10002, 16])}, #{pdp_drive_load.get_dataobject([10002, 13])}, #{(Time.now.to_f - start_time).round(2)}\n";
    end
  end

  schedule.sort!;
  scheduler.schedule = schedule;
  scheduler.start;
  file.close;

  #Load turn off
  pdp_drive_load.set_dataobject([2000, 3], false).wait; # Enable off
  pdp_drive_load.set_dataobject([2000, 1], false).wait; # Run command off
  puts "Load stop.";

  # Motor turn off;
  pdp_drive.set_dataobject([10100, 1], false).wait; # Run command off
  puts "Motor stop after #{(((Time.now.to_f - start_time).round(1))/60.0).round(2)} minutes";
end
# Initialization for the test parameters and save file
def speed_measure_resolver_init(step_size, n_max, load_ref_T, pdp_drive, pdp_drive_load)
  n_ref = step_size;
  n = (n_max/n_ref).to_i;

  # Automatically changes the direction of torque
  if n_ref > 0
    load_ref_T = -load_ref_T;
  end

  # for load_ref_T larger than 10Nm, step start from 60 RPM
  if load_ref_T > 10 || load_ref_T < -10
    n = n-58/2;
    if n_ref < 0
      n_ref = -60/1900.0;
    else
      n_ref = 60/1900.0;
    end
  end

  pdp_drive.set_dataobject([10100, 4], n_ref).wait;     # speed reference
  pdp_drive_load.set_dataobject([2000, 6], load_ref_T).wait;  # Torque reference for load

  pdp_drive.set_dataobject([10100, 1], true).wait; # Run command on, motor

  pdp_drive_load.set_dataobject([2000, 1], true).wait; # Run command on, load
  pdp_drive_load.set_dataobject([2000, 3], true).wait; # Enable command on, load
  puts "Load torque: #{pdp_drive_load.get_dataobject([2000, 6])}, n_ref: #{n_ref*1900}, n_max: #{n_max}\n"

  sleep(5);

  file_name = "#{load_ref_T}-#{Time.now.strftime(’%Y-%m-%d-%H-%M-%S’)}.txt"; # Saved file name
```

(continues)

Appendix 1. (continued)

```ruby
  file = File.open("#{file_name}", "w");
  file.puts "Motor speed reference, Motor speed encoder, Torque, Torque load, Load side speed encoder 2000 rpm, Time"
  start_time = Time.now.to_f;

  schedule = Utils::Schedule.new;
  scheduler = Utils::Scheduler.new;

  return n, n_ref, schedule, scheduler, file, start_time;
end
```