USER'S MANUAL

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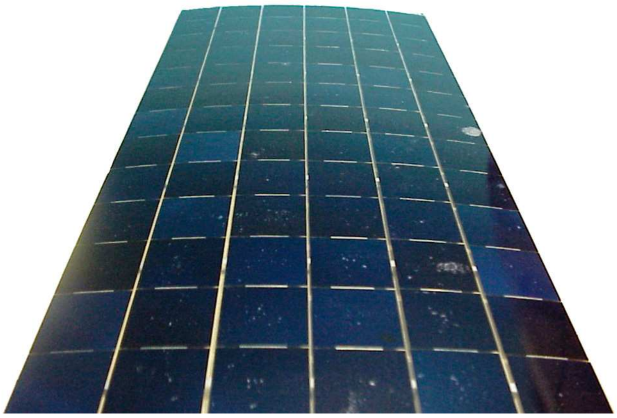
1- INTRODUCTION

In a more-or–less near future, renewable, possibly inexhaustible energy sources like solar energy, will become indispensable. Parallel to the efforts to raise the efficiency of photovoltaic cells, the further components in the solar energy producing process have to be improved.

The *MPPT New Generation* is a top-rate performance voltage converter. Its typical application range are high-efficiency stand-alone power supplies, as e.g. solar vehicles.

Within the specified input range, the *MPPT New Generation* gets a maximum power from a time-variant source, and converts it to the desired output voltage level with an efficiency up to 99%. The *MPPT New Generation* has been developed for the use in Australia's outback. Therefore, it's extremely tough and reliable.



1.1 - QUICK START / POWER UP THE MPPT FOR THE FIRST TIME

- Connect at least 36V on the input (input voltage)
- Leave the output open
- The MPPT starts up
- The output is precharged to approx. 3/4 of Uoutmin (see chapter 4.9)
- If you are using CAN, you can get the mppt's status information like actual mppt state, Uin, Uout, Iin and the boards temperature (see chapter 5)
- Connect your DC-Bus to the output (at least Uoutmin as specified in the order form)
- The MPPT starts tracking

2 - HARDWARE OVERVIEW

The high level design of the Maximum Power Point Tracker *MPPT New Generation* is shown in Figure 2.1. The *MPPT New Generation* is designed for disruption free stand-alone use. The CAN module provides transmission and reception of CAN messages.

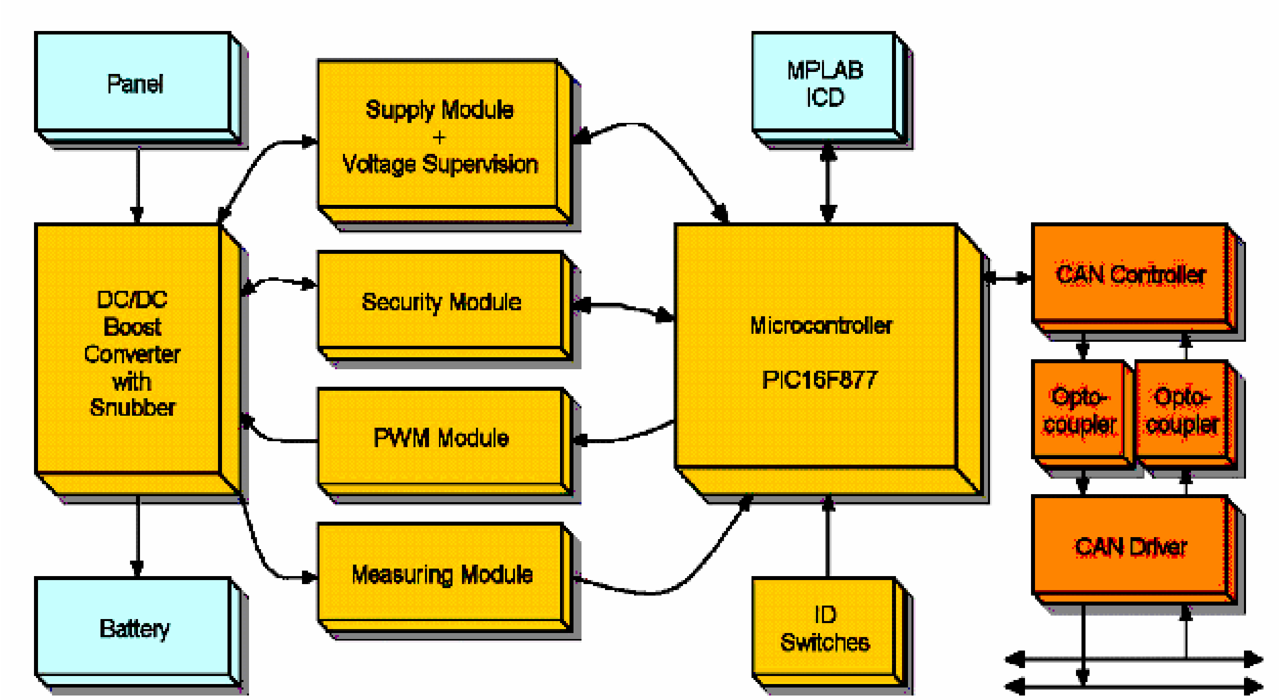


Figure 2.1: Block diagram of the *MPPT New Generation* board

2.1 - DC/DC CONVERTER WITH ACTIVE SNUBBER

The interface between the panels and the batteries is a conventional DC/DC Boost Converter with an active Snubber. The Active Snubber Technology (AST) combined with high efficiency components, increase the efficiency of the whole system up to 99% over a very large power range (see chapter: *4.2 - Functional Description*).

2.2 - POWER CONNECTOR

Only one connector is required to tap the *MPPT new generation* board. So, an error, due to a wrong connection, is no longer possible. One single connector means higher security. The panels and batteries can be directly connected to the *MPPT New Generation* board. The CAN signals pass over a separate connector (see chapter: *5 - Communication via CAN Bus*).

2.3 - Supply Module, Voltage Supervision and Security Module

The supply module is realized using a Flyback Converter. The two supply voltages, +15V and +5V are supervised by a Voltage Monitoring IC. Since an output without load is prohibited for boost converters, a "no charge" protection is implemented in the security module to eliminate this danger. A thermal shutdown protects the entire Boost Converter.

2.4 - PWM Module

Three Pulse Width Modulation (PWM) signals are required to command the Boost Converter with AST (see chapter: *4.2 - Functional Description* and *4.3 - Generation and Timing of the Control Signals*).

2.5 - Measuring Module

Five values are measured by the system: Input current, input voltage, output voltage, cooler temperature and ambient temperature. Current measurement is performed by a shunt and an operation amplifier. The three voltages are simply divided by an adapted voltage divisor (see chapter: *4.6 - Current and Voltage Measuring*). Finally, the two temperatures are measured with two Positive Temperature Coefficient (PTC) Resistors.

2.6 - Microcontroller

The PIC16F877 microcontroller from Microchip is in the core of the *MPPT New Generation* board. This is an 8 bit CMOS Flash Microcontroller with 8 A/D inputs. Its clock rate is 20MHz, which corresponds to 5 million instructions per second. The PIC uses the Serial Peripheral Interface (SPI) to communicate with the peripheral CAN controller.

2.7 - In-Circuit Serial Programming Tools

The MPLAB-ICD 2 (In-Circuit Debugger) is a tool, which simplifies the code development and hardware debugging process. The ICD interface allows the PIC16F877 device to be reprogrammed after the board has been manufactured, via the 5 pin header. So, software changes can be updated very easily. For additional information on In-Circuit Serial Programming please refer to the Microchip In-Circuit Serial Programming Guide. (The ICD is not included in the *MPPT New Generation* pack)

2.8 - CAN-Interface

The MCP2510 CAN controller is the core of the CAN-interface. It handles all transmission and reception message packets via the CAN bus. The MCP2510 CAN controller communicates with the microcontroller over the Serial Peripheral Interface (SPI). The MCP2510 handles low level protocols (see chapter: *5 - Communication via CAN Bus*).
The CAN-interface has to be externally supplied (see chapter: *4.10 - CAN-Interface Supply*).

3 - SOFTWARE OVERVIEW

3.1 – ID STRUCTURE FOR TRANSMISSION VIA CAN BUS

3.1.1 - General ID Structure

The ID structure used by the *MPPT New Generation* is determined by the settings of the DIP-switches at a power start-up or after a manual reset. Changing the DIP switches while the *MPPT New Generation* is running, has no effect on the ID structure.

3.1.2 -Transmit ID Structure

The *MPPT New Generation* transmits a CAN message up on reception of a CAN message with a defined ID (see chapter: *5 - Communication via CAN Bus*). The MPPT message contains seven data bytes. 10 bits are representing the input current, 10 bits the input voltage, 10 bits the output voltage, 8 bits the ambient temperature and 4 bits for status information. The DIP switch settings equal the tracker ID and are assigned to the Base Transmit ID. To assure that each data source has its own unique ID, each DIP switch has to be set differently. (see appendix : *A - Technical Specifications*)

4 - TOPICS IN DETAIL

4.1 - HOW DOES THE MAXIMUM POWER POINT TRACKER WORK?

The MPP Tracker is based on a simple boost converter. Therefore, the output voltage must never drop below the input voltage level. Within the specified I/O voltages, any voltage transmission factor is feasible.
Unlike usual power sources the maximum power point of solar generators is time variant. If sunshine drops, the maximum generated power drops, as well. If the ambient temperature rises, the maximum generated power decreases.

The battery level (or even motor voltage level) also changes, depending on its charge state.

The MPPT monitors input power continuously (see chapter: *4.6 - Current and Voltage Measuring*) consisting of the actual voltage transmission factor and two further neighboring points on the power curve. At some point, the voltage transmission factor is going to be changed corresponding to an eventual new global MPP at one of these neighboring points.

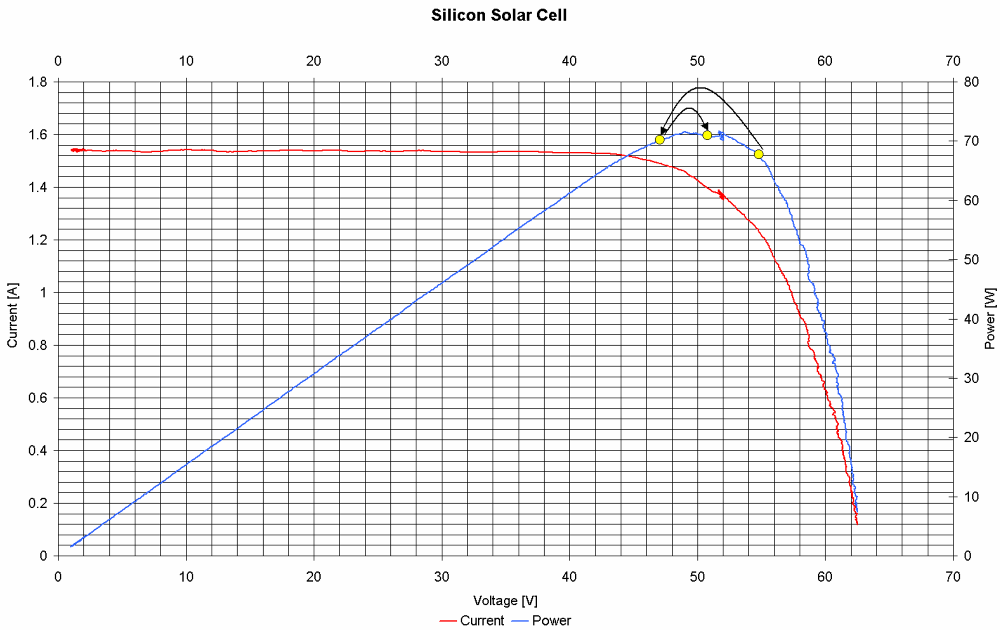


Figure 4.1: Tracking loop

Special algorithms guarantee liberation from a local MPP. The tracking step size influences the tracking accuracy and the tracking speed in inverse proportion. The period of a tracking cycle determines the tracking speed, as well. This does not have to be very fast. The fluctuation of the MPP in response to most ambient change is slow.

In principle, the output voltage could also be kept constant for intermediate circuit applications, using another software algorithm.

4.2 - FUNCTIONAL DESCRIPTION

To simplify the analysis, assuming the input inductor is large enough, the main inductor current I_L can be considered as constant in one switching cycle. Similarly, the output voltage can also be treated as a constant voltage U_{out}. The operation process in a single switching cycle could be separated into ten stages as shown in Fig. 4.3-4.13. The relevant waveforms are shown in Fig. 4.2.

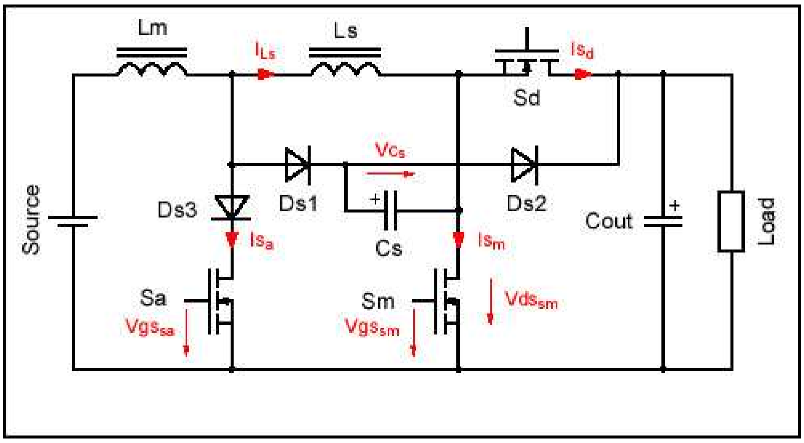


Figure 4.1: Boost Converter using AST

S_M: Main Switch
S_A: Auxiliary Switch
S_D: High-Side Switch (acts as a diode)
L_M: Main Inductance
L_S: Snubber Inductance, $L_M >> L_S$

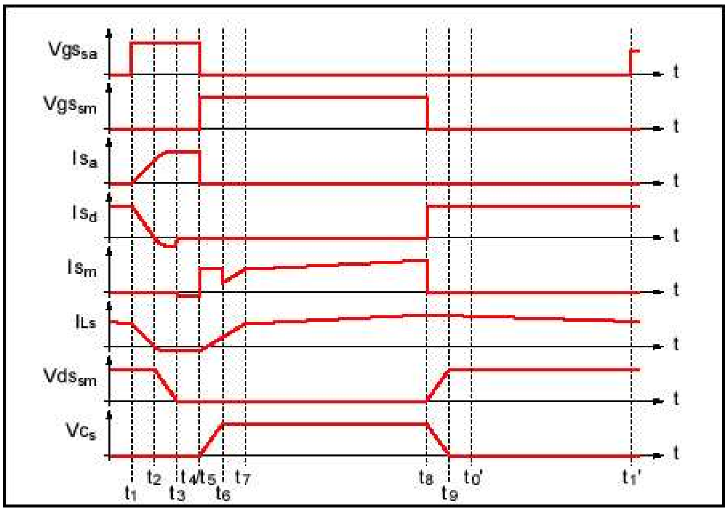


Figure 4.2: Signal Overview

Stage A ($t_0 \rightarrow t_1$): S_A and S_M are off, S_D is on. C_S voltage is zero, and the instantaneous current in the snubber coil $i_{Ls} = I_L$.

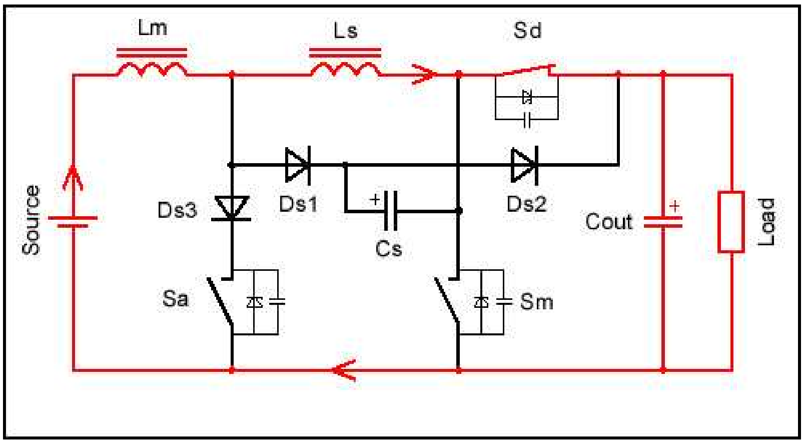


Figure 4.3: Stage A

Stage B ($t_1 \rightarrow t_2$): S_A is turned on, and i_{Ls} decreases linearly, while the current through S_A increases gradually. S_A is switched on with zero current. At t_2, i_{Ls} falls to zero; S_D looses current and is therefore switched off softly. Meanwhile, S_A current reaches I_L. The time interval t_2-t_1 is given by

$$\boxed{t_2 - t_1 = \frac{I_L \cdot L_S}{U_{out}}} \quad [1]$$

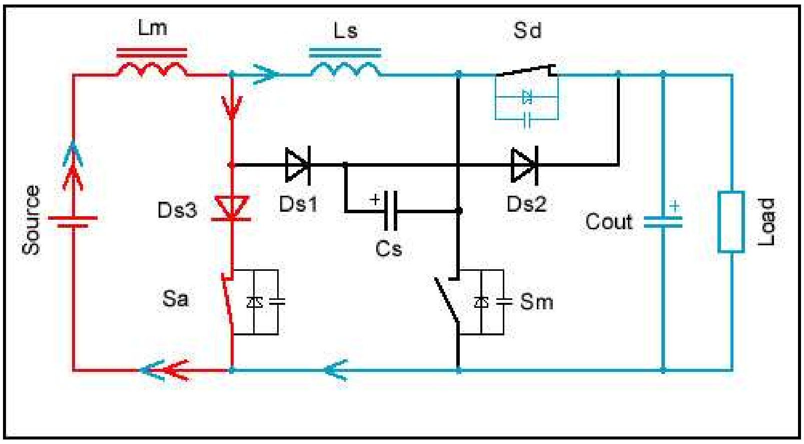


Figure 4.4: Stage B

Stage C ($t_2 \rightarrow t_3$): S_M junction capacitor discharges and S_D junction capacitor charges resonantly through L_S and S_A. U_{DS} of S_A rapidly falls to zero at t_3.

$$\boxed{t_3 - t_2 = \frac{\pi}{2}\sqrt{L_S(C_{SM} + C_{SD})}} \quad [2]$$

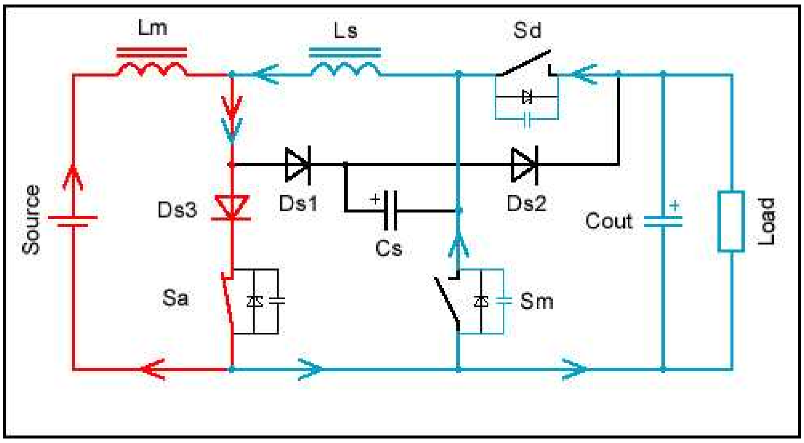


Figure 4.5 : Stage C

Stage D ($t_3 \rightarrow t_4$): Thereafter, the antiparallel diode of S_M starts to conduct a reverse current flowing through L_S until t_4, S_M is turned on with zero voltage.

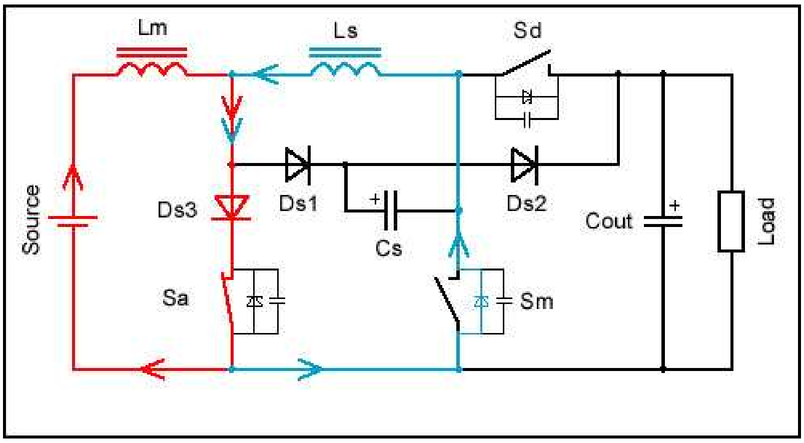


Figure 4.6: Stage D

Stage E ($t_4 \rightarrow t_5$): During a few hundred ns, S_A and S_M are both on, until S_A is turned off at t_5. This period has to be kept short to prevent unnecessary conduction losses.

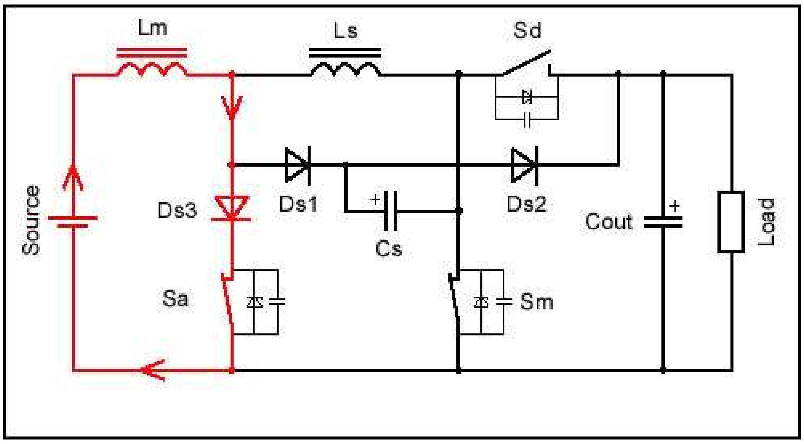


Figure 4.7: Stage E

Stage F ($t_5 \rightarrow t_6$): When S_A is turned off, I_L charges C_S through D_{S1} and S_M. C_S voltage rises gradually, enabling S_A to switch off with zero voltage. At t_6, U_{Cs} is clamped at U_{out}, because D_{S2} starts to conduct.

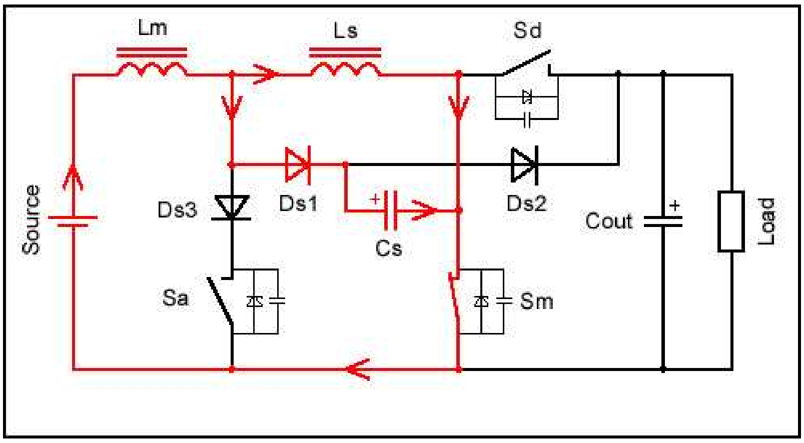


Figure 4.8: Stage F

Stage G ($t_6 \rightarrow t_7$): i_{Ls} rises positively. Part of I_L injects into the load through D_{S1} and D_{S2} and falls linearly. At t_7, i_{Ls} equals I_L, as soon as current in D_{S1} and D_{S2} has fallen to zero. D_{S1} and D_{S2} are turned off with soft commutation.

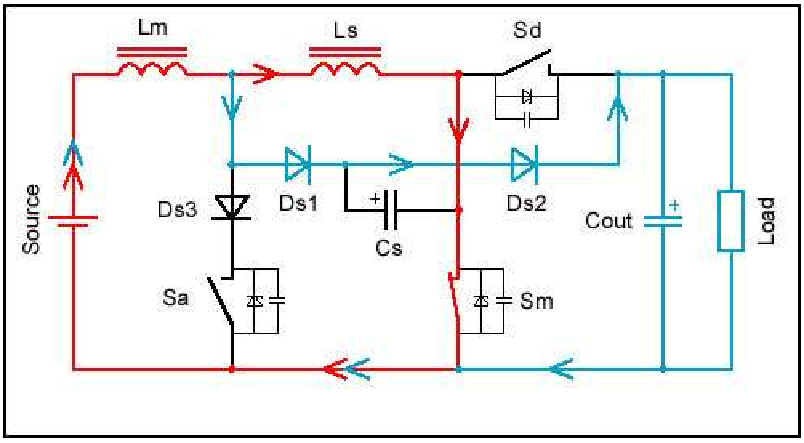


Figure 4.9: Stage G

Stage H ($t_7 \rightarrow t_8$): During this period, S_M conducts I_L as the conventional boost converter.

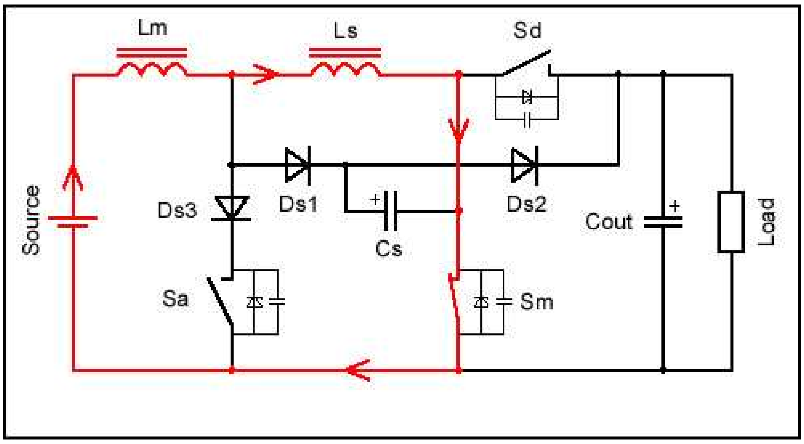


Figure 4.10: Stage H

Stage I ($t_8 \rightarrow t_9$): At t_8, S_M gets turned off. I_L discharges C_S in reverse direction through D_{S2}, and U_{DS} of S_M rises linearly. S_M is therefore turned off with zero voltage. At t_9, C_S voltage becomes zero, and the diode of the S_D FET starts to conduct.

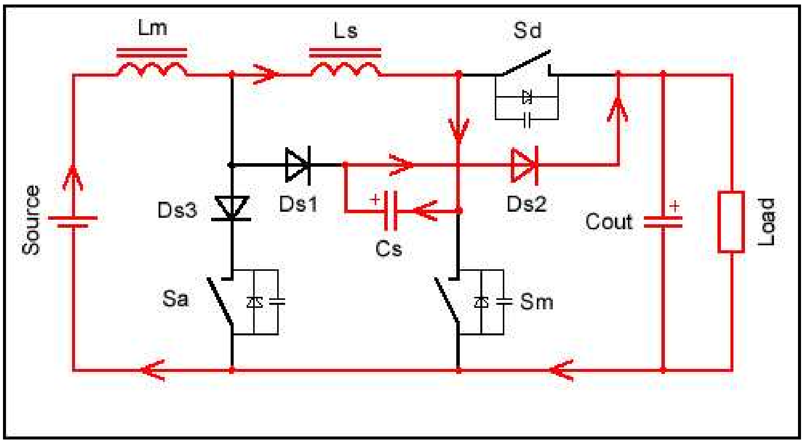


Figure 4.11 : Stage I

Stage J ($t_9 \rightarrow t_0$'): A short time later S_D is turned on with zero voltage. The use of S_D instead of a diode as is common in boost converters, considerably decreases conduction losses.

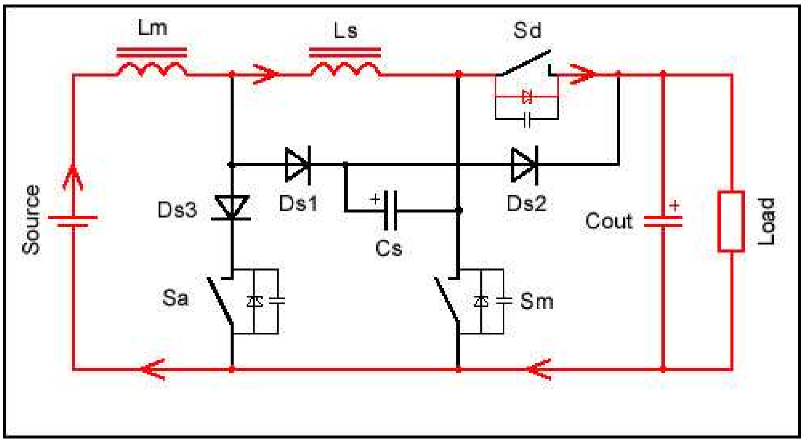


Figure 4.12: Stage J

Stage A' (t_0'→t_1'): During this period, I_L flows to the load through S_D. The operation is the same as that of a conventional boost converter. At t_1, S_A is turned on once more to start the next switching cycle.

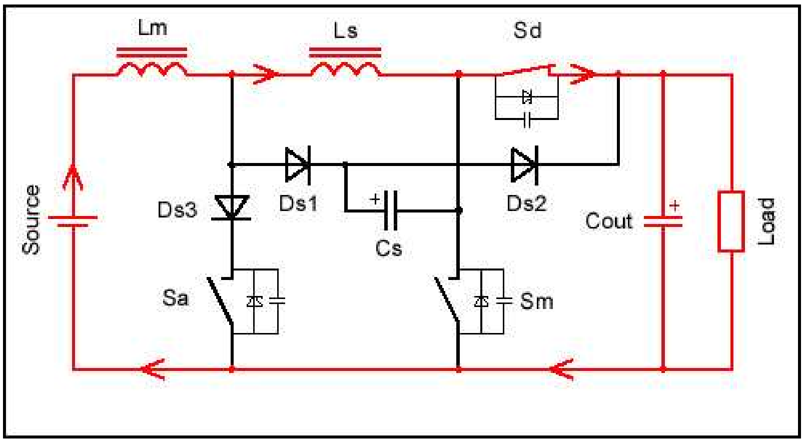


Figure 4.13: Stage A'

Obviously, both the main switch S_M and the auxiliary switch S_A in the proposed circuit are switched under zero-current and/or zero-voltage condition, and all diodes are soft commuted, to avoid increasing the voltage or current stress. D_{S3} prevents a reverse current through S_A at any time.

The voltage conversion factor is approximately given by

$$\boxed{\frac{U_{out}}{U_{in}} = \frac{1}{f \cdot (t_8 \rightarrow t_1')}} \qquad [3]$$

where f is the commutation frequency (see appendix: *A - Technical Specifications*).

4.3 - Generation and Timing of the Control Signals

The generation of the control signals is made by a separate PWM timing unit on the control board. The three used control signals are:

U_{SA}: Gate-source voltage of the auxiliary snubber switch (see figure 4.14 and 15, signal 1)
U_{SM}: Gate-source voltage of the main boost converter switch (see figure 4.14 and 15, signal 2)
U_{SD}: Gate-source voltage of the high-side boost converter switch (see figure 4.14 and 15, signal 3)

The microcontroller provides two basic signals; commutation frequency consisting of t_{ON} and t_{OFF}, and the auxiliary pulse t_{PAUX} for the snubber. The timing unit modifies these signals as follows:

- U_{SM} and U_{SA} overlap, $t_{AM} \cong$ 70ns, to assure a correct function of the snubber (see figure 4.14, signals A and B)
- Dead time between U_{SM} and U_{SD}, $t_{MD}>$ 200ns, to prevent a short-circuit of the output (see figure 4.15, signals B and C)
- U_{SA} and U_{SD} overlap, $t_{AD} \cong$ 100ns (see figure 4.14, signals A and C)

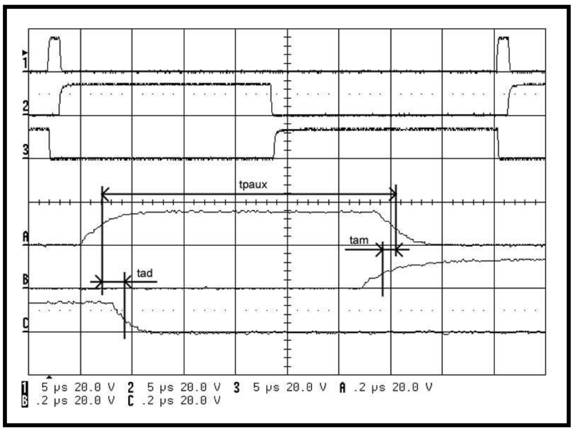


Figure 4.14: Control Signals

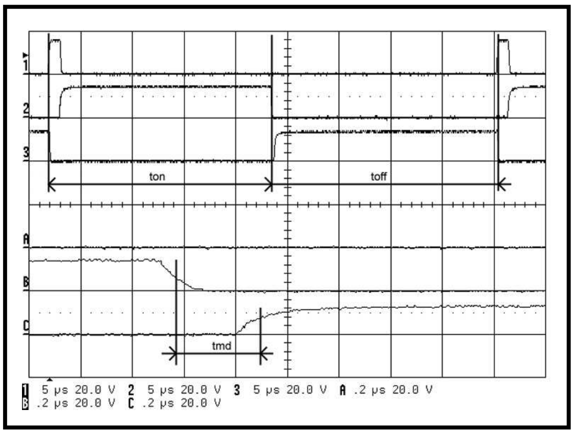


Figure 4.15: Dead Time

The auxiliary pulse has a fixed width, corresponding to the longest discharge, respectively demagnetization time that is possible (see formula *[1]* and *[2]*). The commutation frequency is fixed, as well. Its value is the result of a lengthy efficiency optimization process.

4.4 - LOAD LOSS

If the output load of any boost converter gets lost, the output voltage rises immediately and will destroy the output smoothing capacitor. Therefore a comparator circuit shuts the conversion down, as soon as the voltage exceeds a fixed voltage limit. This method is faster and more reliable than a shutdown by normal output voltage measurement over the microcontroller. The shutdown limit is guaranteed within the specified range.

4.5 - GENERATION AND SUPERVISION OF THE ON-BOARD SUPPLY

Two supplies are realized:

- 5V, 40mA, PIC, PWM Timing Circuit, Voltage Control
- 15V, 30mA, Gate Voltage

Both are generated by a flyback converter with two outputs. The 5V output is fed back to the Si9104 Switchmode Regulator for regulation within the specified range. The 15V supply is unregulated and fluctuates with the different loads. It is fed back to the converter IC. The latter is supplied by this feed back as soon the 15V supply exceeds 10V after a start-up. In the first phase of the start-up, the Switchmode Regulator is directly supplied from the MPPT input.
To be able to provide the on-board supply power, the MPPT input voltage must exceed 36V. What is more, the flyback converter has an approximate efficiency of 50%.

The two on-board supplies are supervised with a MC33161 Universal Voltage Monitor.
If the 5V logic supply drops under 4.75V or has not reached this limit yet, a hardware reset is performed. This guarantees a well defined start-up behavior of the entire MPPT.
If the unstabilized 15V gate voltage supply falls under 11V, the conversion gets shut down, to assure a correct commutation of all FETs. On the other hand, the 15V supply is clamped at an upper limit of 18V by a Zener diode.

4.6 - Current and Voltage Measuring

Correct monitoring of the input voltage and current is essential for an accurate location seeking and tracking of the maximum power point MPP. The measure of the output voltage and battery detection provides important information on the load state (see chapters: *4.4 - Load Loss* and *4.9 - Battery Detection*).

The voltages are measured by a simple voltage divisor. All A/D converters have a range up to 4.1V.

The input current is measured by a precise shunt resistor of 10mΩ. Its voltage drop is amplified with an OPA343 single supply OpAmp.

The microcontroller calculates the present input power by multiplying the input current and input voltage. Inaccuracy of the voltage divisor resistors and shunt voltage drop amplification does not influence the accuracy of the MPP tracking, because they are linear errors.

The commutation of the main current path causes unpreventable distortions all over the converter. The measuring affect is fairly well reduced by 25Hz lowpass filtering of first order. However, this reduces the maximum tracking speed, as well, because faster change of current and voltage is no longer measurable.
In addition, the A/D acquisition is completely synchronized with the moments of commutation in the main circuit.

4.7 - Overheating Protection

An overheating of the semiconductors is, within the allowed domain, extremely improbable. Nevertheless, if the cooler overheats due to any thinkable reason, the converter would immediately shut down. The microprocessor itself has no influence on this event, but after the cooler has cooled down, it resets the overheat shutdown. This procedure can take a few minutes. Do not foreshorten this waiting time by switching off the *MPPT New Generation*!

4.8 – Start-Up and Restart

If there are more than 36 V_{DC} connected to the input and no voltage between the two reset inputs, the supply module begins to generate the needed on-board voltages, and the whole system will start up in a well defined state. This process is called start-up.
The user can enforce a shut-down of the converter by simply connecting Pin1 and 2 (use a simple switch) of the reset-connector (see appendix: *A - Technical Specifications*). The process is exactly the same: As soon as the reset inputs are released, a start-up is triggered.
The converter itself performs a program restart of the microcontroller, if supply drops below 4.75V (see chapter: *4.5 - Generation and Supervision of the On-Board Supply*).

4.9 - BATTERY DETECTION

The MPPT begins tracking upon detection of a Battery. Therefore, the output capacitor is considered empty at the start-up moment, due to its self-discharge. If a battery is connected to the output now, the capacitor short-circuits the battery and an electric arc will result.

To forestall this unpleasant event, a precharge function is available. The MPPT automatically precharge the output capacitor at the start-up to ¾ of the minimal end of discharge voltage. As soon as the output voltage reaches at least the minimal end of discharge voltage level the microcontroller starts with a “delta-test” to make sure a battery is connected. It turns the PWM on for a short period of time and compares the delta of the output voltage. If the delta is less than 0.6V, the microcontroller starts the tracking algorithm. If the delta is more than 0.6V the MPPT rests in the “no charge connected state” until the “delta-condition” is true.

4.10 - BATTERY END OF CHARGE LEVEL

If the battery reaches the end of charge voltage (as specified in the order form) the mppt stops tracking to prevent the battery from overcharging. As soon as the voltage drops again below the end of charge level, the mppt starts tracking again.

4.11 - CAN-INTERFACE SUPPLY

The CAN-driver circuit has to be powered externally by applying a positive voltage between CAN-Supply Voltage and CAN Ground pins on the connector (see appendix: *A - Technical Specifications*).

5 - COMMUNICATION VIA CAN BUS

5.1 - INTRODUCTION

Advances in data communications have created efficient methods for several devices to communicate using a minimum of system wires. The Controller Area Network (CAN) is one of these methods. CAN sends and receives message over a two wire CAN bus. The nodes broadcast their individual messages over the CAN bus, while the receivers are set-up to accept the message and anticipate an acknowledgment signal (ACK) indicating the receipt of a non-corrupted message. The protocol of the CAN has two states and the bits are either dominant (logic 0) or recessive (logic 1). The CAN communication protocol is a Carrier Sense Multiple Access with Collision Detection (CSMA/CD). That means if two nodes on the network start transmitting at the same time, the nodes will detect the collision and take appropriate action. A CRC field is present in the frame and is used by the receiving nodes to determine if transmission errors have occurred. The CAN protocol implements the two lower layers of the ISO (International Standards Organization) / OSI (Open Systems Interconnection) Reference Model represented in Figure 5.1.

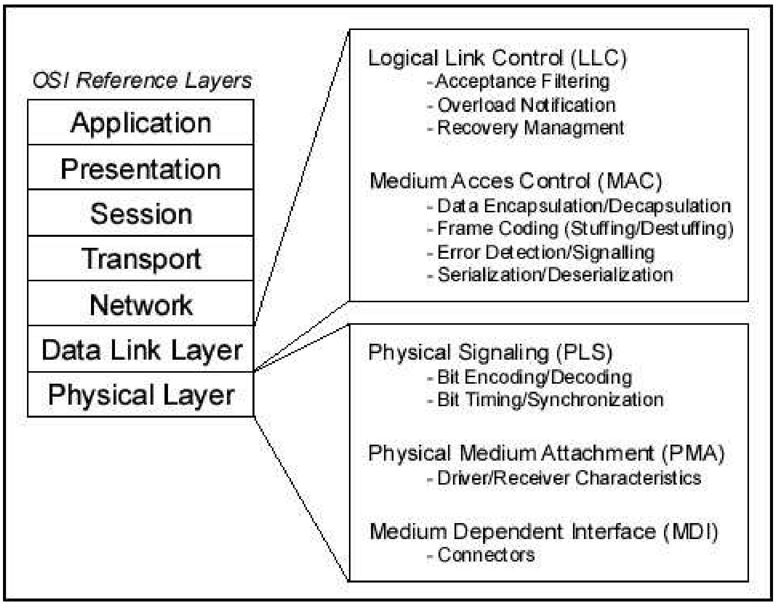


Figure 5.1: ISO/OSI Reference Model

5.2 - SYSTEM HIGHLIGHTS

- ✓ Implements Full CAN V2.0A and V2.0B
- ✓ Compatible with ISO 11898 (CAN High-Speed Applications)
- ✓ System with a independent CAN Controller and transceiver
- ✓ Standard and extended data frames
- ✓ Support of remote frames
- ✓ 2 full acceptance filters masks
- ✓ 6 full acceptance filters
- ✓ Programmable Bit Rate from 10kbit/s to 1Mbit/s
- ✓ Maximum Bus Length at 1Mbit/s: 30m
- ✓ Electromagnetic Interference Protection due to the differencial CAN bus
- ✓ Galvanic isolation of CAN bus
- ✓ Nominal Impedance of bus line: 120Ω (105Ω - 132Ω)

5.3 - IMPLEMENTED IN THIS VERSION

- ✓ Full CAN V2.0A
- ✓ ID standard
- ✓ Nominal Bit rate 125 kbit/s
- ✓ Bus terminated on MPPT (124Ω)

5.4 - RECOMMENDATIONS

These recommended DC parameters (see Figure 5.2) for bus line cables are suitable for ISO 11898 based networks. To minimize the voltage drop on long distances, the termination resistor should be higher than in the ISO 11898 standard.

Bus Length	Bus Cable: Length-Related Resistance	Bus Cable: Bus-Line Cross-Section	Termination Resistance	Maximum Baudrate
0 … 40 m	70 mΩ/m	0.25 mm^2 … 0.34 mm^2 AWG23, AWG22	124 Ω (1%)	1 Mbit/s at 40 m
40 … 300 m	< 60 mΩ/m	0.34 mm^2 … 0.6 mm^2 AWG22, AWG20	127 Ω (1%)	500 kbit/s at 100 m
300 … 600 m	< 40 mΩ/m	0.5 mm^2 … 0.6 mm^2 AWG20	150…300 Ω	100 kbit/s at 500 m
600 m … 1 km	< 26 mΩ/m	0.75 mm^2 … 0.8 mm^2 AWG18	150…300 Ω	50 kbit/s at 1 km

Figure 5.2: DC Characteristics

5.5 - CAN MESSAGE FRAME DESCRIPTION

The type of message used in this application is a standard data frame. Data frames consist of Arbitration Fields, Control Fields, Data Fields, CRC Fields, a 2 bit Acknowledge Field and an End of Frame.

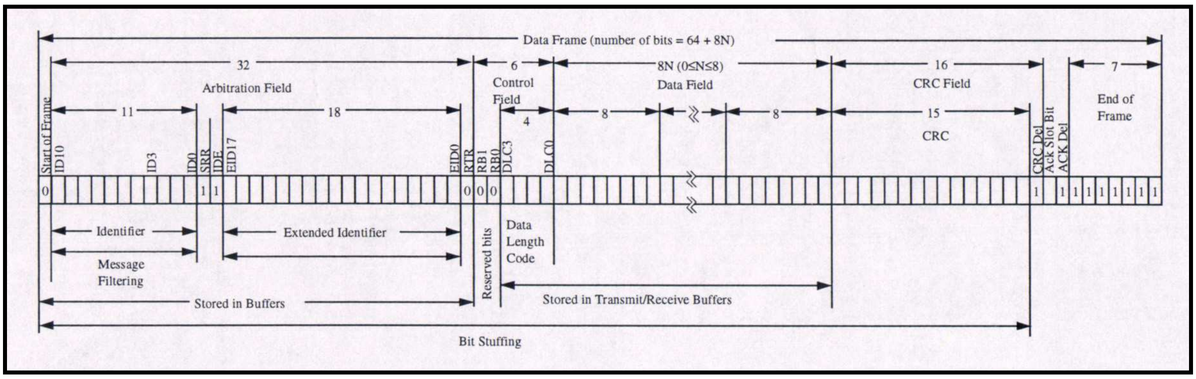


Figure 5.3: Standard Data Frame

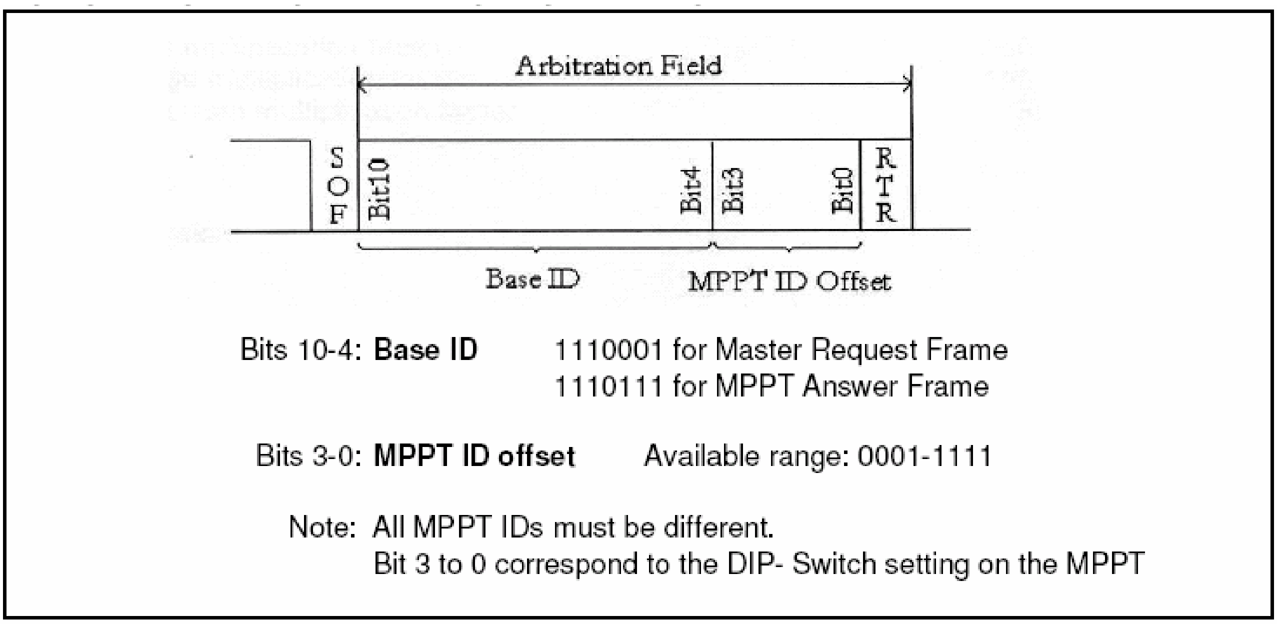
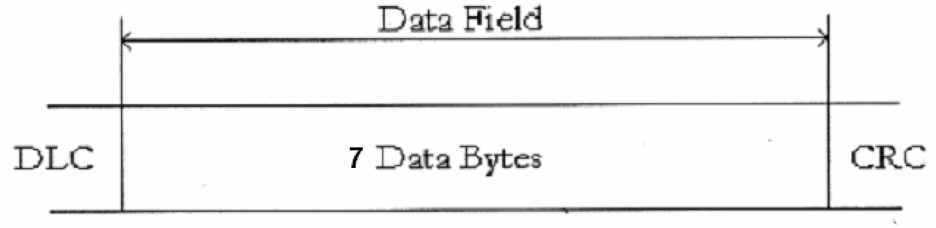


Figure 5.4: Structure of the Identifier Field



Name	Bit7	Bit6	Bit5	Bit4	Bit3	Bit2	Bit1	Bit0
BYTE1	BVLR	OVT	NOC	UNDV	x	x	MSB Uin*	
BYTE2	LSB Uin*							
BYTE3	x	x	x	x	x	x	MSB Iin*	
BYTE4	LSB Iin*							
BYTE5	x	x	x	x	x	x	MSB Uout*	
BYTE6	LSB Uout*							
BYTE7	T_{amb}[°C]**							

BVLR: Battery Voltage Level Reached Flag
0: $U_{out} < U_{outmax}$ 1: $U_{out} = U_{outmax}$

OVT: Overtemperatur Flag
0: $T_{cooler} < 95$ °C *** 1: $T_{cooler} \geq 95$ °C

NOC: No Charge Flag
0: Battery is connected 1: No Battery is connected

UNDV: Undervoltage Flag
0: $U_{in} > 26$ V 1: Uin ≤ 26 V

* Number of amperes or volts per LSB are client specific.
** Steps of 5 °C.
*** Once the OVT-Flag is set, there is a hysteresis of about 8 °C until the OVT-Flag is reseted

Figure 5.5: Structure of MPPT Answer Data Field

5.7 - CAN Id Determination

On the controller board of the MPPT is a DIP-Switch with 4 Positions.
The Layout of the DIP-Switch is seen on Figure 5.7

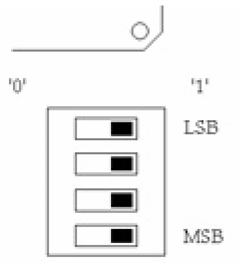
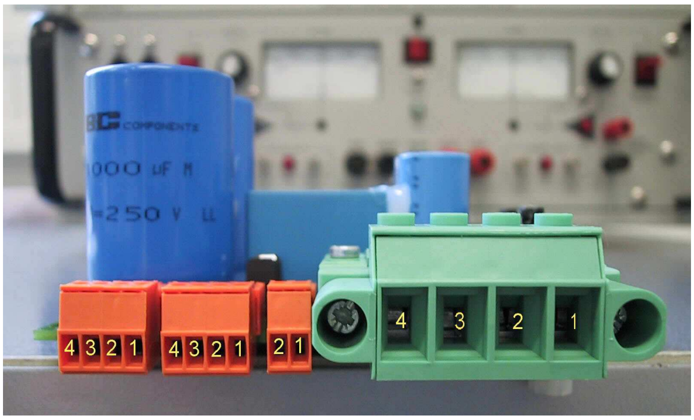
LSB	Bit 0 of MPPT CAN ID	
…	…	
MSB	Bit 3 of MPPT CAN ID	

Figure 5.7: DIP-Switch settings

APPENDIX A: TECHNICAL SPECIFICATIONS

Connection Table:

<table>
<tr><td>1
2
3
4</td><td>Panel minus
Panel Plus
Battery +
Battery -</td><td rowspan="4">

Connector Front side view:
Interface Connector (left) and Power Connector (right)</td></tr>
<tr><td>1
2
3
4</td><td>CAN In Ground****
CAN In Low****
CAN In High****
CAN In Supply Voltage****</td></tr>
<tr><td>1
2
3
4</td><td>CAN Out Ground****
CAN Out Low****
CAN Out High****
CAN Out Supply Voltage****</td></tr>
<tr><td>1
2</td><td>Shutdown +***
Shutdown -***</td></tr>
</table>

The Panel minus input must not be short-circuited to Power GND. Otherwise, no more panel current and power is measured.

****CAN voltages are galvanic separated from Power GND.
***By simply connecting Pin1 and 2 (use a simple switch, the Tracker is shut down). Drawback: There is no galvanic separation between the GND and the PowerGND, so use a switch for each tracker individually

LED SIGNALLING*

LED 1 (close to PIC)	LED 2 (PWM)	Description
on flashing flikering	off on on	Error state. At least one of the following conditions is true: -no battery connected -battery level reached -overtemperatur -undervoltage -tracking mode

* Use CAN to determine the exact status of the MPPT.

APPENDIX B: TYPICAL WAVEFORMS (MEASURED)

To give an idea of the real waveform to the reader, four representative waveforms have been measured. The drain-source voltage/current waveform of S_A, the voltage/current waveform of Ls, the voltage/current of L_M and the U_{DS} voltage of S_M and U_{DS} of S_D.

All waveforms are measured at a power of 200W with a conversion factor of 2 and an input voltage of 84V. The two first waveforms of each figure are U_{GS} of S_A (CH1) and S_M (CH2).

Legend
- Figure 6.1: CH3 : U of L_M; CH4 I of L_M
- Figure 6.2: CH3: U of L_S; CH4 I of L_S
- Figure 6.3: CH3: U_{DS} of S_M; CH4 U_{DS} of S_D
- Figure 6.4: CH3: U_{DS} of S_A; CH4 I_{DS} of S_A

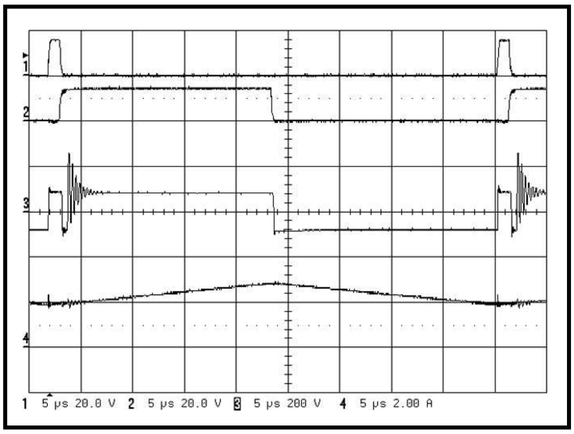


Figure 6.1: U and I of L_M

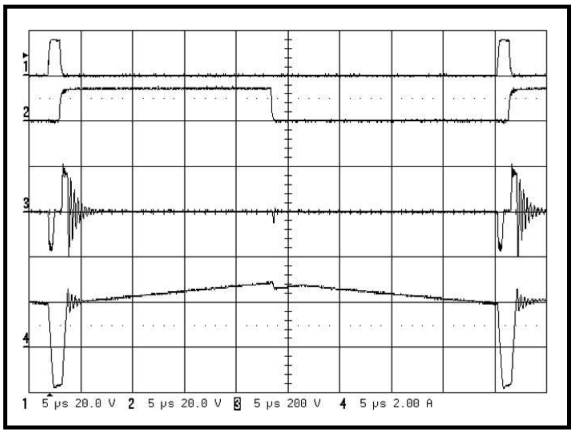


Figure 6.2: U and I of L_S

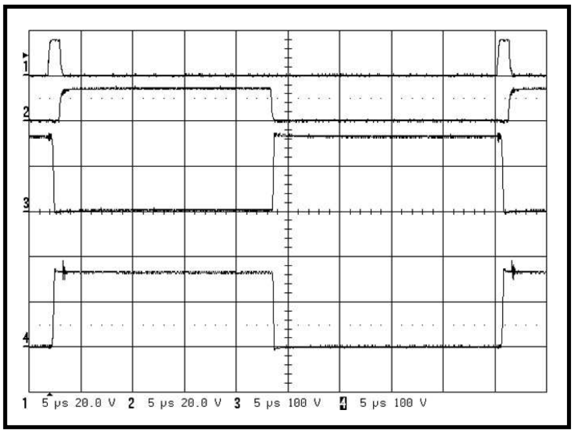


Figure 6.3: U_{DS} of S_M and S_D

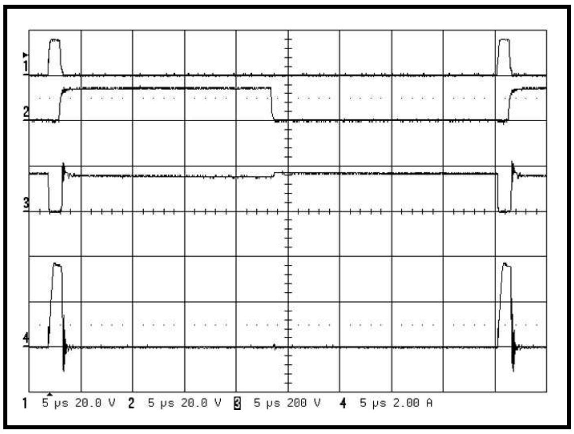


Figure 6.4: U_{DS} and I_{DS} of S_A