A distributed combined heat and power plant control unit

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A distributed combined heat and power plant control unit.

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Sammanfattning
Abstract

Today it is of great importance that we have a good supply of heat and electricity in all situations. For this reason ABB Powerman AB has designed a miniaturized distributed combined heat and power plant that can be run on different fuels that can easily be extracted from the environment, for example digester or landfill gas. Because of the small size and the possibility to select and change the type of fule the power plant can be placed almost anywhere. It produces both heat and electricity and has an efficiency of up to a bit more than 90%. To make the most out of the energy input there has to be a state of the art controller to control and supervise all parts of the power plant. This report describes the design work from idea all the way to a printed circuit board (PCB) of such a controller, including functional tests.

Nyckelord
Keywords

Combined heat and power plant, electronics design, control unit, microcontroller, galvanic isolation, PCB design.

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Linköping, December 16, 1997

Thomas Nilsson

Contents

Chapter 1
INTRODUCTION

1.1 Background

ABB Powerman AB in Linköping, a part of the ABB power generation group is a development company specialized in small, motor based combined heat and power (CHP) plants for distributed generation of heat and electrical power. The power plants are small units, about half a freight container in size. They can be placed almost anywhere and work unmanned. In most cases one wants them to work day and night all year without having to take any notice of them. As with most mechanical systems this is not an easy thing to achieve. With the telecommunication possibilities of today, however, maintenance can be minimized by having one single control centre to monitor, let us say all the CHP plants in one country via modem. This way a technician can be sent when needed, for ordinary scheduled service or when an event that calls for service occurs.

The power plant constitutes a complex combination of a gas fueled spark ignited engine, a synchronous 400V electrical generator, heat exchangers in both the exhaust and cooling systems as well as sensors, actuators and stepper motors to provide good control and supervision possibilities. In order to make all of these highly sophisticated components working together in the best and most efficient way possible as an entire unit, a state of the art control system is needed.

This report will describe the result of about one year of part time design work of such a controller unit.

1.2 Report Outline

Chapter 2 gives some general information about CHP plants and then discusses them from a comprehensive point of view, involving several interconnected CHP plants being part of a widely spread system of centrally supervised CHP networks.

The controller design is discussed in Chapter 3 where all the different modules of the controller has its own dedicated section in which it is thoroughly described.

Chapter 4 deals with all the inputs, outputs and signals that has to be controlled and measured.

In 4.6, the delicate problem of distribution of a galvanic isolated signal is discussed and an example of how to solve the problem is presented.

Chapter 2
COMBINED HEAT AND POWER PLANTS

2.1 CHP plants, what they are and how they work

When hearing the words ‘power plant’ most people usually think of nuclear reactors or huge fossil driven power plants that distribute heat and/or electricity to maybe hundreds of thousands of customers. ABB Powerman however, has developed a miniaturized combined heat and power (CHP) plant that causes little environmental strain by operating on natural gas, LPG, LNG or bio fuels such as digester gas, landfill gas or ethanol and having a high fuel efficiency to give a low CO_2 emission. The size of the CHP unit is as little as 2.4 x 1.2 x 2.4 m and with a weight of only 3600 kg a powerman CHP plant can be placed almost anywhere that you have access to any of the above fuels and have use for the power produced.

The prime mover in this CHP is an Otto engine from the car and truck industry that has been rebuilt by ABB Powerman for operation on the type of fuels mentioned above. The engine is hooked up with a synchronous generator for 400V electrical power generation and the heat evolved in the exhaustion- and cooling systems is taken care of by heat exchangers for hot water production.

This small CHP unit is designed for automatic unmanned operation with remote supervision and control. To make all of this possible a unit that can control, supervise, keep log of events and communicate with systems inside the CHP plant and other CHP plants as well as a control center is needed. In Figure 2.1 below some of the components inside the CHP plant are shown.

Figure 2.1 A CHP plant with open doors. The V8 engine is placed in the upper right corner and below it are the heat exchangers. To the left is the control unit cabinet with the door opened, the dark area is the control unit. The work and result of this thesis is the design of this control unit, from design ideas all the way to implementation of a printed circuit board, including functional tests. A more detailed picture of the final result is seen in Figure 5.2.

Figures 2.2 and 2.3 below shows two different locations where power-plants are being tested with different kind of fuels.

Figure 2.2 A CHP plant running on digester gas.

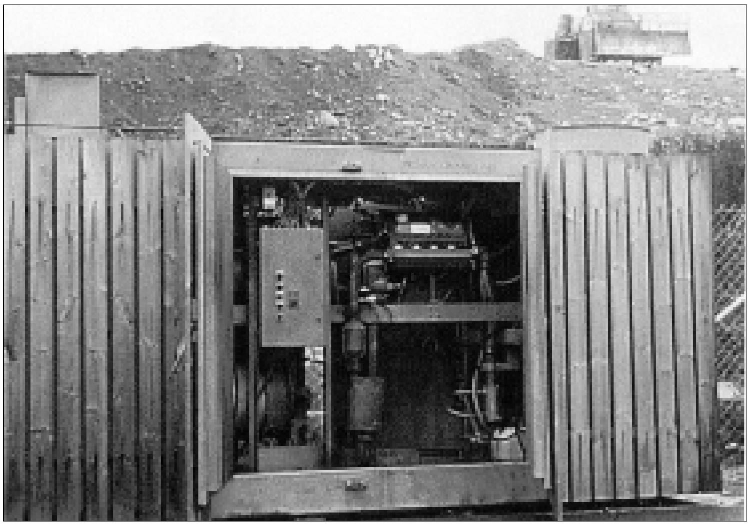

Figure 2.3 A landfill gas driven CHP plant.

The objects in Figure 2.4 below symbolizes the different components inside a CHP unit.

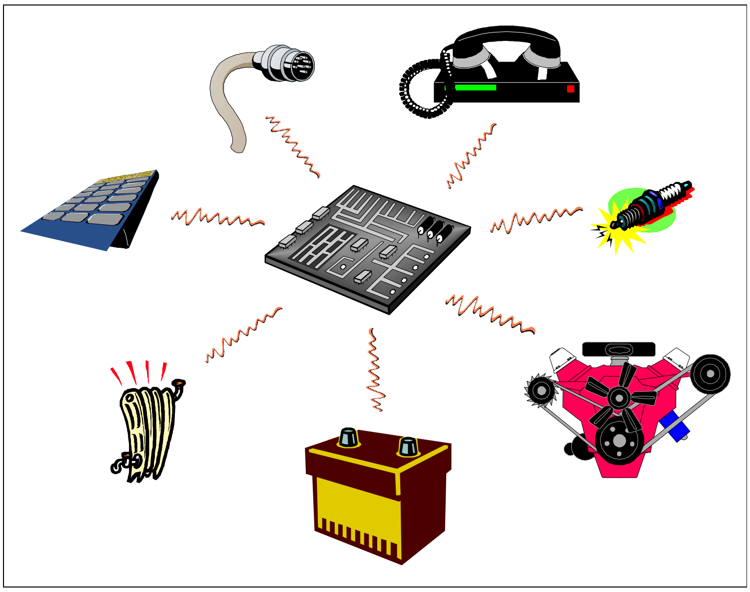

Figure 2.4 Components inside the Powerman CHP unit.

The PCB in the middle represent the control unit and clockwise from top right the components it controls and supervises are,

- Modem, for communication with a remote control center the control unit is connected to a modem hooked up with the telephone net.
- Spark plug, the ignition system supplied by Mecel AB is a state of the art system for control of the ignition sequence. The control unit communicates with the ignition system via an RS232 link and some digital outputs. A CAN interface is available for future communication with the CAN protocol that is often used in the truck and car industry.

- Otto engine, the control unit has full control over fuel and water injection. It measures temperatures and speed for the most efficient operation possible.
- Battery, the electrical system is supervised and controlled to make sure that the generator always is in phase with the power net that it is supplying with electricity.
- Radiator, temperatures and flows are measured and controlled to get the most out of the heat exchangers.
- Terminal, a small keyboard and LCD is used for easy, at site monitoring and change of temperatures, parameters etc.
- Connector, an RS485 interface is used for communication over longer distances with other CHP plants. With this network it is enough if one of the CHP plants in the network has a telephone/modem connection with the remote control center, through which all of the plants in the network can communicate with the control center.

Some technical data about the Powerman CHP plant,

- Fuel input 335 - 535 kW, natural gas, LPG or bio gas.
- Power output 100 - 160 kW.
- Heat output 200 - 320 kW at 50 - 60 ^{o}C hot water return.

2.2 Distributed CHP plants

As was mentioned in section 2.1 above, several CHP plants can be connected with each other in an RS485 network. The reason for this is that in some areas it might be desirable to have several CHP plants with a relatively short distance between them. When this is the case it is very cost effective to have only one phone line for the modem connection that serves all the CHP plants in the area. Figure 2.5 below gives an example of this.

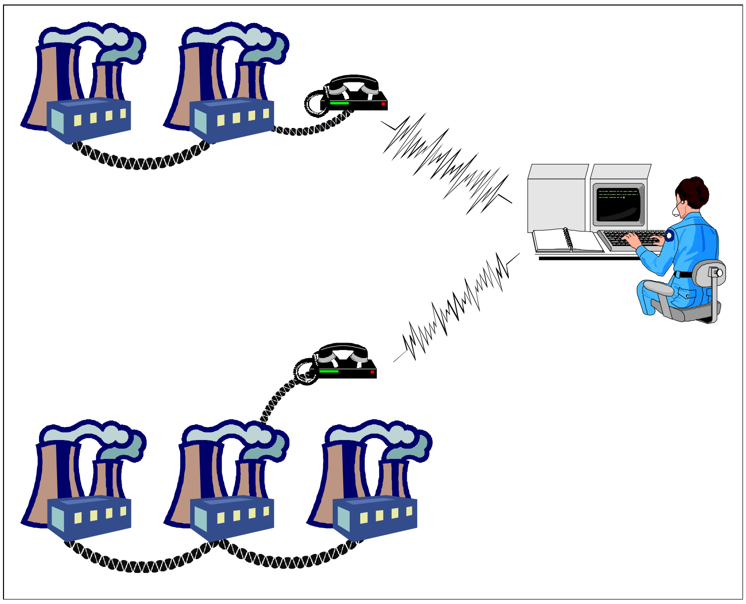

Figure 2.5 Example of a system of interconnected CHP plants.

The connection between the power plants are thus RS485 twisted pair and RS232 is used for connection to the modem that communicates with the remote control center.

This network serves several purposes. All power plants in one network can easily be regularly monitored to check that they are working properly. If for instance, something breaks in a power plant, the controller in that plant sends a message to the plant that has the modem connection with the remote control center. A communication link between the control center and the broken CHP plant is then established and information about the problem can be sent to the control center. The operator at the control center can then take appropriate action to overcome the problem or, if needed send a service technician to repair the power plant.

If the software in a power plant needs to be changed or updated, the new code can be sent via the modem and the power plant controller can then reprogram its own program memory with the new software. This is a very efficient way of updating all CHP plants in operation when a new version of software is released compared to visiting every power plant site and changing software manually, which of course is an alternative way of doing it.

Chapter 3
THE CONTROL UNIT

As mentioned earlier in the report the goal of this project was to design the control unit of the power plant. The design has been made in a modular way and the block diagram of the controller in Figure 3.1 below shows the different building blocks.

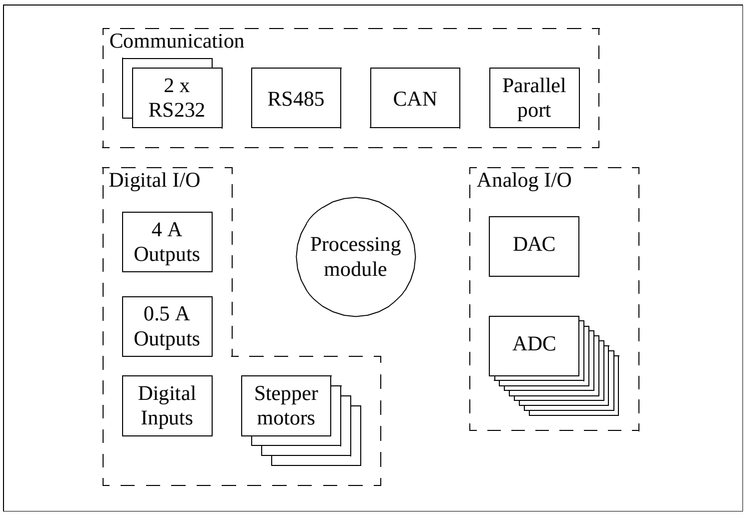

Figure 3.1 Block diagram of the control unit.

All of the different blocks will be thoroughly explained in the sections of this chapter.

3.1 The Processing module

The heart of the controller is the processing module which is based on an MC68332 microcontroller from Motorola. The MC68332 is very well suited for a task like this, involving internal combustion engines, because of the internal block called TPU which is explained in section 3.1.1.2.

By the expression ‘Processing module’ we will mean that part of the controller containing the microcontroller and its peripherals such as memory and RS232 drivers. The block diagram in Figure 3.2 below shows the structure of the processing module.

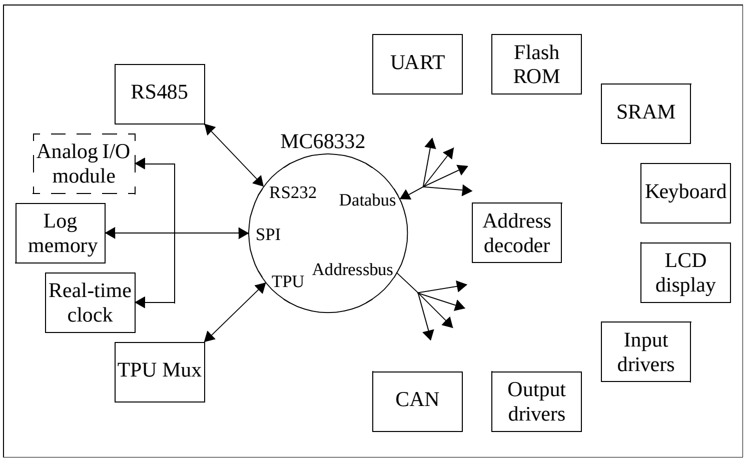

Figure 3.2 Block diagram of the processing module.

As the block diagram indicates, some of the peripherals are connected in a regular way via address- and databuses while the others are connected via the SPI-bus or directly to the microcontroller. As will be seen later, some components in the analog I/O module are also connected to the SPI-bus.

3.1.1 The microcontroller, MC68332.

The MC68332 [1] is a highly integrated modular microcontroller based on the well known MC68020 processor. It incorporates a number of useful modules some of which are of interest to this project and are listed below,

- System Integration Module
- Time Processor Unit
- Serial Peripheral Interface
- Serial Communications Interface

3.1.1.1 System Integration Module, SIM

The SIM contains much of the functionality needed for a microcontroller to work, the ones of particular interest to us are the external bus interface and the chip select block.

The external bus interface (EBI) is simply the address and databuses together with the handshaking signals and the logic to generate and evaluate the handshaking. On the MC68333, which has onchip flash memory it is possible to turn the EBI off if one wants to run the processor in single chip mode. The reason for this is to make it possible to use the address, data and handshaking pins as I/O's instead. In this design however, the microcontroller is used more like a traditional CPU with external program and data memory. The MC68333 was considered as an alternative but the limited amount of program memory made the decision fall on MC68332 with external flash.

The chip select block of the SIM is very useful since it removes the need for additional hardware to provide external chip select signals. It includes twelve programmable chip selects, which is more than enough for the peripherals. The chip select signals controlled by the SIM are,

- CSRAM chip select for the SRAM,
- CSROM chip select for the Flash EEPROM,
- CSCAN chip select for the CAN chip,

- CSSER1 chip select for the external UART,
- CSSER2 chip select for the external UART,
- CSPAR chip select for the external UART,
- CSOUT used together with address bits 0-4 to generate chip select for the digital output registers,
- CSIN used together with address bits 0-4 to generate chip select for the digital input registers.

All chip select signals are active low signals. A PLD is used to create chip select signals for the numerous amount of I/O’s and the SPI chips.

Those interested to know more about the SIM are advised to see [4].

3.1.1.2 Time Processor Unit, TPU

The main reason for choosing this particular microcontroller is that it has an onchip TPU that takes care of all timing concerning gas and water injection as well as ignition for all the cylinders. The TPU is a semi-autonomous microcontroller in it self, designed for timing control. It operates in parallel with the processor, scheduling tasks, processing instructions and performing in- and output.

The TPU is set up with timing parameters and an RPM-sensor gives information about current engine speed and angle, thus making it possible to calculate when to inject and ignite each cylinder. The MC68332 is equipped with 16 TPU channels but since the engine has 8 cylinders and gas, water as well as ignition has to be controlled for each, the channels are insufficient. The problem is however easily solved by multiplexing some channels. This is possible since not all channels are needed at the same time. One channel can, for instance, be used to control the gas injection of two cylinders that have injection cycles that do not overlap. This is further explained in section 3.1.9 below.

Those interested to know more about the TPU are advised to see [2].

3.1.1.3 Serial Peripheral Interface, SPI

The SPI is a part of the queued serial module (QSM) in the MC68332. Some of the standard SPI features are listed below,

- Full duplex, three wire synchronous data transfers, or
- Half duplex, two wire synchronous data transfers,
- Master or slave operation,
- Programmable master bit rates,
- Programmable clock polarity and phase.

The SPI in the MC68332 is actually an enhanced version called QSPI with some extra features apart from the ones mentioned above. In this text, however, we will refer to it just as the SPI.

The SPI is used for communication with several peripheral units such as the real time clock and EEPROM used for event logging. It is also used to communicate with the DAC and ADC's. The format of the data sent on the bus is entirely dependent on the peripheral with which the MC68332 is communicating. For further information on that subject the reader is advised to see the databooks and sheets of the circuits of interest.

For those interested to know more about the SPI, reference [3] might come in handy.

3.1.1.4 Serial Communications Interface, SCI

The SCI is the other part of the QSM mentioned in 3.1.1.3. It is a full duplex asynchronous serial bus.

In this design it is connected with an RS485 isolated communication interface for communication with other CHP's.

Those interested to know more about the SCI are advised to see [3].

3.1.2 Address decoder

The address decoder is implemented in a MACH111 PLD. It generates chip select signals for nine output registers, four input registers and the SPI chips. It also generates a direction signal for a bus driver that drives the peripheral data bus. All of the microcontroller peripherals that are mapped into the address space are connected to this bus, except for the program and data memories, which are connected directly to the microcontroller.

3.1.3 Program and data memory

The processing module has a Flash EPROM for storage of program code and an SRAM for storage of variables and data.

3.1.3.1 Flash EPROM

The program memory can be either a 1 Mbit (128 kbyte) or a 4 Mbit (512 kbyte) Flash EPROM, depending on the needs. Both work fine with the hardware design since both memories have the same pin configuration, except for the lack of a few address pins on the smaller memory.

The design has been made with the Am29F010/040 memories from AMD in mind. These memories are divided into blocks which can be independently erased, and this is used to make the special feature of remote updating of program code possible. Since CHP's can be spread over a large area, like Sweden, it would be a very costly operation to update the system software if an engineer had to visit all the CHP's locally. With these types of memories this is not necessary, since the microcontroller itself can erase all blocks of memory except one, in which the code for erasing, receiving new code and programming is located.

3.1.3.2 Static RAM

The size of the data memory is 1 Mbit (128kbyte) and the design has been made for the M5M51008 SRAM from Mitsubishi. It is a standard 1 Mbit SRAM.

3.1.4 Universal Asynchronous Receiver/Transmitter, UART

A UART provides the controller with another two asynchronous serial communication links apart from the MC68332 onchip SCI, these extras are used for RS232 communication.

The UART used here is a widely used chip, TL16C552 from Texas Instruments. The chip has a dual asynchronous communications element (ACE), baudrate generator and an enhanced bidirectional printer interface in the same capsule. It also has an interface well suited for cooperation with the MC68332. The 16 byte internal FIFO register minimizes the number of microcontroller interrupts.

Those interested to know more about the TL16C552 UART are advised to see [6].

3.1.5 Controller Area Network, CAN

The CAN is a two-wire serial data communication bus, with data rates of up to 1 Mbit per second, for real-time applications that was originally design by Bosch in Germany for use in car electronics. Because of the reliability of the CAN bus, it is today used in many applications outside the car industry and has become an international standard documented in ISO 11898 and ISO 11519. See also and [8].

Since CAN was originally developed to work in such a harsh environment as a car, it has been furnished with extensive error detection and is well suited for communication within a CHP as several of it’s components originate from the car industry and the environment is just as noisy as that of the engine compartment of a car.

A CAN controller from Intel, a chip called 82527, has been added to the control unit to provide the system with CAN. The 82527 is a Full-CAN 2.0B, chip which means that it can send and receive packages of data with extended identifiers and that the controller can store packages of data. See for more information on the 82527 CAN controller.

3.1.6 User interface

The user interface of the system is very simple and consists of a 5-row by 4-column wide keyboard and a 4-row by 20-character long backlit LCD. The keyboard and display have been mapped into the microcontrollers address space and can thus easily be accessed by simply reading or writing an address.

3.1.7 I/O Drivers

The input and output drivers form interfacing buffers between the processing module and the different I/O modules. All the drivers are mapped into the address space of the microcontroller and, hence, all the output drivers are registers. The octal D-type flip-flop 74HC273 with clear have been used for the output drivers and the octal buffer 74HC541 with three state outputs for the input dittos.

3.1.8 RS485 communication

For communication between CHP's the controller has been provided with an isolated RS485 data interface. The interface comes complete in one chip and only a few external components in form of some resistors and an inverter are needed. The chip is connected to the microcontrollers asynchronous serial communications interface for easy operation.

The RS485 chip used, a MAX1480 from MAXIM allows half duplex communication of up to 250kbit/s or 2.5Mbit/s depending on what version of the chip that is used MAX1480B or A. The MAX1480B is equipped with reduced-slew-rate drivers to enhance EMC and reduce reflections caused by improper termination, this is the reason for the lower bit rate.

In Figure 3.3 below an example of four CHP's interconnected with an RS485 network is shown.

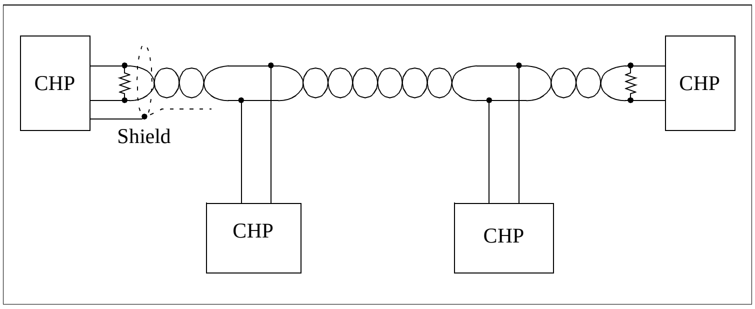

Figure 3.3 Example of CHP units in an RS485 network.

As the figure shows it is a twisted pair interface, terminating resistors of 120 Ω are needed at each end of the network.

The RS485 standard is defined for cable lengths of up to 1200 m and this design should work fine up to that length, this has however not been tested. If communication over longer distances is necessary, repeaters can be put at every 1200 m giving another 1200 m for every extra repeater added. When the length grows there will be quite a considerable time delay for the signal to reach from one end to the other, in which two units may transmit at the same time. Larger distances can also give rise to large differences in ground potential. This difference can be in the form of DC, AC or almost any noise or waveform and they may cause very large currents to flow. Putting repeaters at shorter distances between the CHP units will reduce the problem and prevents interference and/or damage from ground potential differences.

The MAX1480 is described in [9].

3.1.9 TPU multiplexers

As mentioned in section 3.1.1.2 the 16 TPU channels of the microcontroller are not quite enough to suffice for all the signals that the TPU must handle. These signals are,

- 8 fuel injection coils,
- 8 water injection coils,
- 8 ignition signals to external ignition system,
- 2 inputs for RPM measurement,
- Generator control

Plain mathematics shows that we need 27 I/O’s to take care of all signals. The problem is solved by the fact that most of the fuel- and water injection as well as the ignition signals never are active at the same time. This makes it easy to multiplex those signals. The resource allocation of the TPU channels looks like this,

Channels	Usage
0, 14	RPM measurement
1 - 8	Water injection coils
9 - 10	Fuel injection coils
11 - 12	Ignition
13	Reserved for future use
15	Generator control

Table 3.1 Resource allocation of TPU channels.

In Figure 3.4 below a simple schematic view of how the TPU channels have been multiplexed is shown. An I/O port in the microcontroller is used to address the TPU data to the right output so that when a TPU channel becomes active the addressed output changes its state.

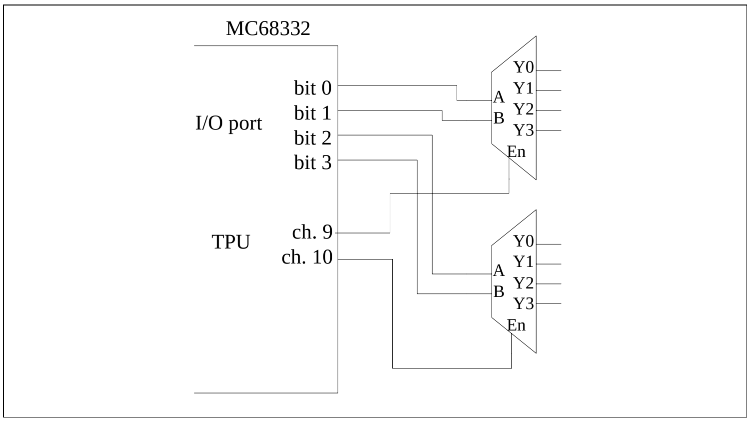

Figure 3.4 Multiplexing of TPU channels.

3.1.10 Real Time Clock

For the controller to be able to set a date and time stamp on its loggings it has been equipped with a real time clock (RTC) that keeps track of date and time. The RTC used is a chip called DS1306 from Dallas Semiconductor [10] and some of its features are,

- counts hours, minutes, seconds, month, date, day of week, and year with leap year compensation,
- 96 byte non volatile RAM,
- Two alarms,
- 1 Hz and 32768 kHz clock outputs,
- SPI interface for easy interfacing with the microcontroller,
- Dual power supply pins for primary and backup power supplies,

- Operating range is 2.5V to 5.5V.

For backup supply a 0.22F backup capacitor is used. The timekeeping current for the backup supply with primary supply at 0 volt is 1 µA at 5 volts and 0.4 µA at 2.5 volts. If we make an approximation and assume that the current decreases linearly with the voltage, we can use the well known capacitor discharge formula (3.3) for calculating a theoretical value of how long the backup capacitor will keep the RTC running.

$$V_C = V_0 e^{-\frac{t}{RC}} \tag{3.3}$$

Solving for t gives,

$$t = -RC\ln\left(\frac{V_C}{V_0}\right) . \tag{3.4}$$

With

$$V_C = 2.5 \text{ V}, V_0 = 5 \text{ V}, C = 0.22 \text{ F}, R = \frac{5V}{1\mu A},$$

the numerical value of t becomes

$$t \approx 7,6 \cdot 10^5 \text{ s}.$$

which is almost 9 days. Since we have not considered any leakage current in the capacitor this is an optimistic approximation. It is, however, well in accordance with data given in a datasheet from Philips [19], so the leakage current is small compared to the timekeeping current. This shows that the capacitor will hold the RTC running without any problem until a service technician arrives to take care of any problems that may have caused the loss of power.

3.1.11 Log Memory

For safe storage of the event log a non volatile memory of EEPROM kind is used, a chip called X25642 from Xicor [13]. It is a 64kbit CMOS internally organized as 8 * 8k with a 4 wire SPI interface for easy interfacing with the microcontroller. The chip has a block lock protection making it possible to write protect 1/4, 1/2 or the whole memory, the read/write endurance is at least 100,000 cycles and the data retention 100 years.

Chapter 4

SIGNALS, INPUTS AND OUTPUTS

This chapter will explain the signals to be measured and controlled as well as the digital and analog I/O modules that handles these signals.

4.1 Digital I/O

The digital I/O module is divided into three sections, one input, one low power output and one high power output section.

4.1.1 Digital Inputs

The digital input interface is of a simple but very functional design with an optocoupler to provide for galvanic isolation between the input signals and the controller. A series resistor limits the optocoupler diode current and a parallel capacitor and diode are added to minimize the effect of transients.

How these components are connected can be seen in Figure 4.1 below. A high input turns the optocoupler diode on, resulting in a low output. Thus, the input stage is inverting.

There are 32 digital inputs, all designed according to the principle in Figure 4.1.

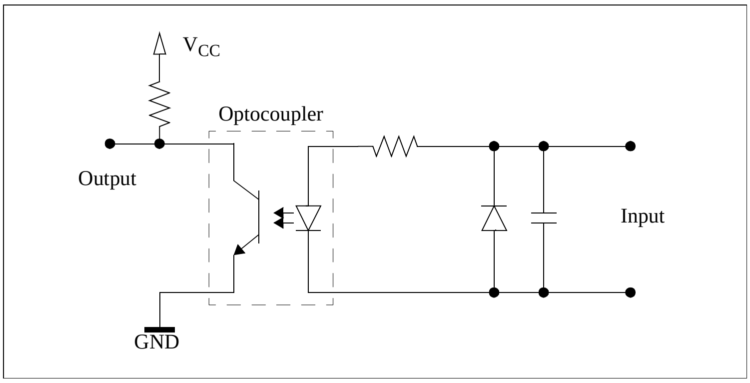

Figure 4.1 Schematic view of the digital input stage.

4.1.2 Low power digital outputs

There are 34 low power digital outputs. Low power means that they can deliver an output current of up to 500 mA. The design of a low power output stage is shown in Figure 4.2 below.

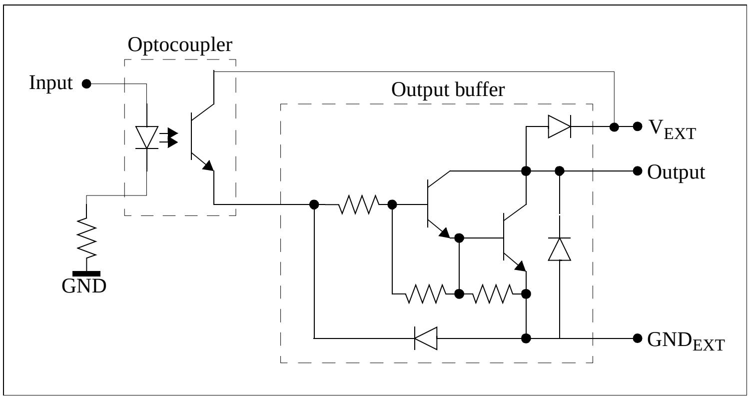

Figure 4.2 Schematic view of the low power output stage.

The low power outputs also have a galvanic isolation via an optocoupler. The output buffer used is a ULN2803, which is specified for output currents of 500 mA. As the figure shows, a high input will couple the output to GND_{EXT}. The effect of this is that any device controlled has to have the 'other end' tied to V_{EXT}, the external supply voltage. This is a good way of not having the base-emitter current flowing through the controlled device, which would be the case if the supply voltage is applied at the collector and the device connected between emitter and ground.

4.1.3 High power digital outputs

The controller has 23 high power digital outputs that can deliver an output current of at least 4A. Tests have shown that if they are loaded with 4A continuously, a cooling element should be used. However, the outputs are used to control injection coils and are therefore active less than 50% of the time, hence, coolers will probably not be needed. Further testing in a real environment will give the answer.

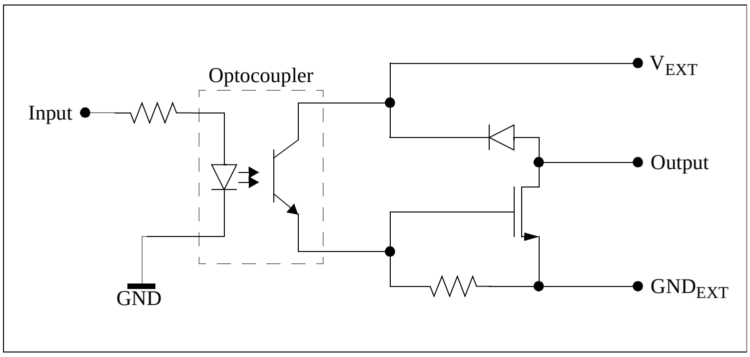

Figure 4.3 Schematic view of the high power output stage.

The output stage schematic is shown in Figure 4.3 above. A power N-channel MOSFET, BUZ10, has been used as output transistor to minimize power consumption in the transistor. For data on BUZ10 from SGS-Thomson see [14].

The purpose of the diode from output to V_{EXT} is to extinguish transients and the back current caused by inductive loads at turn off.

4.2 Stepper motors

The controller has the capability of controlling four bipolar stepper motors. A simple stepper motor control circuit from Siemens, the TCA3727 has been used for this purpose. They work with a minimum of external components, a couple of resistors and some capacitors are all that is needed. The stepper motor controllers have been mapped into the address space of the microcontroller so that controlling them is as easy as writing data to an address.

4.3 Analog I/O

The analog I/O module consists of two major blocks, the input and the output block.

4.3.1 Analog inputs

There are as many as 72 analog input channels divided into 9 IC's of 8 channels each. However, not quite all of the channels are used so that a total of 63 analog inputs are to be handled. Naturally many of these are alike and we can divide the type of analog signals to be measured into a few subgroups according to Table 4.1 below.

The abbreviation Diff. means that it is a differential measurement, that is, the measurement is made at two points and not with reference to ground of the control unit.

All signals are adjusted by filters and/or amplifiers to be within the region $\pm 2,048V$ or $0-4,096V$ so that the same ADC, a MAX186 with an internal reference voltage source of $4,096V$ from MAXIM, can be used for all conversions, see [18].

Region	Diff.	Description	Number of inputs
$\pm 4V$		50Hz signal, to be sampled at 1kHz	3
$\pm 6V$		50Hz signal, to be sampled at 1kHz	2
$\pm 70mA$		50Hz signal, to be sampled at 1kHz	4
4-20mA			1
0-1V	Yes		2
0-20V	Yes	CHP unit battery voltage	2
0-4,5V	Yes		1
0-200mV	Yes	Pt-100, temperature	23
0-130mV	Yes	Pressure	9
0-40mV	Yes	Thermo converter	10
0-5V		Knock sensor	1
	Yes	Unspecified for future additions	5
		Total:	63

Table 4.1 Analog input signals

4.3.1.1 Active filters

The $\pm 4V$, $\pm 6V$, $\pm 70mA$ are all used to measure the phase of the power net and the generated power. For this reason it is important that all of these signals are measured at the same time. To assure this, S/H circuits are used to freeze the value at those channels at the same instance, so that their values then can be converted by the ADC's involved. The S/H circuits used are LF398M from National Semiconductors [15]. The MAX186 ADC do have internal S/H so that it is possible to freeze 8 channels at the same time in one chip, but in this case the signals are spread over two ADC's, so that there would be a time gap between the measurements if the internal S/H units where used.

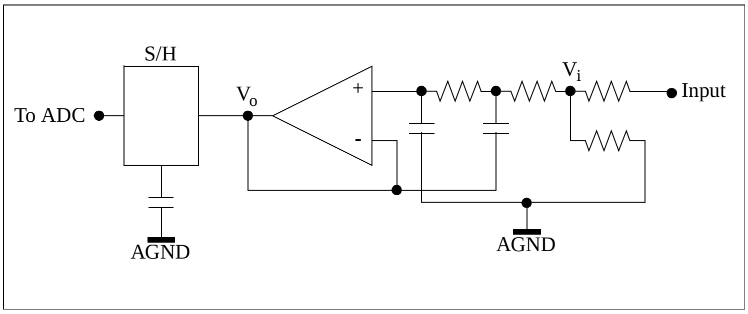

Figure 4.4 Analog input stage with active filter.

A schematic of the input stage with an active filter used for the signals mentioned in the previous paragraph is shown in Figure 4.4. The first two resistors form a voltage divider to adjust the incoming signal to the region measured by the ADC. The filter is of a low pass type with the -3dB cut off frequency f_c = 100Hz to filter out any high frequency noise.

If we replace the resistors and capacitors with their respective Laplace equivalents, we can easily find the transfer function and plot the amplitude and phase spectrums.

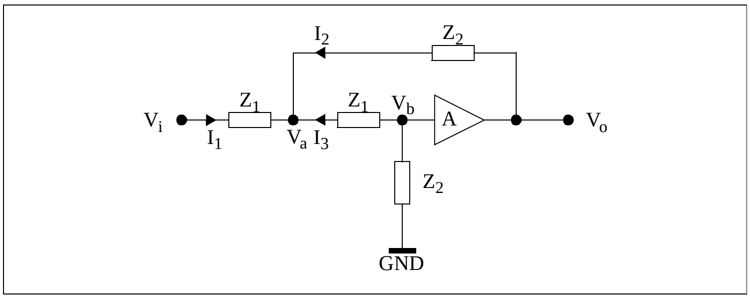

Figure 4.5 Filter schematic used to find the transfer function.

KCL gives

$$I_1 + I_2 + I_3 = 0. \tag{4.2}$$

With

$$I_1 = \frac{V_i - V_a}{Z_1} \qquad I_2 = \frac{V_o - V_a}{Z_2} \qquad I_3 = \frac{-V_a}{Z_1 + Z_2} \tag{4.3}$$

and A = 1, the transfer function can be found to be

$$\frac{V_o}{V_i} = \frac{Z_2^2}{Z_1^2 + Z_2^2 + 2Z_1Z_2} \tag{4.4}$$

which becomes

$$\frac{V_o}{V_i} = \frac{\frac{1}{(RC)^2}}{S^2 + S\frac{2}{RC} + \frac{1}{(RC)^2}} \tag{4.5}$$

when

$$Z_1 = R \qquad Z_2 = \frac{1}{SC}\ . \tag{4.6}$$

The amplitude and phase spectrums can be seen in Figures 4.6 - 4.8 for two different frequency ranges. Values for the resistors and capacitors are chosen from existing values so that f_c = 100Hz approximately. The X-axis are shown in frequency, (Hz) and the Y-axis in the phase diagram is in radians.

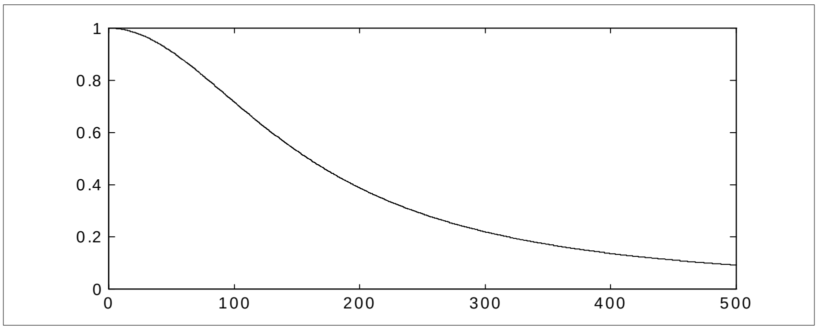

Figure 4.6 Amplitude spectrum, f = 0 - 500Hz.

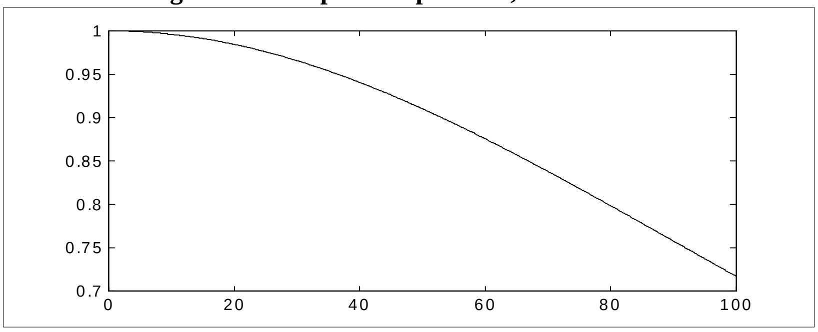

Figure 4.7 Amplitude Spectrum, f = 0 - 100Hz.

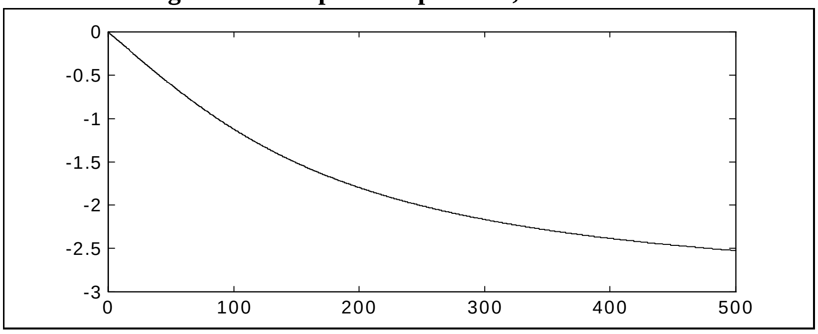

Figure 4.8 Phase spectrum, f = 0 - 500Hz, Y-axis is in radians.

Figure 4.9 below shows the actual result of a frequency sweep from a few Hz and up to 200Hz on five input channels of one of the ADCs in the design. The Y-axis is in millivolts and the X-axis is samples since the signals where sampled by the controller and then transferred to Matlab for plotting.

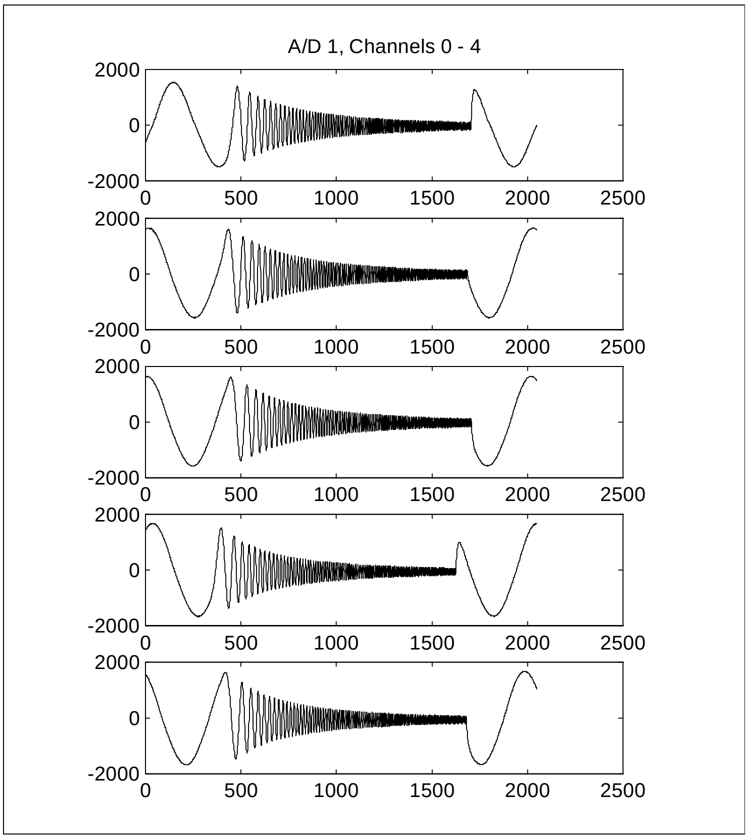

Figure 4.9 Actual filter output of frequency sweep.

4.3.1.2 Pt100 temperature measurement

For temperature measurement Pt100 resistive sensors and thermo converters are used.

With the Pt100 sensors a four wire solution is used to avoid problems caused by extra resistance added by long cables, see Figure 4.10 below.
With a current source and a high impedance voltmeter, the current through the sensor is well known. The current through the voltmeter can be neglected as can the voltage drop in the wires leading to it, hence no error is induced by the length of the wires. A reasonable question here would be if this is really necessary, would the wire resistance make any measurable difference in the two-wire case? Well, let us see, assume that we connect the current source and the voltmeter together at the right end of Figure 4.10 and that the resistance in the wires are 0.5 Ω each, making a total of 1 Ω.

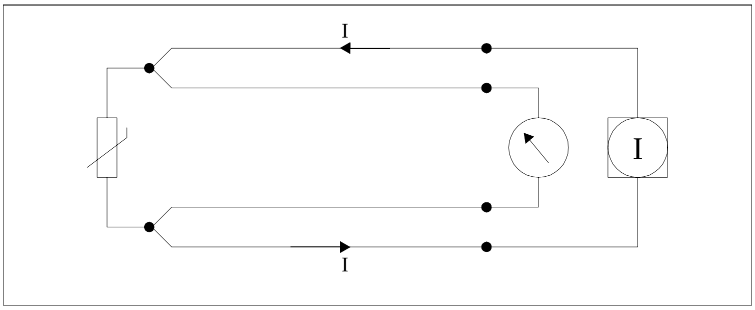

Figure 4.10 Four wire connection of a Pt100 temperature sensor.

For a Pt100 sensor this extra resistance equals about 3^{o}C. Thus we would read 3^{o}C too much with a two-wire solution, that has to be considered as quite a large error.

4.3.1.3 Thermo converter measurement

A thermo converter uses the fact that different metals emit or absorb a different amount of electrons at the same temperature. If two metal wires of different kinds are connected there will be a voltage between them that depends on the temperature where the two metals meet. This voltage is then measured to establish the temperature. There is however one problem, at some point the sensor has to be connected to the printed circuit board (PCB) of the controller unit and at this point the metals of the thermo converter meet the copper of the PCB and the same effect arises. Therefore, the temperature where the sensor is connected to the PCB, the reference point, has to be measured also so that the result can be corrected. This is done with an ambient temperature sensor chip from Linear Technology, the LTC1392, see [17].

4.3.2 Analog outputs

The controller unit has four analog outputs provided via an ADC from Maxim called MAX510, see [18]. It is an ADC with four channels and an SPI interface for communication with the microprocessor.

The analog outputs are a bit special by the fact that they have a galvanic isolation and are therefore discussed more thoroughly later in this chapter in section 4.6.

4.4 Current sources

To provide a stable current to the Pt100 temperature sensors and the pressure sensors, a small current source chip is used. The chip is a LM334 3-terminal adjustable current source from National Semiconductor that is programmed with a resistor to supply a 1mA current.

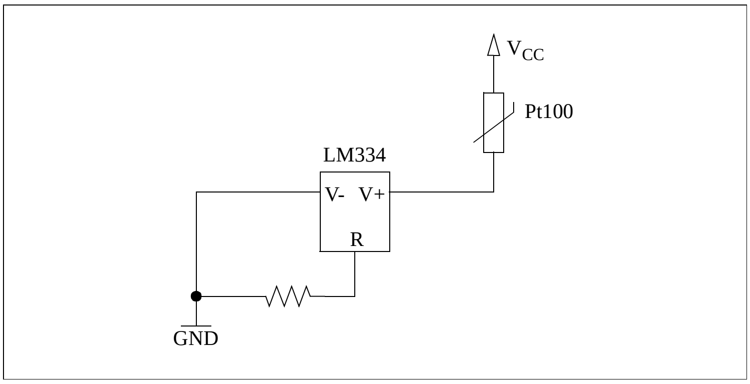

Figure 4.11 Schematic of the current source with a Pt100 sensor.

The connection shown in Figure 4.11 was first used for the current source. However, this turned out not to be the best way. The voltage difference is measured over the Pt100 sensor with an operational amplifier coupled as a difference amplifier. The difference is in the range of a couple of hundred mV but the voltages in the nodes with reference to ground are about 5V. The output voltage of an operational amplifier is given by

$$v_0 = -A_d(v_2 - v_1) - A_a\left(\frac{v_1 + v_2}{2}\right) \quad , \tag{4.4}$$

with definitions as in Figure 4.12 below. A_d is differential mode gain and A_a is common mode gain.

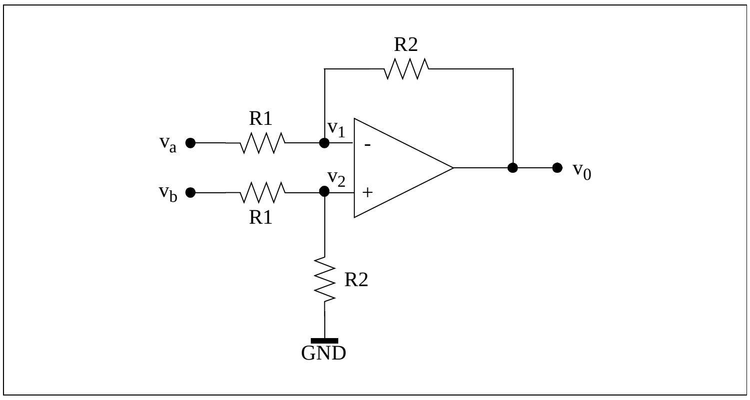

Figure 4.12 Typical design of a differential amplifier.

With the design of Figure 4.12 it can, after some approximations, be shown that

$$v_0 = \frac{R2}{R1}(v_b - v_a) + \frac{A_a}{A_d}\left(\frac{v_a + v_b}{2}\right) \quad . \qquad (4.5)$$

The second term of (4.5) is proportional to the common mode signal and is reduced by the CMRR (A_d/A_a). However, if the input voltages are high and the difference between them are low, there is a risk that the common mode signal adds a significant error to the output.

In the controller design an OP from National called LMC660 is used. The CMRR of LMC660 has a typical value of 83dB, according to the databook [16]. With $v_a = 4,9V$, $v_b = 5V$ and a CMRR of 83dB the second term of (4.5) becomes approximately $0,87mV$. This is almost an error of 1%. For this reason a redesign has been made for the next version of the controller, with the only difference being that the current source is placed between V_{cc} and the Pt100 sensor instead of between the sensor and ground.

4.5 Power supply

The controller is powered by a 12V source but since all the electronics in the controller use ±5 V, voltage regulation is needed.

The 5V supply is provided by a common 7805 voltage regulator and some capacitors.

To provide -5V a voltage inverter from MAXIM, the MAX665 is used. According to the datasheet [18], only two capacitors are needed to make the circuit work. The result, however, turned out to be all but satisfactory. There where transients of about 50mV at a frequency of 10MHz. These transients turned up in the output signals of the differential amplifiers and made the output signal significantly distorted. The temperatures measured seemed to vary quickly a few degrees up and down. The problem was easily solved with just another two components, an inductor and another capacitor. Figure 4.13 below shows the new design.

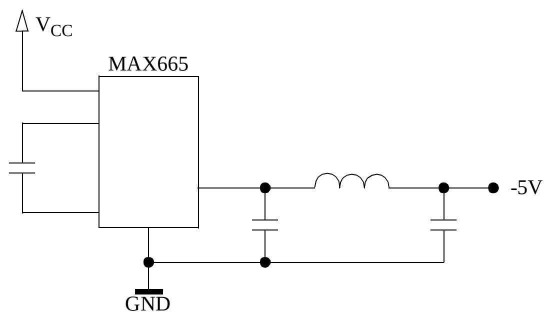

Figure 4.13 Schematic of the voltage inverter circuit.

4.6 Galvanic Isolation of Analog Signals

In many applications today, one wants to send or receive signals without having any electrical connections. When working with digital signals this is usually no big problem. The problem arises when the signal is of an analog nature. In the controller of the CHP plant there are four analog outputs that have a galvanic isolation from the outside world.

To transfer the signal an optocoupler is used but the problem is how to know what output signal a certain amount of current through the LED gives rise to. The solution is quite simple. Use two identical photodiodes, one to create the output and one for feedback! In this way we can always create an output signal that is proportional to the input signal.

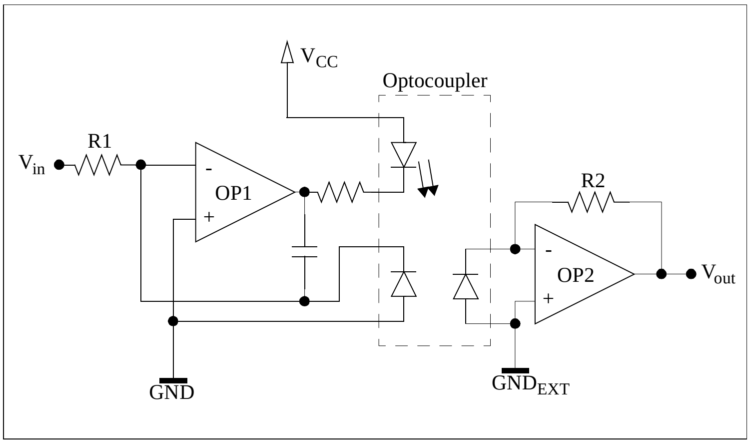

Figure 4.14 Schematic of analog galvanic isolation.

The figure above shows a schematic diagram of how this can be done. A similar approach has been presented by Siemens but with the difference that the input signal is fed to the positive input of OP1 while the feedback is connected to the negative input. This causes the input voltage at both OP terminals to be V_{in}. When V_{in} comes close to V_{cc} trouble may occur since many Ups cannot handle input signals close to V_{cc}. In the design in Figure 4.14 the input terminals of OP1 are at virtual ground, resulting in a design that is stable at all input signal levels.

Assume that we have stable operation and that V_{in} increases, this increases the potential at the negative input of OP1. The OP reduces the output which makes the light from the LED more intensive. The current through the input photodiode increases which causes the potential at the negative input to decrease. After a short while the system has stabilized. On the output side a similar course of events has occurred, when the current through the output photodiode increases, OP2 increases the output voltage to maintain zero input difference. Voila, an increase/decrease of the input voltage causes an increase/decrease on the output. Equation (4.6) gives the relationship between output and input voltage.

$$V_{out} = \frac{R2}{R1} \cdot V_{in} \ . \qquad (4.6)$$

It is easily obtained by considering the two currents through the photodiodes, which are the same, let us call them I. The voltage drop across R1 must equal V_{in} since the OP input terminal is at virtual ground, thus

$$I = \frac{V_{in}}{R1} \ . \qquad (4.7)$$

At the output side the same current flows through R2, hence

$$I = \frac{V_{out}}{R2} \ . \qquad (4.8)$$

Now, substituting (4.7) in (4.8) and solving for V_{out} gives the result (4.6).

Chapter 5
PCB DESIGN

When all functions of the controller have been decided and the schematic work has come to an end, a PCB has to be designed to build the controller. In this case, when a microcontroller unit, ‘high power’ outputs and sensitive analog circuitry all co-exist on one PCB, the PCB, which is of multilayer type with a total of four layers, becomes quite complex. The layout is made in a modular way in order to try to isolate the different parts of the design as much as possible from each other. The two inner layers are dedicated to power planes, that is, the first inner layer is split into two parts, digital and analog ground while the second inner layer is split into digital and analog power.

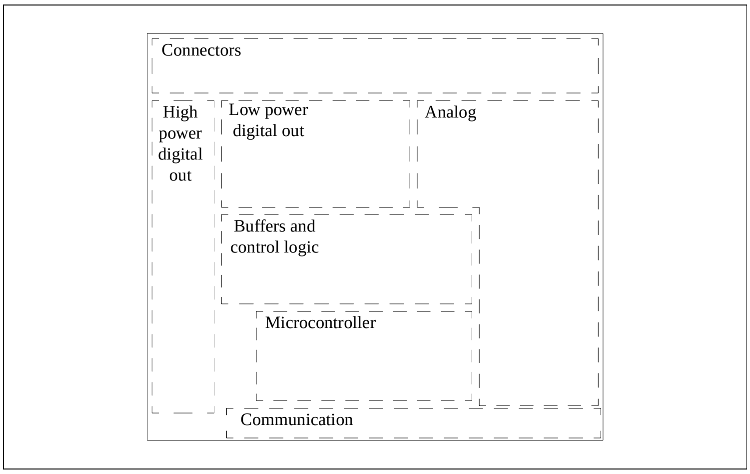

Figure 5.1 Block diagram of PCB layout.

Mostly due to all the I/O connectors the PCB becomes very large, approximately 350 x 350 mm. To prevent it from becoming too weak it is a good idea to use a laminate of about 2,5 mm thickness instead of the de facto standard of 1,55 mm. Otherwise there is a risk that large SMD's will loosen and unpick if the PCB is bent slightly.

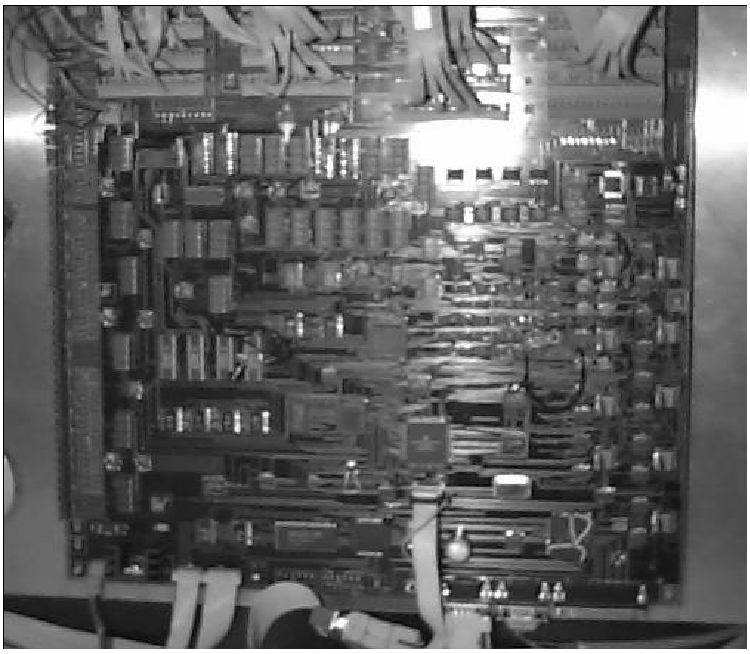

Figure 5.2 A control unit prototype PCB.

In Figure 5.2 above a picture of the PCB is shown. The cables in the top of the picture comes from a testbench specially designed to test the unit. The to cables at bottom left are the connections for keyboard and display and the cable to the right is just below the microcontroller which connects it to a PC based development system.

Abbreviations

ACE	Asynchronous Communications Element
ADC	Analog to Digital Converter
A/D	Analog to Digital (most often meaning a converter)
CAN	Controller Area Network
CMOS	Complementary Metal-Oxide Semiconductor
CMRR	Common Mode Rejection Ratio
DAC	Digital to Analog Converter
D/A	Digital to Analog (most often meaning a converter)
EBI	External Bus Interface
EMC	ElectroMagnetic Compatibility
EPROM	Erasable Programmable Read Only Memory
EEPROM	Electrically Erasable Programmable Read Only Memory
FET	Field Effect Transistor
FIFO	First In First Out (often describing data flow in a memory)
IC	Integrated Circuit
I/O	Input / Output
KCL	Kirchoffs Current Law
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MOS	Metal-Oxide Semiconductor

MOSFET	Combination of MOS and FET
OP	OPerational (amplifier)
PCB	Printed Circuit Board
PLD	Programmable Logic Device
QSM	Queued Serial Module
QSPI	Queued Serial Peripheral Interface
RAM	Random Access Memory
RTC	Real Time Clock
RPM	Revolutions Per Minute
S/H	Sample and Hold
SIM	System Integration Module
SMD	Surface Mount Device
SPI	Serial Peripheral Interface
SRAM	Static Random Access Memory
TPU	Time Processor Unit
UART	Universal Asynchronous Receiver/Transmitter

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