INSTITUT FÜR ELEKTROTECHNIK
MONTANUNIVERSITÄT
Franz-Josef-Straße 18
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Magisterarbeit

Master Thesis

PC-gestütztes Erfassungssystem für Spannungen und Ströme eines Vakuum-Induktionsofens

PC-based Acquisition System for Voltages and Currents of a Vacuum Induction Furnace

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DANKSAGUNG

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Aufgabenstellung

Vakuum-Induktionsöfen werden als wesentliche Produktionseinrichtung insbesondere in der Herstellung von hochlegierten Spezialstählen benötigt. Sie werden über spezielle Mittelfrequenz-Umrichter hoher Leistung betrieben. Zur Sicherung der Produktionsqualität und als deren Nachweis ist es vorteilhaft, aussagekräftige elektrische Größen der Anlage kontinuierlich und mit hoher Auflösung aufzuzeichnen. In der Master Thesis sind, aufbauend auf ein vorbereitetes Messsystem, die am besten geeigneten 16 Messsignale zu selektieren, die Messverstärker zur Skalierung der Signale anzupassen, eine Messsignalauskopplung aufzubauen, die gesamte Schaltung zu dokumentieren, die Speicherung der Messsignale zu prüfen und aufgenommene Messignale im stationären Betrieb sowie bei Transienten exemplarisch zu beschreiben.

Abstract

Nowadays, the vacuum inductive furnace is one of the most important and frequently used units for melting in metal industry. The Böhler-Metalltechnik company also uses the inductive furnace as a main unit of production process for special quality high alloy steels. A continuous supervision of production can be accomplished by monitoring decisive electrical power quantities, certain interactions of the load especially during the melting process. Also transient conditions at the grid influence operation of the inductive furnace. The task of this master thesis is to realize a computer based measurement system for continuously measuring and storing the voltages and currents of the inductive furnace. In this measurement system, sensors for voltages and currents are chosen and installed, sensor supplies are established, and analog signal transmission and scaling of signals are accomplished. Finally, by means of special measurement software DEWESOFT 6.3, measuring signals from the furnace unit are stored in external hard disks. These data in the hard disks can be analyzed in detail afterwards in order to evaluate operation and transient conditions.

Kurzfassung

Heutzutage ist der Vakuum-Induktionsofen eine der wichtigsten und häufigst eingesetzten Anlagen für das Schmelzen in der Metallindustrie. Als wesentliche Produktionsanlage für hochlegierte Qualitätsstähle hat auch die Firma Böhler-Metalltechnik den Vakuum-Induktionsofen verwendet. Eine kontinuierliche Produktionsüberwachung kann erfolgen durch Aufzeichung der entscheidenden Größe im elektrischen Leistungsfluss, bestimmter Wechselwirkungen der Last besonders während des Schmelzprozesses. Auch Ausgleichsvorgänge im Netz beeinflussen den Betrieb des Induktionsofens. Die Aufgabe dieser Diplomarbeit ist es, ein PC-gestütztes System, welches die Spannungen und Ströme in den kritschen Zuständen erfassen und speichern kann, zu entwerfen. Mit diesem Erfassungssystem können die Spannungen und Ströme, die wir zur Messung ausgewählt haben, ununterbrochen gemessen und gespeichert werden. In diesem Messsystem sind Aufnehmer für Spannungen und Ströme gewählt und eingebaut, Wandler-Stromversorgung sind eingesetzt, und die Analogsignalübertragung und Skalierung durchgeführt. Schließlich werden mit Hilfe der speziellen Messsoftware DEWESOFT 6.3 die Messsignale aus der Ofeneinheit auf externen Festplatten abgespeichert. Diese Daten auf den Festplatten können später im Detail untersucht werden, um den Betrieb und Übergangszustände zu bewerten.

Catalogue

1 Inductive heating basics

Induction furnaces are one of the most important and frequently used production units in metal industry. They have many advantages such as high efficiency, high product quality, environmental friendliness, and production safety. Induction furnaces are based on the induction law. With the help of the alternating field in the coil and resistance of the objects, electrical energy is converted into heat energy and this heats up the objects to be heated until they melt. There are many kinds of induction furnaces, according to the frequency. They could be divided into high frequency furnace, middle frequency furnace and low frequency furnace. According to the structure, they could be divided into coreless induction furnace and channel induction furnace. In general, the operation of the induction furnace is reliable and stable, but under certain conditions, some special situations could appear in operation. Therefore, it is necessary to build up a real-time monitoring and measuring system for the induction furnaces, so that we analyze the situation in detail deeply afterwards and derive measures if necessary.

1.1 Principle of inductive heating

Inductive heating is a kind of direct heating method. In inductive heating, inside the objects to be heated we create heating energy by means of the alternating magnetic field, and not through convection, heat conduction or radiation. Based on the induction law, for conductors being placed in alternating magnetic field, eddy currents will be generated in the conductors. (See Fig. 1.1) According to the Joule's law, if the current flows inside the conductors and the conductors have their own resistance, then heating energy will be created in the conductors. The conductors will be heated by this heating energy.

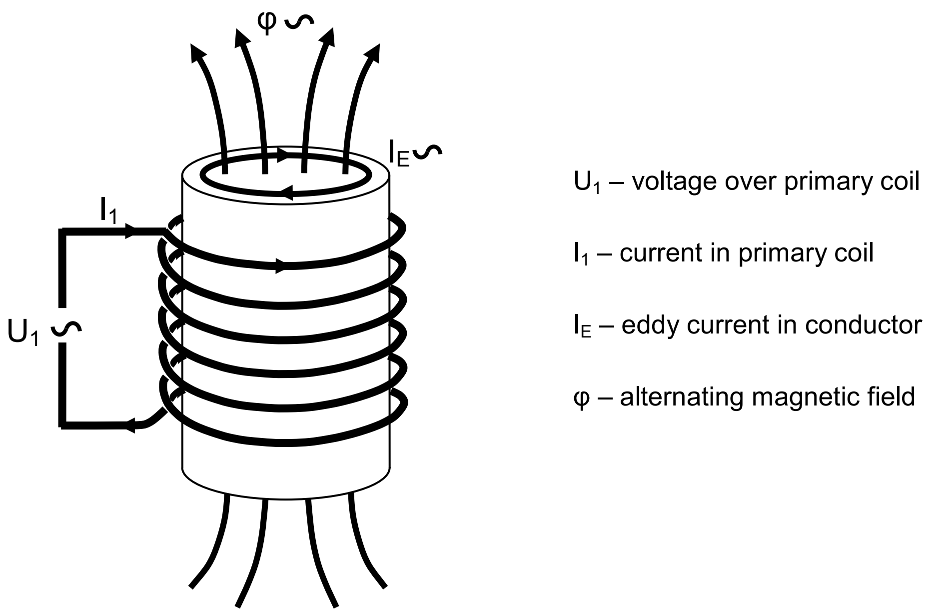


Figure 1.1 Principle of inductive heating [1]

The principle of induction heating is similar to the transformer principle (Fig. 1.2). The alternating voltage is connected to the primary winding, and this creates an alternating magnetic field. We place the secondary winding in the magnetic field, alternating voltages are generated in the secondary winding.

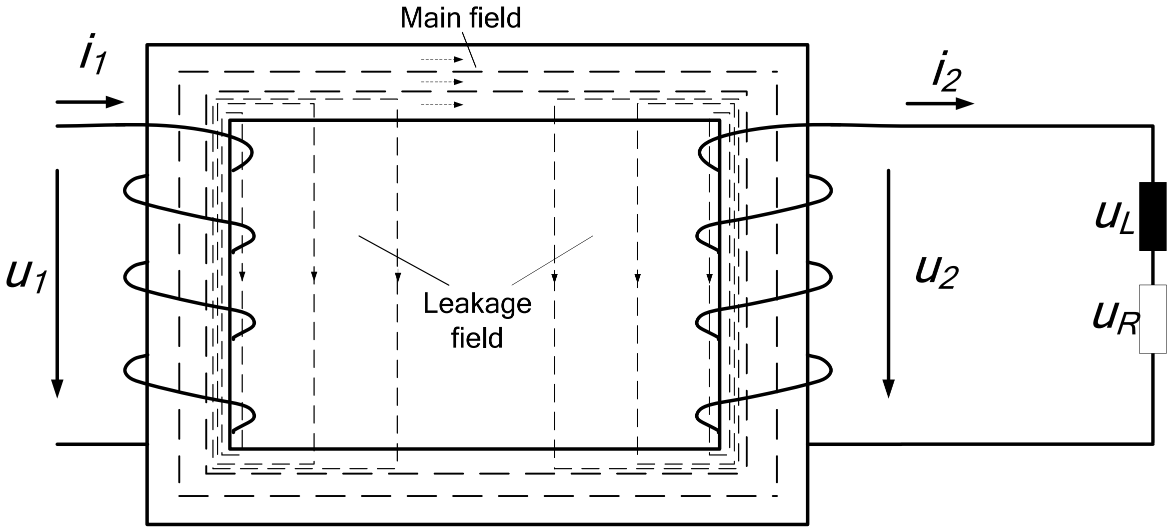


Figure 1.2 Principle of transformer with resistive load content

Eddy currents are generated and flow inside the conductors but the eddy currents are not evenly distributed in the conductors. Therefore, the principle of skin effect is introduced as follows. Skin effect means, the eddy currents generated in the conductors are mainly distributed on the surface of the conductors, only a few parts of the currents are near the core of the conductors. Due to the skin effect, about 86% of the power is transformed into heating energy on the surface with a certain depth, which is called penetration depth. Only about 14% of the power is absorbed at inner section (up to r-δ) of the conductors. The distribution of the eddy currents within the conductors is showed in Fig. 1.3.

Penetration depth is an important parameter for the induction heating method. It is determined by electromagnetic properties of the conductors that are to be heated and the frequency. The formula for the penetration depth is given as follows:

$$\delta = \frac{1}{\sqrt{(\pi \cdot f \cdot \mu \cdot \kappa)}} \tag{1-1}$$

κ - Electrical conductivity

μ - Permeability

f - Frequency

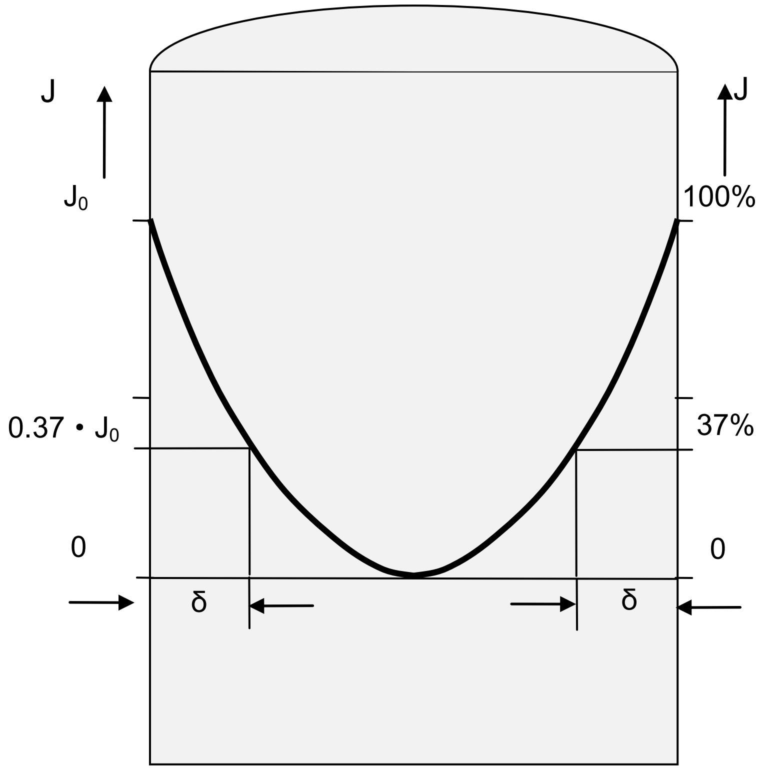


Figure 1.3 Distribution of the eddy current [1]

1.2 Induction furnace

Induction furnaces are based on induction law. Many types of induction furnaces exist. In this section, several types of induction furnaces will be introduced, and then we take transformer for instance to analyze the resistance and reactance of the primary winding and secondary winding. The alternating voltage on the primary winding is offered by system voltage converted through rectifier and inverter. We will discuss the inverter and the semiconductor components of the inverter in detail.

1.2.1 Types of induction furnaces

There are many kinds of induction furnaces, but their operation principle is almost the same. In other furnaces, the voltages are induced in alternating magnetic field within the conductors. But due to the diversity of the demands on the production purpose and product quality, the forms of the furnaces are also different. As follows, we will discuss the structure and the working methods of the furnaces. Generally speaking, induction furnaces could be divided into coreless induction furnace type and channel induction furnace type.

Coreless induction furnace

Coreless induction furnaces are widely used in metal industry. Figure 1.4 shows the structure of this furnace type. It consists mainly of inductive coils, crucible, thermal insulating layer and cover of the furnace. The metal to be melted is placed into the cylindrical crucible. The crucible is made of fireproof and electrical insulating material. The crucible is surrounded with inductive coils. The coils are connected to an alternating voltage. Within the coil in the crucible area, an alternating magnetic field is generated. The inductive coils are cooled down by water cooling. The heat loss of the inductive coils and the heat that is transferred through the wall of the crucible must be transferred to a heat exchanger by water cooling.

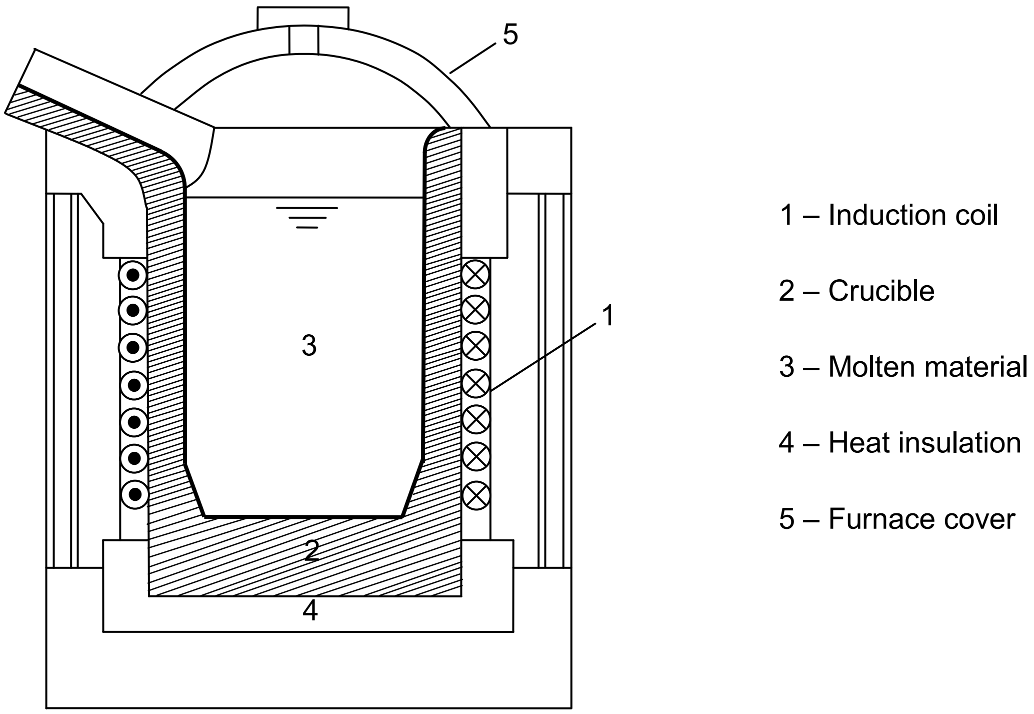
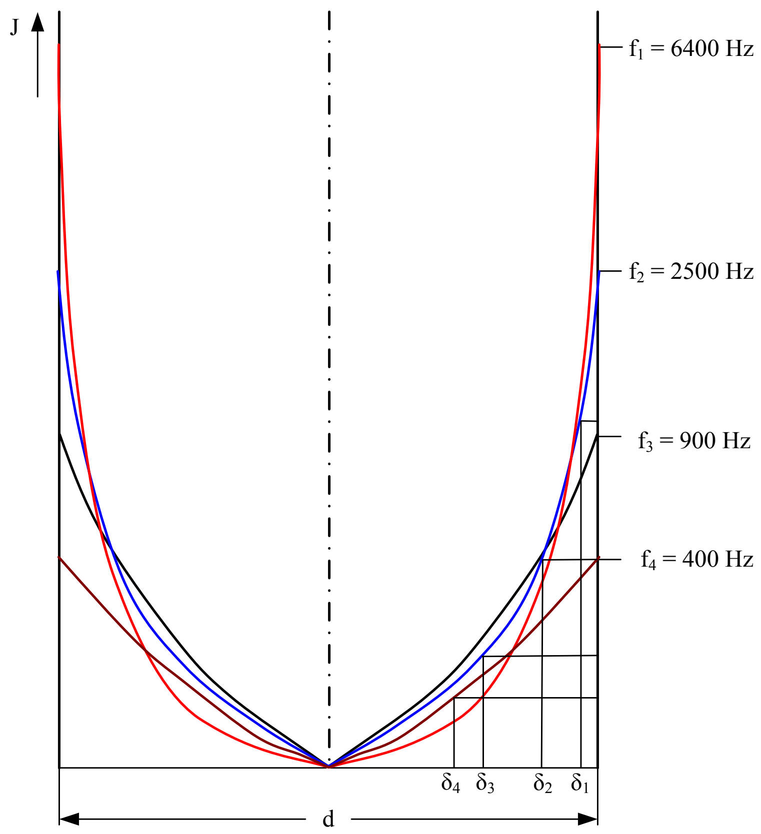


Figure 1.4 Coreless induction furnace [1]

Compared with transformers, the inductive coils are equivalent to the primary winding, the metal conductors to be heated are secondary winding. In induction furnace the secondary winding is short-circuited. In the conductors eddy currents are generated by alternating magnetic field. Due to the skin effect described above, the main part of the currents flow near the surface of the conductors within penetration depth. The current densities in different frequency are given in Fig. 1.5.



d: diameter of molten material
J: current density inside the molten material

Figure 1.5 Current density in different frequency [1]

In Fig. 1.5 we could see that the penetration depth decreases by increasing frequency. By decreasing penetration depth, the current density near the surface of the conductor will become higher.

An important phenomenon in inductive furnace is fluid agitation. It is caused by electromagnetic forces at the inhomogeneous fields inside crucible. The fluid agitation in crucible furnace is shown in Fig. 1.6.

The eddy currents flow inside the molten materials which are located in the crucible of the furnace. Due to the existence of the magnetic field in the crucible, electromagnetic forces will be generated in the molten materials, in which the eddy currents flow. These electromagnetic forces point radially to the center of the crucible, and the fluid molten materials are moved inwards by these forces. At the center of the crucible, the molten materials meet each other and suppress themselves to flow upwards and downwards. Through this, the circular flows of the fluid molten materials are generated. This is also called **fluid agitation**.

With the help of fluid agitation, we could obtain following advantages:

1. Concerning the temperature distribution and the chemical composition of the object, the melt could be homogenized;

2. Due to the homogenization of the melting the burnout by adding alloy components could be avoided.

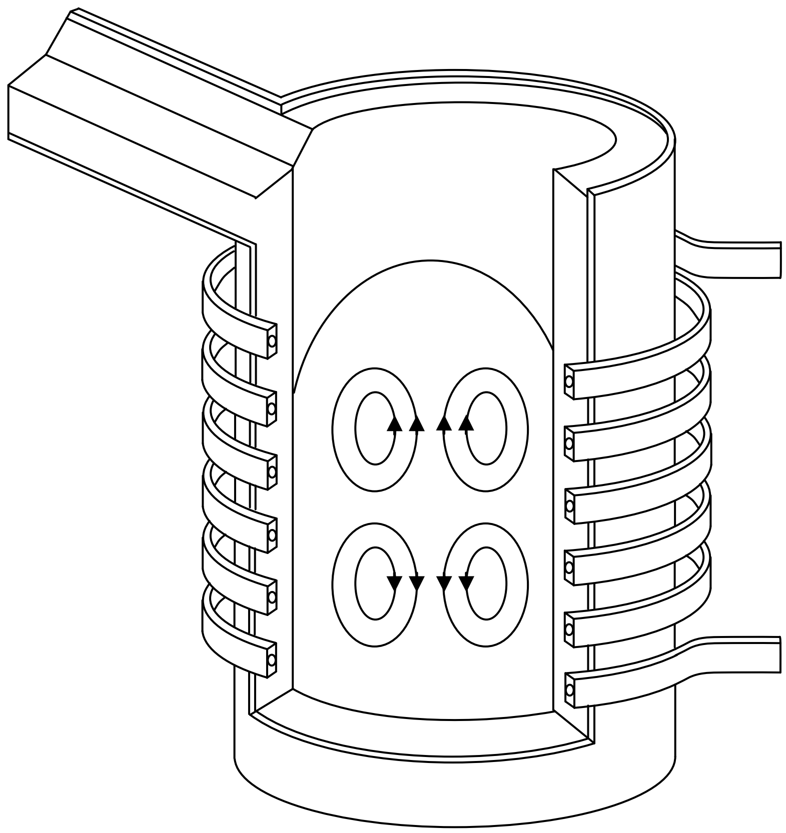


Figure 1.6 Fluid agitation in crucible furnace [1]

Channel induction furnace

The channel induction furnace has a higher efficiency. In continuous operation, the energy loss is less. Fig. 1.7 shows the structure of a channel induction furnace. It contains a fireproof furnace chamber and one or several inductors. Due to the different power in operation, the inductors could be cooled down by air cooling or water cooling. Inductor consists of inductive coils, a surrounding cooling cylinder, a closed iron core and fireproof coating. A channel is formed in induction unit so that the melting could be hold inside. The cooling cylinder is made of copper or non-magnetic iron.

In theory, the channel induction furnace could be considered as a transformer with iron core. The primary winding is a single-winding or multi-winding coil, this coil is spooled around the closed iron core. In the channel the melting is injected as secondary winding. This winding is shorted, and therefore the transformer is in short circuit state. We apply alternating voltage on the primary winding, generate an alternating magnetic field, this magnetic field is located mainly within iron core. In the secondary winding, i.e., the melting in the channel, a high voltage is induced, and then short circuit currents flow inside the melting. With the help of electromagnetic force, the heat generated in the melting is carried to the furnace chamber in form of heat flow, and the metal in the chamber is heated up and melted.

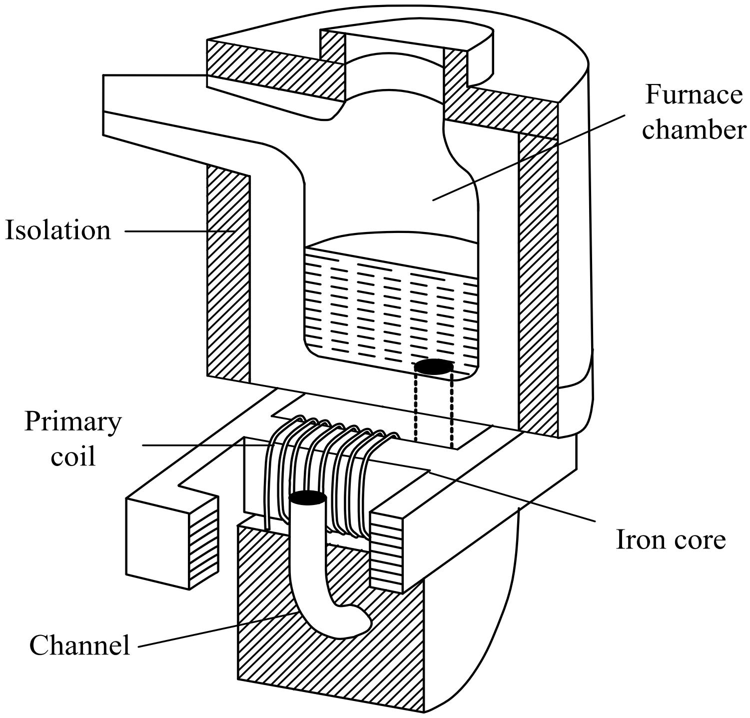


Figure 1.7 Channel induction furnace [1]

1.2.2 Determination of electrical parameters in equivalent circuit

Since the working principle of induction furnace is similar to transformer, we take the coreless induction furnace as an example to analyze the parameters in the equivalent circuit (Fig. 1.8). The coil in the induction furnace is equivalent to the primary winding in transformer, the object to be melted is the secondary winding in transformer. The secondary winding is shorted, so the equivalent circuit of the furnace is obtained as Fig. 1.9. In the equivalent circuit, R_1 and R_2 are separately the resistance of primary winding and the molten material in crucible, L_1 and L_2 are the leakage inductance of primary winding and the molten material, P is the transmission ratio of the primary current and secondary current.

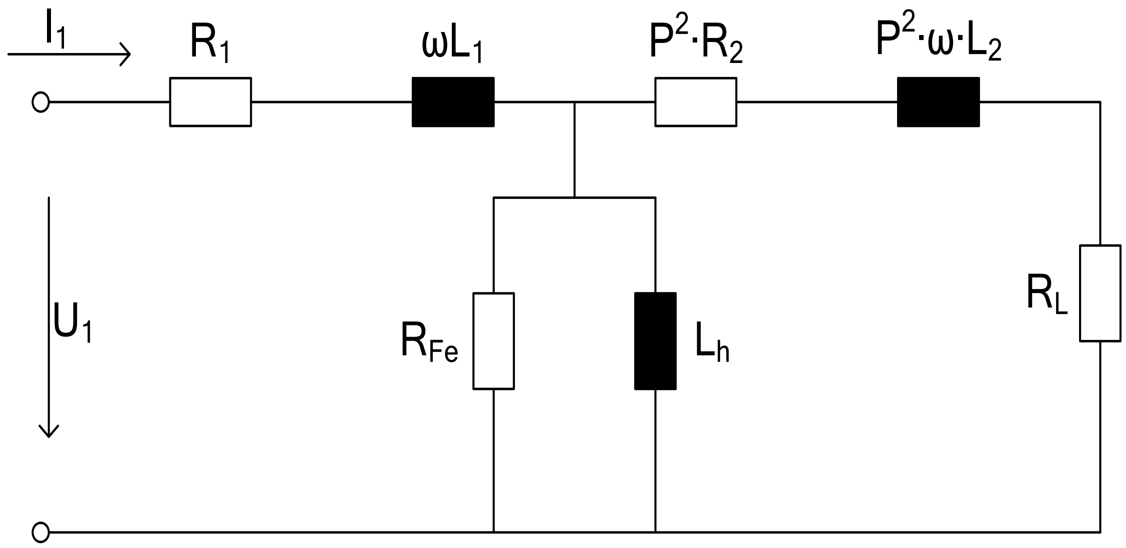


Figure 1.8 Equivalent circuit of transformer

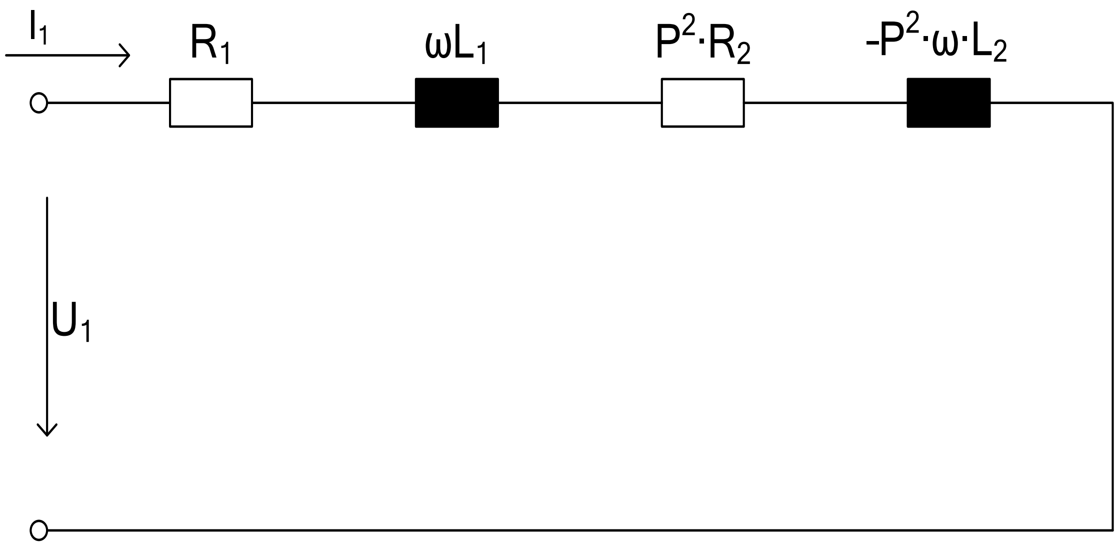


Figure 1.9 Equivalent circuit of inductive furnace [1]

The electrical parameters in equivalent circuit of coreless induction furnace are related to the geometric structure of the furnace. Fig. 1.10 shows the simplified geometric structure of the coreless induction furnace. We can calculate the parameters of the equivalent circuit through this. In the simplified structure, the parameters of the windings and the metal to be melted such as length, width, and diameter of the coil are indicated. There is one point that should be mentioned. By calculating the parameters, we assume that the crucible is fully up to length l_2 charged and the fluid metal is evenly distributed in the crucible. In the following formulas, index 1 stands for primary side, index 2 stands for secondary side.

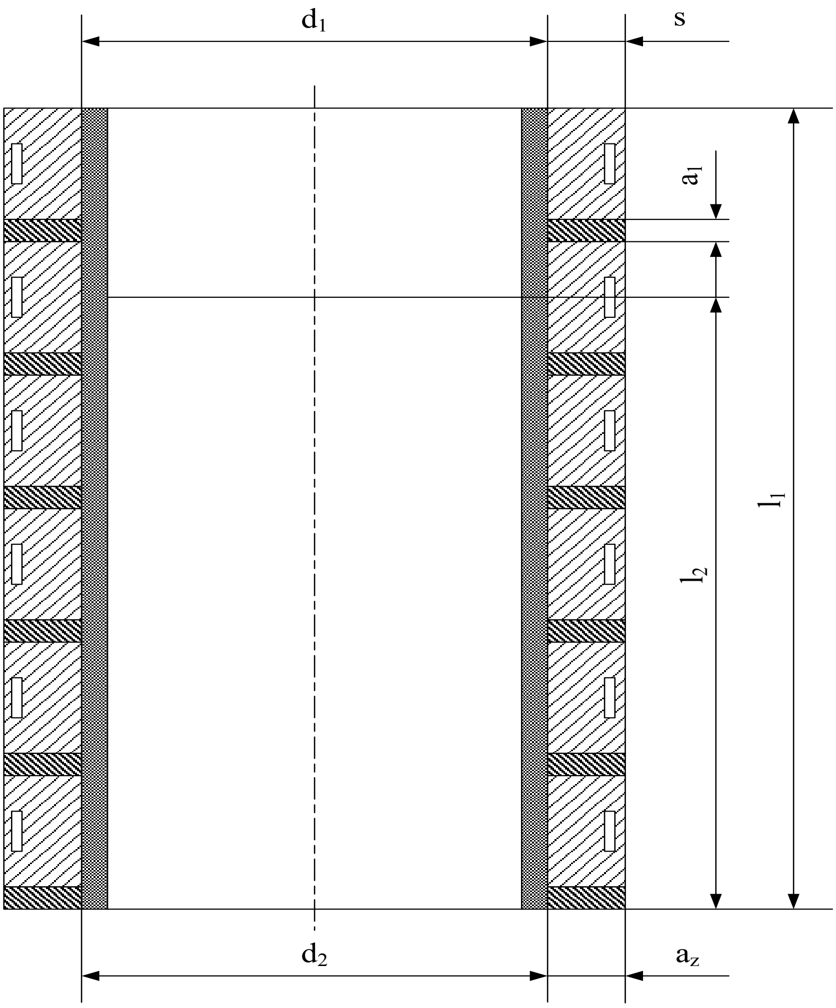


Figure 1.10 Simplified geometric structure of the coreless induction furnace [1]

Meanings of the parameters in the picture above [1]:

d_1 – Inner diameter of the primary coil

l_1 – length of the primary coil

s – Width of the primary coil

d_2 – Outer diameter of the object

l_2 – level of molten material in crucible

a_1 – insulation distance between primary windings

a_z – wall thickness of the crucible

If the width of the primary winding s and the penetration depth δ meet the relation $s > 0.5\pi\delta$, the resistance of primary winding R_1 could be calculated as follows [1]:

$$\mathbf{R}_1 = \frac{1}{\kappa_1} \cdot \frac{n^2 \cdot \pi \cdot d_1}{(I_1 - \frac{1}{2} \cdot n \cdot a_1) \cdot \delta_1} \qquad (1\text{-}2)$$

The leakage inductance of primary winding [1]:

$$\mathbf{L_1} = \mu_0 \frac{n^2 \cdot d_1}{8 \cdot \pi} \cdot \mathbf{F}(\frac{d_1}{I_1}) \qquad (1\text{-}3)$$

The resistance of secondary winding, namely the resistance of the metal to be melted R2 is [1]:

$$\mathbf{R}_2 = \frac{1}{\kappa_2} \cdot \frac{\pi^2 \cdot d_2^{/}}{I_2 \cdot \delta_2} \qquad (1\text{-}4)$$

Leakage inductance of secondary winding [1]:

$$\mathbf{L_2} = \mu_0 \frac{d_2^{/}}{8 \cdot \pi} \cdot \mathbf{F}(\frac{d_2^{/}}{I_2}) \qquad (1\text{-}5)$$

The auxiliary function F is given in Fig. 1.11.

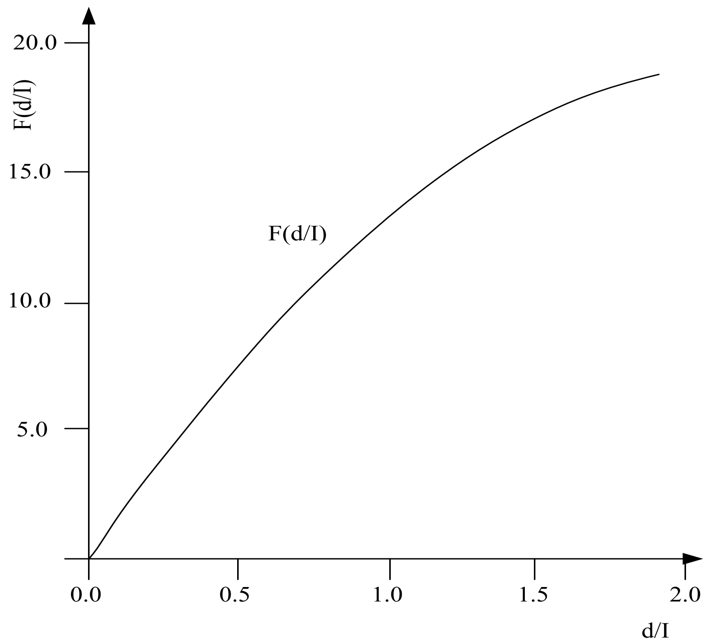


Figure 1.11 The auxiliary function F [1]

1.3 Operational performance of the unit

The furnace used in Böhler-Metalltechnik is coreless induction furnace. The furnace circuit is shown in figure 1.12.

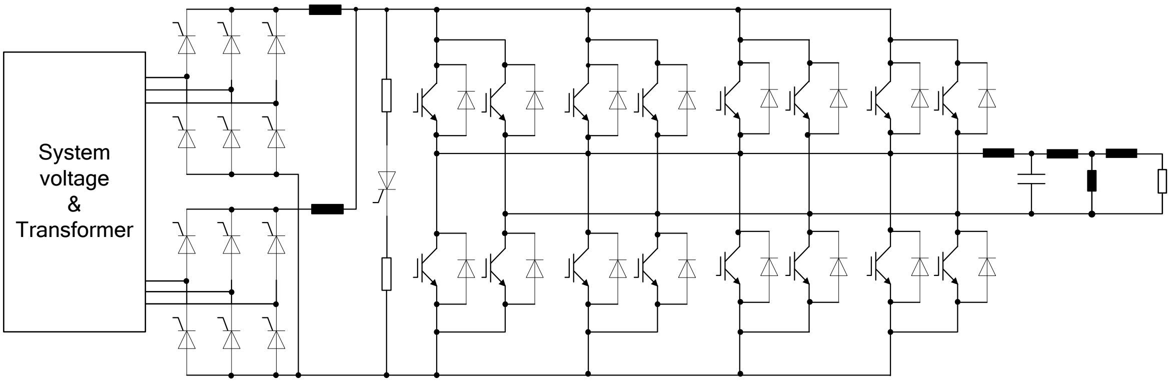


Figure 1.12 Furnace circuit in Böhler-Metalltechnik

In figure 1.12 we can see that the furnace contains a 12-pulse thyristor-rectifier. This 12-pulse rectifier consists of two 6-pulse rectifiers in parallel connection. On the output side of the rectifier there are crowbar protection unit and four IGBT-inverters in parallel connection. The crowbar unit has the function of protection against DC-overvoltage. On the output side of the inverters we can see the inductor. As we have discussed in section 1.2, the inductor can be treated as a transformer. This inductor can be equivalent to a resonant circuit in figure 1.13.

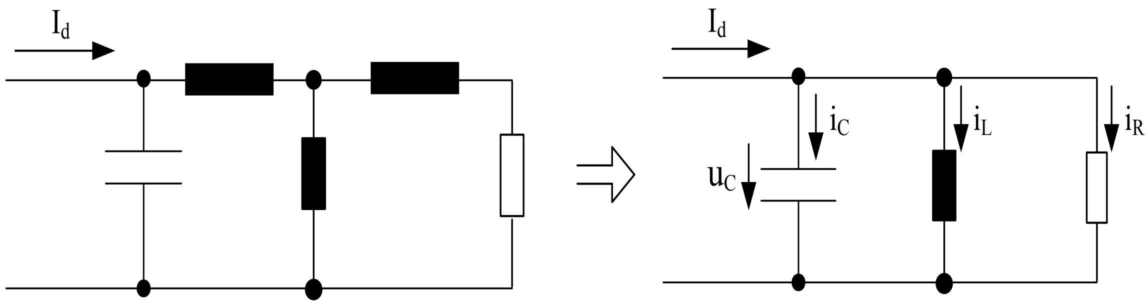


Figure 1.13 Resonant circuit of the inductor

Due to the existence of the resistor in the circuit, this is a damped resonant circuit. Fig. 1.14 shows the currents and voltage in this resonant circuit under precondition I_d=0.

In Figure 1.14 we can see that the peak values of the currents i_C, i_L, i_R and voltage u_R in the resonant circuit become smaller gradually when the output current I_d=0. Under this condition the melting process in the furnace can not work properly. It is necessary to compensate the damped currents and voltage in the resonant circuit with the current I_d. Current I_d is the output current of the IGBT-inverter. Due to this the commutation process in inverter is very significant to the stable operation of the induction furnace. Fig. 1.15 shows the complete process of the commutation in the inverter.

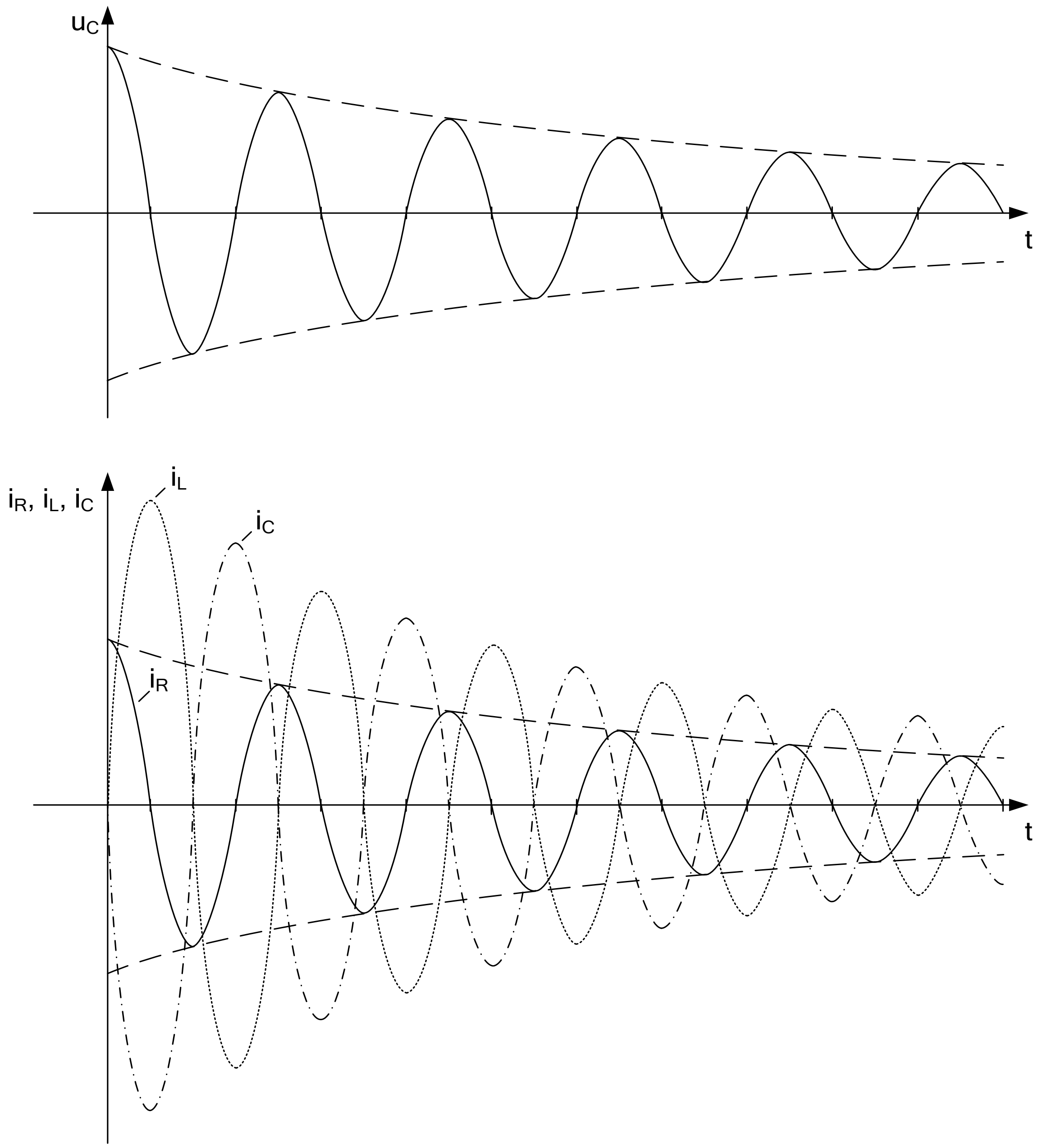


Figure 1.14 Currents and voltage in the resonant circuit

In Fig. 1.15 we can see that a complete commutation contains mainly three steps: firstly, the IGBT1 and 4 are turned on, the current I_d flows from the current source to the inductive coil of the furnace through IGBT1, and flows back to the current source through IGBT4 (Fig. 1.15-a); as the second step, all the four IGBTs are in on-stage, the currents flow through each IGBT. The current values through each IGBT are indicated in Fig. 1.15-b; finally the IGBT1 and 4 are turned off, the current I_d flows from current source to inductive coil through IGBT3 and back to the current source through IGBT2. A more detailed explanation of the currents and voltages during the commutation are given in Fig.1.16.

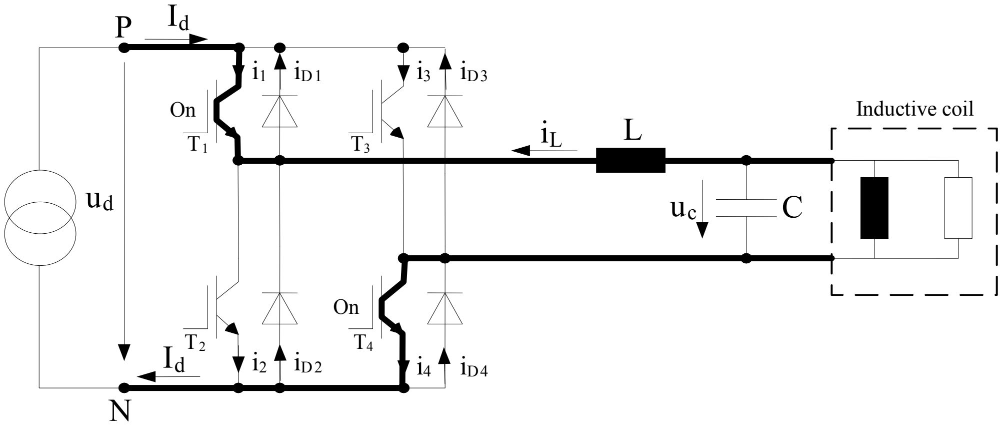


Figure 1.15 (a) the first step of commutation (T_1 , T_4 On-state, instant before t_1)

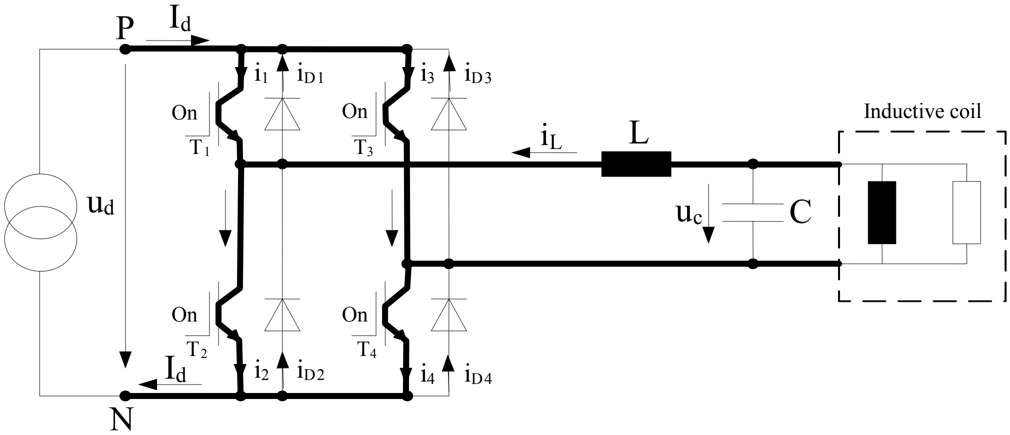


Figure 1.15 (b) the second step of commutation (T_1 , T_2 ,T_3 ,T_4 On-state, instant between t_1 and t_3)

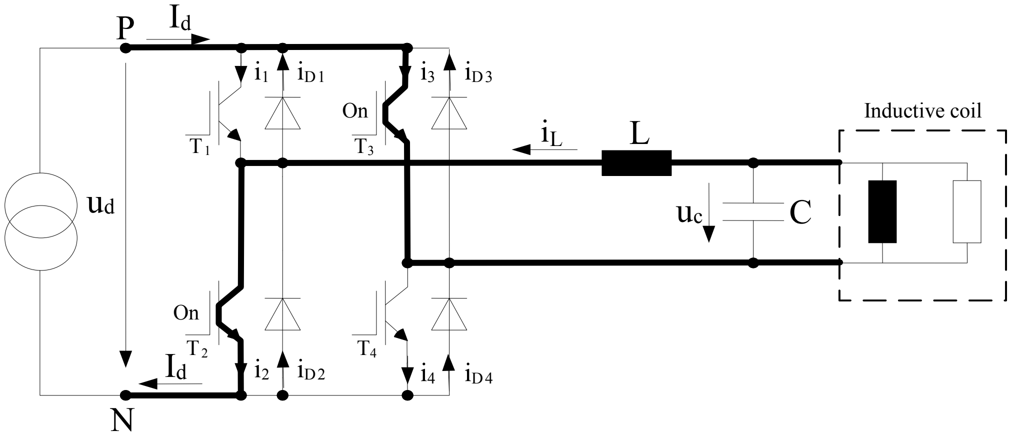


Figure 1.15 (c) the third step of commutation (T_2 ,T_3 On-state, instant after t_3)

Figure 1.15 Commutation process of inverter

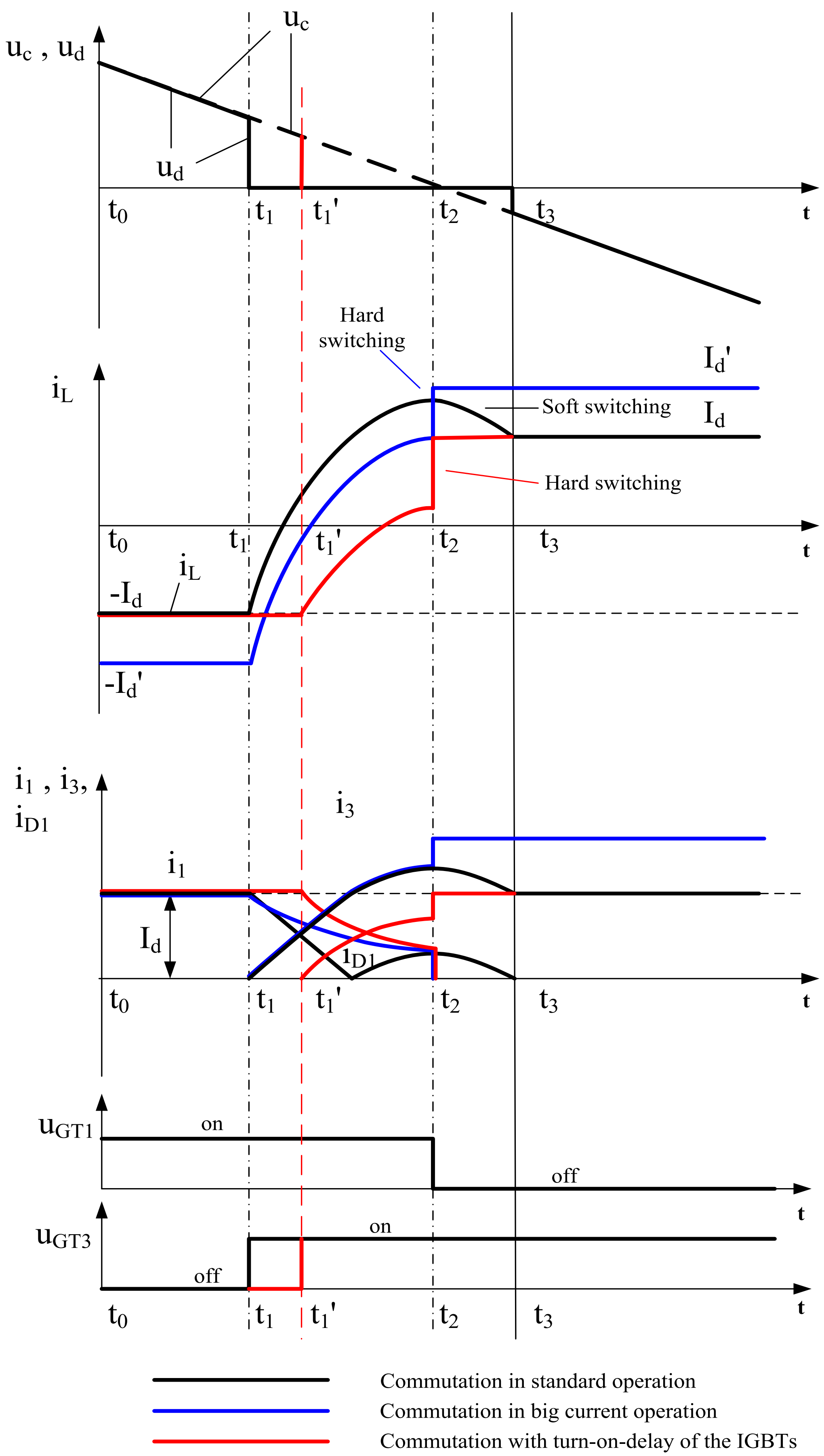


Figure 1.16 Time course of the voltages and currents in commutation

Fig. 1.16 shows us the time courses of the voltage u_c, currents i_L, i_1, i_3 and the on/off-state of the IGBTs in different operations. u_c is the voltage over the capacitor parallel to the inductive coil; i_L is the current through inductor L; i_1, i_3 are separately the currents through IGBT1 and IGBT3. We use several time points from t_0 to t_3 to describe the time course of the voltages and currents in standard operation (black line in Fig. 1.16).

$t_0 \leqslant t < t_1$: In this period IGBT1 and 4 are turned on, IGBT2 and 3 are in off-state. Capacitor C is discharging and the voltage u_c reduces. The voltage u_d over the current source has the same value as u_c. Current i_1 is equal to the current I_d through the current source and current i_L is equal to $-I_d$. Current i_3 is zero.

$t_1 \leqslant t < t_2$: At t_1 the IGBT2 and IGBT3 are turned on. At this moment all the four IGBTs are in on-state, the circuit between points P and N are shorted by the IGBTs. The voltage u_d reduces to zero at t_1 and the capacitor C continues discharging. The current i_L increases from $-I_d$ to zero and then continues increasing. Current i_1 reduces from I_d to zero in a short time and current i_3 goes up from zero. After that, current I_{D1} through Diode D_1 increases from zero and D_1 is now in on-state.

$t_2 \leqslant t < t_3$: At t_2 the IGBT1 and IGBT4 are turned off. Voltage u_c over capacitor C reduces to zero and then the capacitor is charged with negative voltage. Due to the on-state of the Diode D_1 and IGBT4, the circuit between P and N is still shorted and the voltage u_d is still zero. Current i_L reaches its peak value and then goes down. Current i_3 and i_{D1} decrease from their peak values at t_2.

$t_3 \leqslant t$: At t_3, current i_{D1} reduces to zero and current i_3 decreases to I_d. Meanwhile, current i_L through the inductor L reaches I_d. Diode D_1 is now in off-state and the voltage u_d has the same value at u_c. At this time this commutation comes to end.

The blue curves in figure 1.16 shows the time course of the voltages and currents in commutation in big current operation. In big current operation, the current from the current source $I_d^{'}$ is bigger than the current I_d in standard operation. In this commutation the current i_L can not increase to current I_d at t_2 and it jumps to current I_d, this is called “hard switching” (Fig.1.16).

The red curves in figure 1.16 shows the time course of the voltages and currents in commutation with turn-on-delay IGBTs. In this commutation the IGBT3 is turned on at $t_1^{'}$, $t_1^{'}$ is later than the scheduled time t_1. Therefore, at t_2 the current i_L can not increase to I_d and the hard switching happens again.

1.4 Individual tasks of the thesis

A continuous monitoring of operation of the vacuum induction furnace produces a profound documentation about the production process for each melting activity. Therefore, a measuring system should be established for continuous monitoring and measuring of the voltages and currents in the furnace circuit, and record them in hard disks through computer. By means of this equipment, the critical voltages and currents could be detected immediately and appropriate measures could be taken to minimize the risk of damage to the furnace. Afterwards, the data recorded in hard disks could be analyzed in detail. Combined with the operating performance and the operation report of the furnace in company Boehler, the tasks of this thesis are determined as follows:

1 Selection of measurement signals;

2 Voltage and current transducers and power supplies;

3 Scaling of the measurement signals (-10V--+10V);

4 Collection of the measured values (AD converter, Labview/DEWEsoft);

5 Storage of the data (USB-hard disk and PC with UPS);

6 Analysis and evaluation of the operation performance.

2 Voltages and currents of the circuit

In this chapter, we will explain the voltage and current signals in the circuit of the induction furnace. The overview circuit is given as follows, it is divided into three parts: (1) Transformer; (2) converter; (3) coil part.

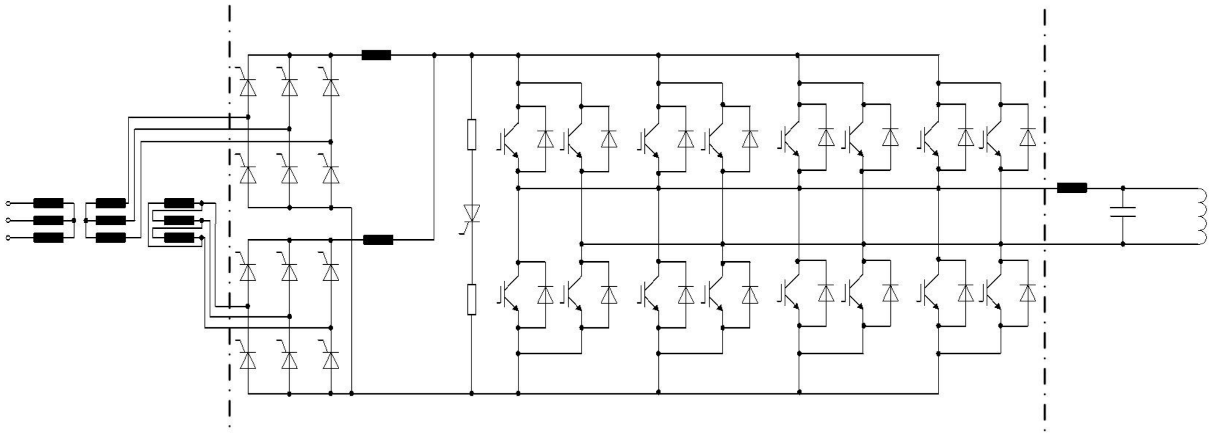


Figure 2.1 Overview circuit of furnace in three parts

2.1 Voltages in the transformer

In this furnace unit, a three-winding transformer is used. The connecting types between the primary side and secondary side are separately Yy0 and Yd5 (Fig. 2.2). The rated value of the phase to phase voltage on the primary side is 20kV. The rating value of the phase to phase voltage on secondary side is 380V. The voltages on the primary side and secondary side are very significant to the operation of the induction furnace. All the important voltages in the transformer are indicated in the Fig. 2.3.

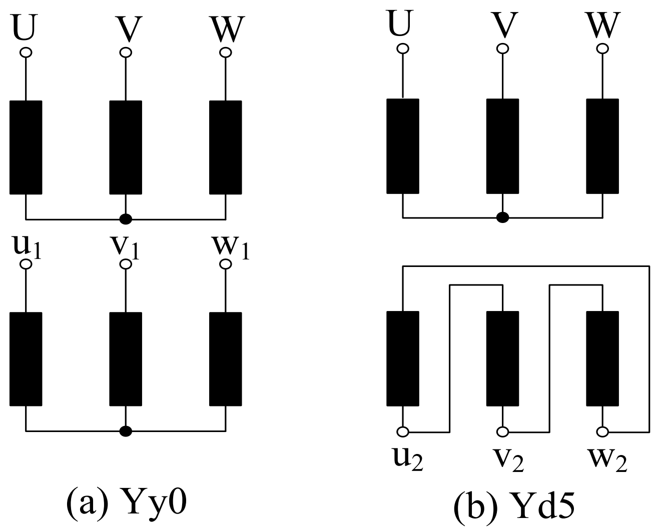


Figure 2.2 Connection types of transformer

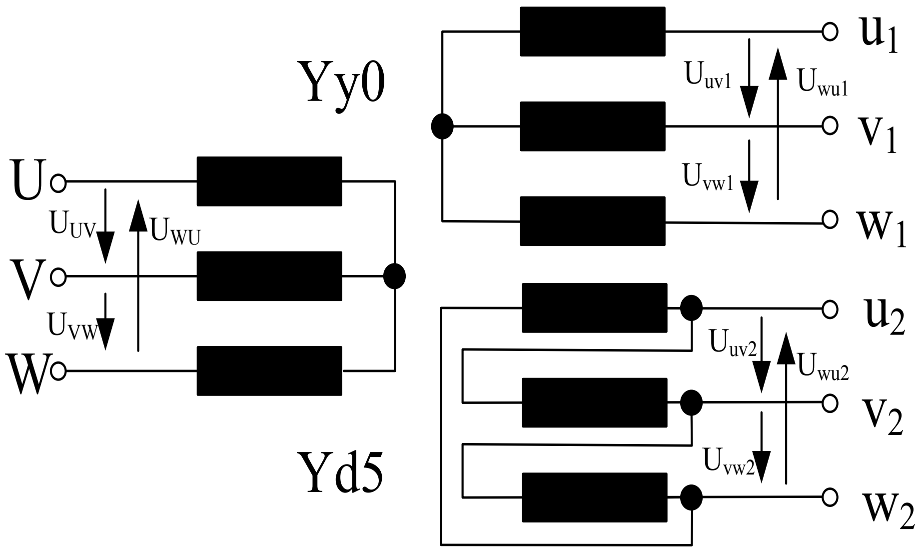


Figure 2.3 Three-winding transformer

The following table gives us a specification for each signal in the transformer.

Table 2.1 Overview of the signals in the transformer

Signal No.	Signal name	Signification
1	U_{UV}	Phase to phase voltage between the phase U and phase V on the primary side of the transformer
2	U_{VW}	Phase to phase voltage between the phase V and phase W on the primary side of the transformer
3	U_{WU}	Phase to phase voltage between the phase W and phase U on the primary side of the transformer
4	U_{uv1}	Phase to phase voltage between the phase u_1 and phase v_1 on the secondary side of the transformer
5	U_{vw1}	Phase to phase voltage between the phase v_1 and phase w_1 on the secondary side of the transformer
6	U_{wu1}	Phase to phase voltage between the phase w_1 and phase u_1 on the secondary side of the transformer
7	U_{uv2}	Phase to phase voltage between the phase u_2 and phase v_2 on the secondary side of the transformer

Signal No.	Signal name	Signification
8	U_{vw2}	Phase to phase voltage between the phase v_2 and phase w_2 on the secondary side of the transformer
9	U_{wu2}	Phase to phase voltage between the phase w_2 and phase u_2 on the secondary side of the transformer

2.2 Voltages and currents in the converter

The converter part in the induction furnace includes rectifier, inverter and the CROWBAR overvoltage protection circuit between the rectifier and inverter. The important current and voltage signals in this part are indicated in Fig. 2.4.

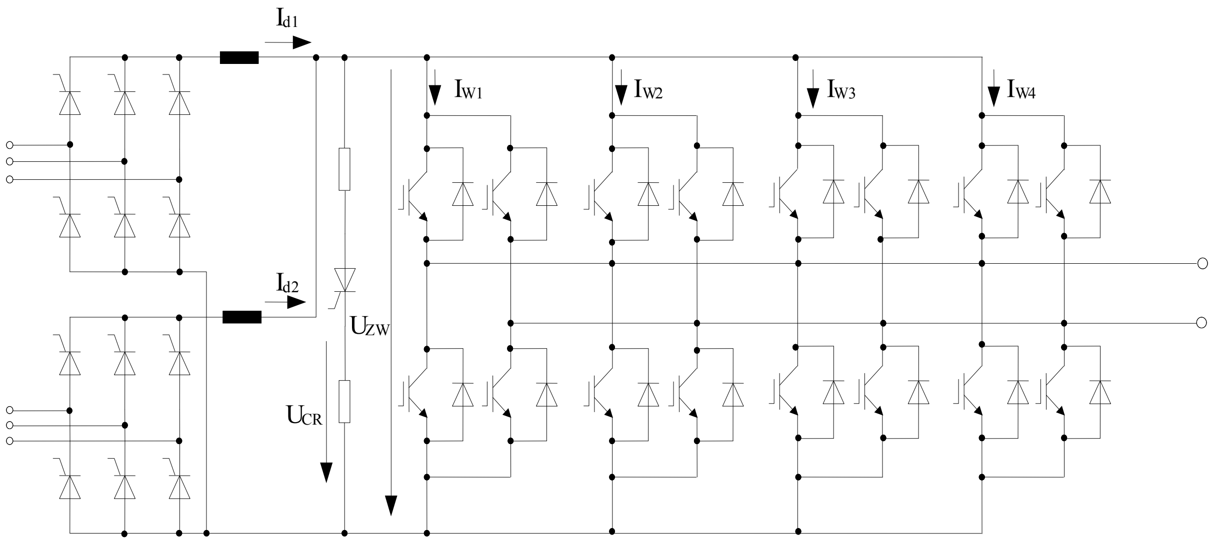


Figure 2.4 Circuit of the converter

The specifications of the signals are given in the table below:

Table 2.2 Overview of the signals in the converter

Signal No.	Signal name	Signification
1	I_{d1}	Direct current output from rectifier1
2	I_{d2}	Direct current output from rectifier2
3	U_{CR}	Voltage over the crowbar resistor

Signal No.	Signal name	Signification
4	U_{ZW}	DC voltage of the link between rectifier and inverter.
5	I_{W1}	Current flows through the first inverter1
6	I_{W2}	Current flows through the first inverter2
7	I_{W3}	Current flows through the first inverter3
8	I_{W4}	Current flows through the first inverter4

2.3 Voltage and current in the coil

The coil part consists of inductive coil, capacitor and inductor. In section 1.3 we have discussed the commutation process in detail. Based on the commutation the important voltage and current signals in this part are indicated in the Figure 2.5.

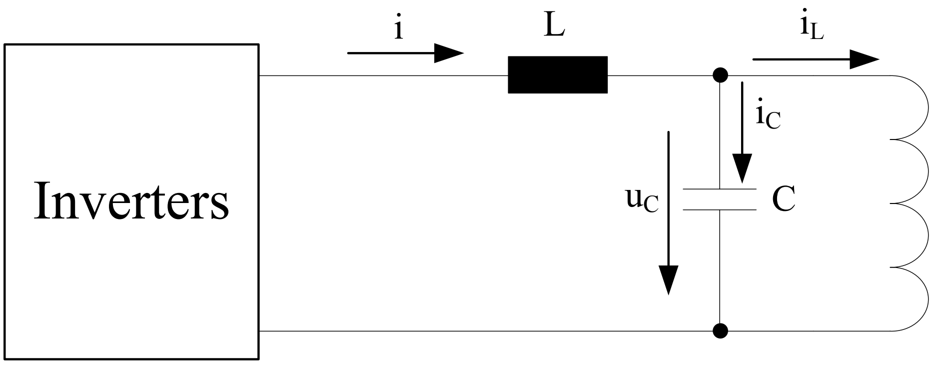


Figure 2.5 Circuit of the coil in the furnace

The overview of these signals is showed in the following table:

Table 2.3 Overview of the signals in the coil

Signal No.	Signal name	Signification
1	i	Current output from inverters
2	i_L	Current through the coil of the furnace
3	i_C	Current through the capacitor C
4	u_C	Voltage over the capacitor parallel to the crucible

3 Measurement fundamentals

3.1 Difference amplifier

A difference amplifier is a type of anolog electronic circuit. Based on the operational amplifier the difference amplifier is realized. With the help of a difference amplifier, the voltage difference of two input voltages can be amplified according to the different demands on amplifications.

3.1.1 Operational amplifier

An operational amplifier has a very high internal amplification factor. It can be used for both DC and AC signals. Here, the internal structure of the operational amplifier will not be discussed in detail. The operational amplifier is considered as an independent component to use. Fig. 3.1 shows the symbol of the operational amplifier in the circuit.

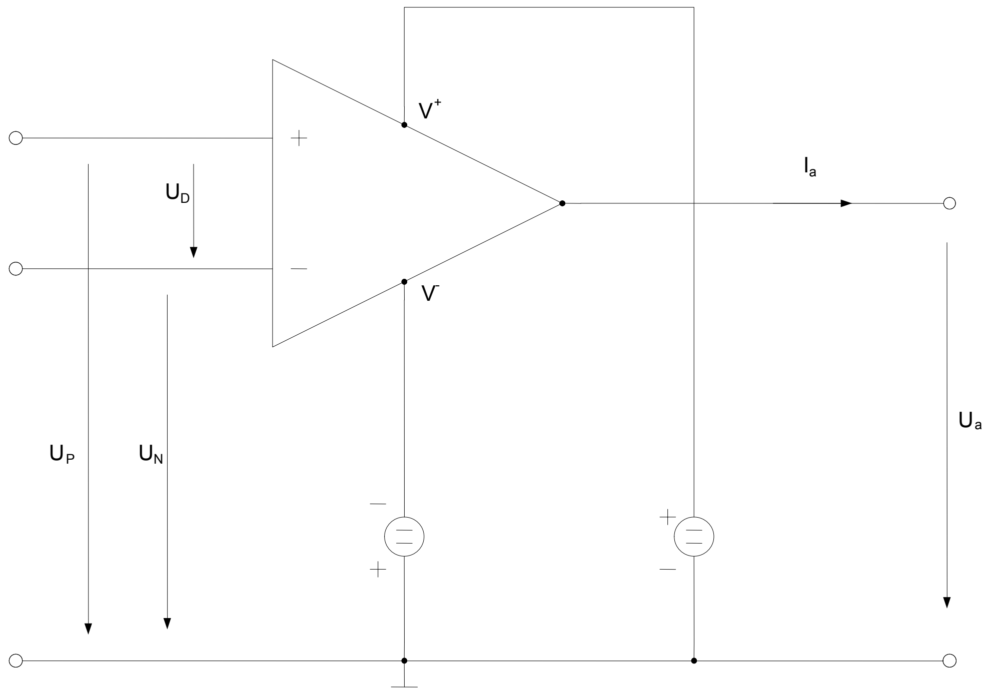


Figure 3.1 Operational amplifier [4]

The standard integrated operational amplifiers need ±15V supply voltages. These two voltages are indicated in the symbol above (see Fig. 3.1), but usually these voltages are not indicated in a functional circuit diagram. The input stage of an operational amplifier is generally designed as a difference input. For this reason the operational amplifier has two inputs. P is non-inverting input and indicated with plus sign; N is inverting input and indicated with minus sign. At low frequency the output voltage is in-phase with the voltage difference of the two inputs. The basic operational behaviour between the input and output terminations is described as formula 3-1:

$$U_a = V_0(U_P - U_N - U_{offset}) + V_{CM}\frac{1}{2}(U_P + U_N) \tag{3-1}$$

U_a – output voltage of the amplifier.

V_0 – difference gain of the operational amplifier.

U_P – input voltage at P-terminal

U_N – input voltage at N-terminal

U_{offset} – offset voltage of the operational amplifier

V_{CM} – common mode gain

The difference gain has a finite value, this value is between 10^4 and 10^7. This kind of amplification is also called open loop amplification, which means amplification without negative feedback. Figure 3.2 gives us a typical process of an output voltage. This output voltage U_a is as function of the voltage difference U_d. In figure 3.2 we could see that in the area of $U_{a\,min}<U_a<U_{a\,max}$ the output voltage U_a is approximately proportional to the voltage difference U_d. When the limit value is reached, the output voltage will not increase as the increasing of U_d. That is to say, the amplifier is controlled. The limit values $U_{a\,min}$ and $U_{a\,max}$ are 3V less than the positive and negative operation voltage of the operational amplifier, namely ±12 V.

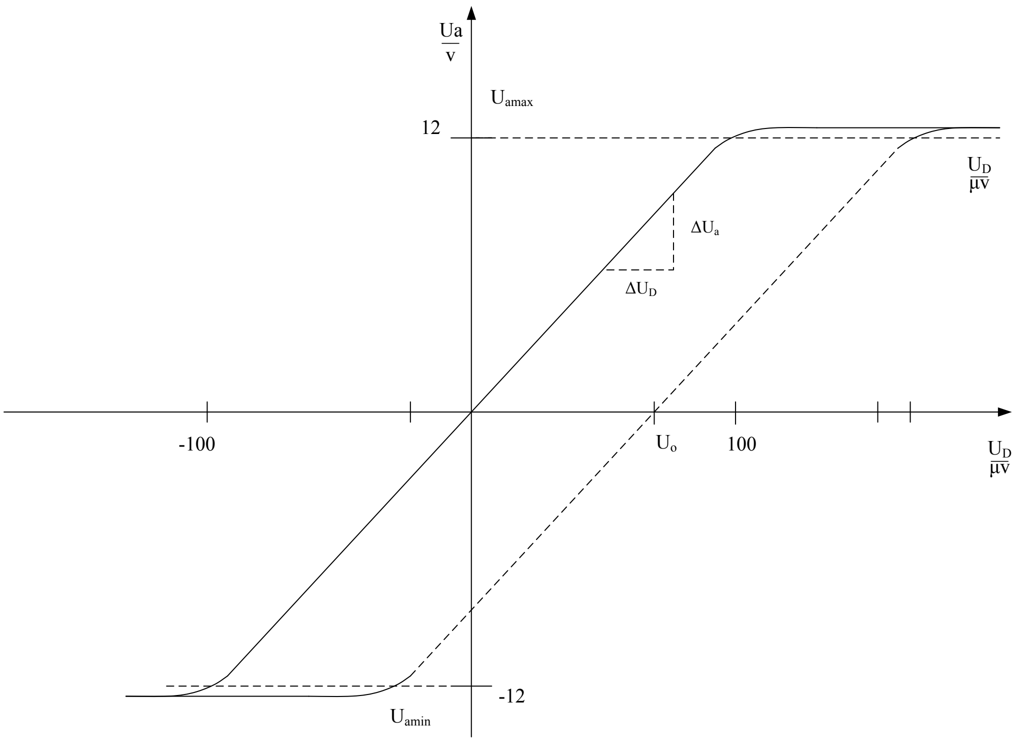


Figure 3.2 Output voltage in function with input voltage difference [4]

In ideal operational amplifier, the transfer curve goes through the origin which is showed with real line in Fig. 3.2 above. But in fact the transfer curve does not go through the origin: the input voltages $U_P = U_N = 0$, the output voltage is not equal to zero, like the broken line in

Figure 3.2 above. In order to get the output voltage $U_a = 0$, it is necessary to apply a voltage between the input terminals U_P and U_N, this voltage is defined as offset voltage U_{offset}.

$$U_{offset}=U_P-U_N \tag{3-2}$$

Usually the offset voltage has only some µV to mV; in many situations it can be ignored. But in case of precision measurement it should be taken into account. If the offset voltage is compensated to zero, the following formula could be induced from the formula above:

$$U_a=A_DU_D=A_D(U_P-U_N) \tag{3-3}$$

The frequency response of operational amplifier is shown in Fig. 3.3.

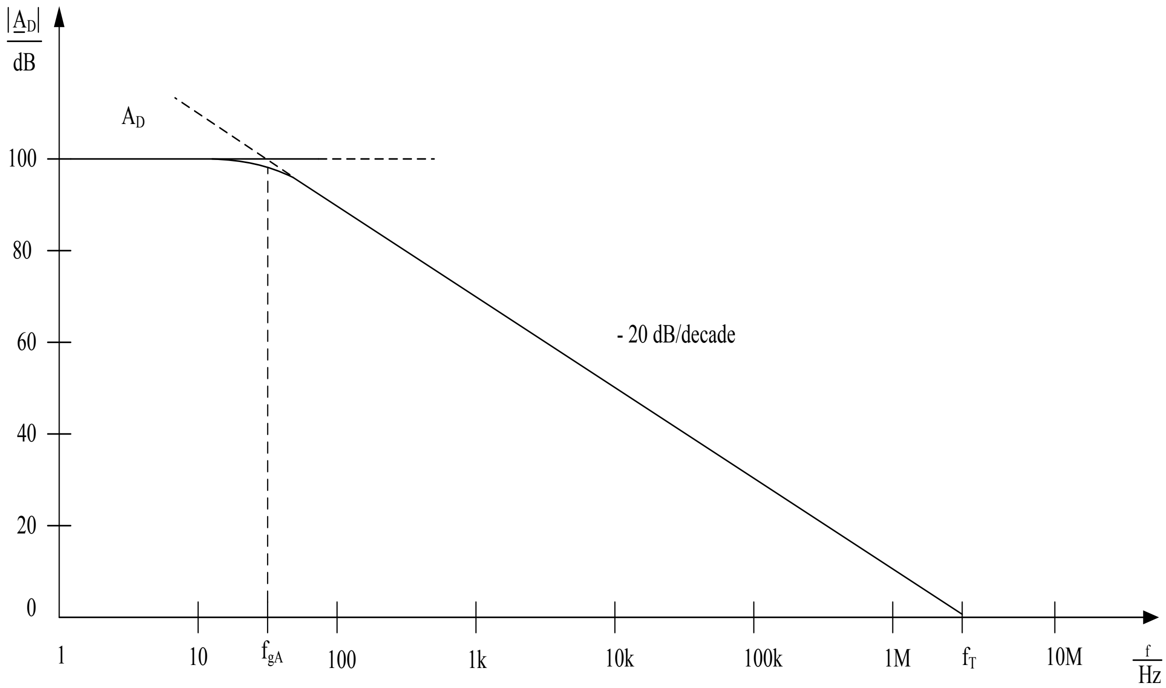


Figure 3.3 Frequency response of operation [4]

From figure 3.3 we can see that the frequency characteristic of an operational amplifier is similar to a low-pass filter. In low frequency area, the amplification ability of the amplifier is high, but if the limit frequency f_{gA} is exceeded, with the increasing of frequency the amplification factor decreases.

The table below shows the parameters of an operational amplifier with the operation voltage of ±15V.

Table 3.1 Parameters of operation amplifier [4]

Parameter	Symbol	Ideal Value	Real value typical
open-loop gain	v	∞	$10^5 ... 10^7$
common-mode gain	v_{Gl}	0	10
common-mode rejection voltage	G	∞	$10^4 ... 10^6$
open-loop bandwidth, cut-off frequency	B, f_g	∞	10...100Hz
transit frequency (gain×bandwidth)	f_t	∞	1...100Mhz
differential input impedance	r_D	∞	1...100MΩ
common mode input impedance	r_{Gl}	∞	1...10GΩ
input bias current	I_B	0	<50nA
offset-current	I_O	0	<5nA
offset-voltage drift	$\Delta U_O / \Delta \vartheta$	0	5μV/K
maximal output voltage	$U_{a\max}$	∞	U_b-2V
maximal output current	$I_{a\max}$	∞	20...100mA
output impedance	r_a	0	1kΩ

3.1.2 Difference amplifier

Operational amplifier has two input terminals, one is non-inverting input and the other is inverting input. Usually the output voltage has the same sign with the non-inverting input voltage, and has an opposite sign to the inverting input voltage. Based on the operational amplifier the difference amplifier can be realized. If we apply two voltages at the two input terminals of the difference amplifier, the voltage difference of the two input voltages will be amplified. The Fig.3.4 below shows us a circuit diagram of a difference amplifier.

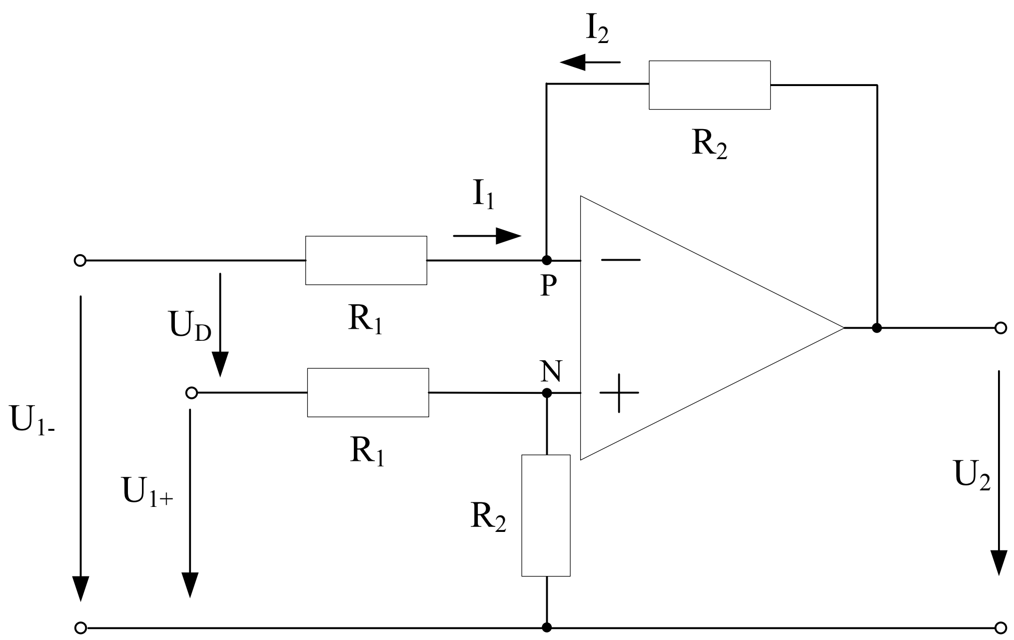


Figure 3.4 Difference amplifier

For the difference amplifier in Figure 3.4 we have following deductions:

$$I_1 + I_2 = 0\,, I_1 = \frac{U_{1-} - U_N}{R_1}\,,\; I_2 = \frac{U_2 - U_N}{R_2} \tag{3-4}$$

$$\Rightarrow \quad \frac{U_{1-} - U_N}{R_1} + \frac{U_2 - U_N}{R_2} = 0 \tag{3-5}$$

$$U_N = U_P\,,\; U_P = U_{1+}\frac{R_1}{R_1 + R_2} \tag{3-6}$$

$$\Rightarrow \quad U_N = U_{1+}\frac{R_1}{R_1 + R_2} \tag{3-7}$$

From formula (3-5) and formula (3-7), we get:

$$U_2 = \frac{R_2}{R_1}(U_{1+} - U_{1-}) \tag{3-8}$$

Formula (3-8) shows the transfer function of the difference amplifier in Fig. 3.4.

3.2 Low-pass filter

3.2.1 Fundamentals of low-pass filter

The low-pass filter is a kind of electronic filter in which the signals with low frequency could be transferred without change, but the signals with high frequency will be damped and lag in phase.

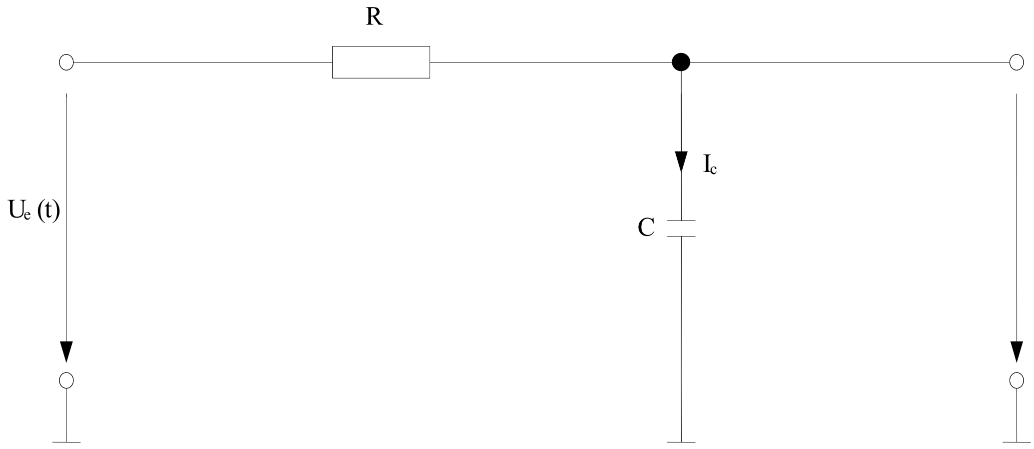


Figure 3.5 Circuit diagram of Low-pass filter

From the circuit above, the following transfer function can be obtained.

$$\underline{A}(\mathrm{j}\omega) = \frac{\underline{U}_a}{\underline{U}_e} = \frac{1/\mathrm{j}\omega}{R + 1/\mathrm{j}\omega} = \frac{1}{1 + \mathrm{j}\omega RC} \quad (3\text{-}9)$$

The frequency characteristic and the displacement of the phase are given below:

$$|\underline{A}| = \frac{1}{\sqrt{1 + \omega^2 R^2 C^2}}, \qquad \varphi = -\arctan \omega RC \quad (3\text{-}10)$$

Fig. 3.6 gives us the Bode plot of the frequency characteristic and the phase shift.

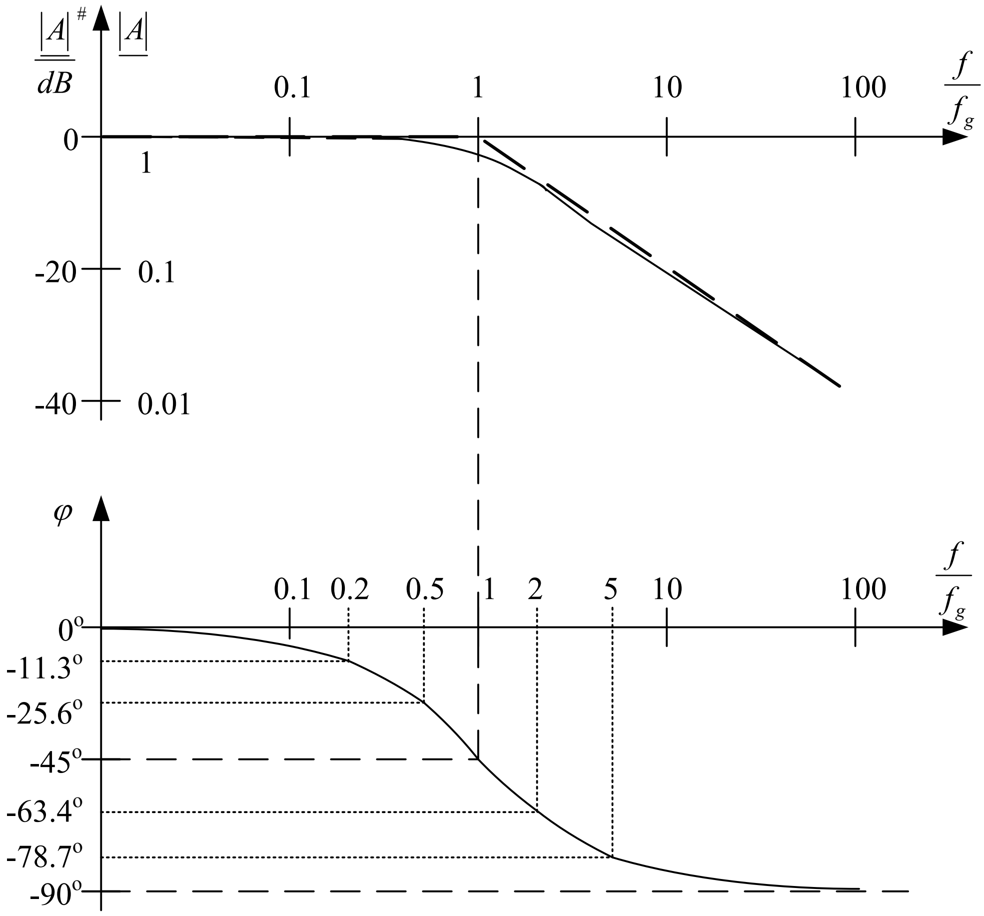


Figure 3.6 Bode plots of the frequency characteristic and the phase shift

From the diagram above, under the cut-off frequency, we get the following equation:

$$|\underline{A}| = \frac{1}{\sqrt{2}} = \frac{1}{\sqrt{1+\omega_g{}^2 R^2 C^2}} \tag{3-11}$$

So that,

$$f_g = \frac{1}{2\pi}\omega_g = \frac{1}{2\pi RC} \tag{3-12}$$

3.2.2 Bessel low-pass filter

Generally used low-pass filters are Bessel low-pass filter, Butterworth low-pass filter and Tschebychev low-pass filter. The step responses of these three low-pass filters are shown in Figure 3.7.

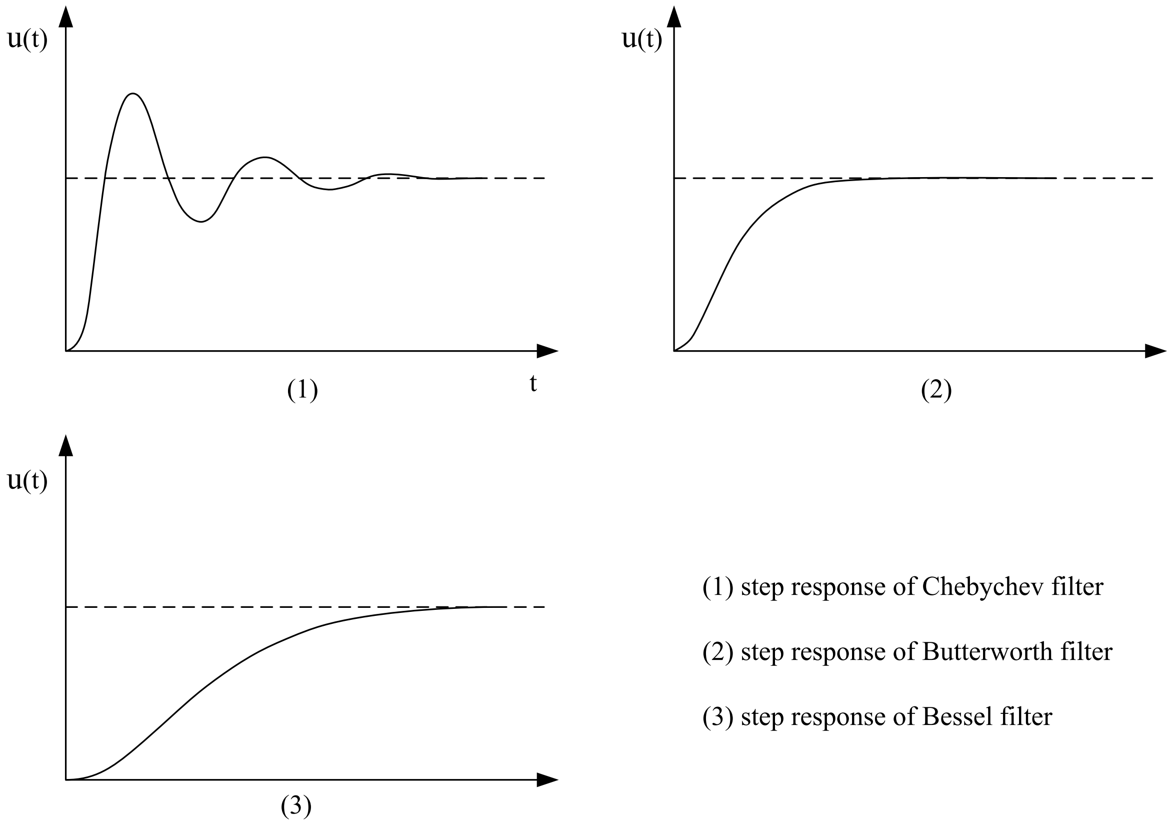


Figure 3.7 Step responses of low-pass filters

In Figure 3.7 we can see that Tschebychev filter has the most ringing and overshoot in step response; Butterworth also has some ringing and overshoot in step response; Bessel filter has the best step response with little ringing or overshoot. In our case, we take use of Bessel low-pass filter. The Bessel low-pass filter that we use has following circuit structure:

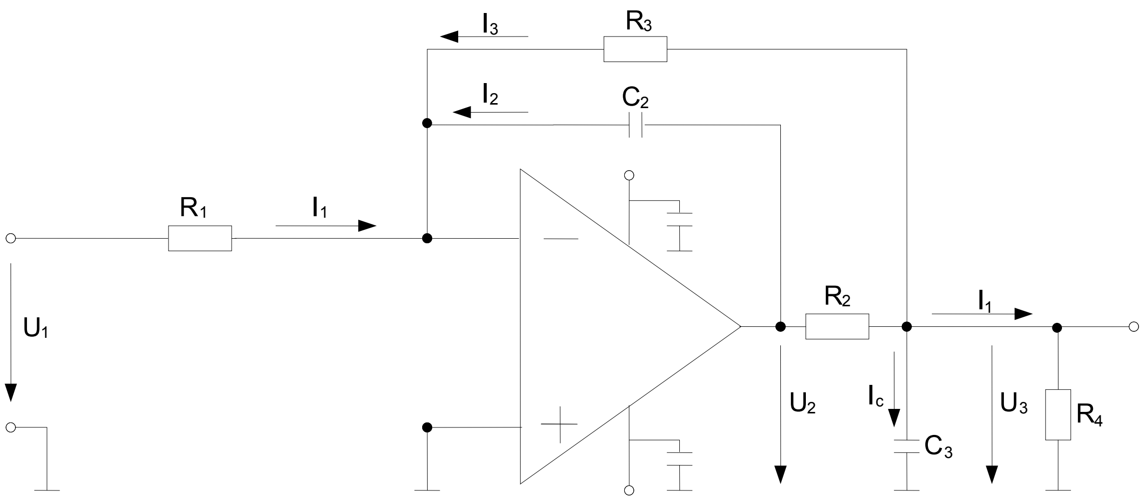


Figure 3.8 Circuit diagram of Bessel low-pass filter

For the filter above, we have following deduction:

$$I_1 = \frac{U_1}{R_1}, \quad I_3 = \frac{U_3}{R_3}, \quad I_4 = \frac{U_3}{R_4} \tag{3-13}$$

$$I_2 = sC_2U_2, I_C = sC_3U_3 \tag{3-14}$$

$$I_1 + I_2 + I_3 = \phi \tag{3-15}$$

$$U_2 - U_3 = R_2 \cdot (I_3 + I_4 + I_C) \tag{3-16}$$

$$\frac{U_1}{R_1} + sC_2U_2 + \frac{U_3}{R_3} = \phi \tag{3-17}$$

$$U_2 - U_3 = R_2 \cdot (\frac{U_3}{R_3} + \frac{U_3}{R_4} + sC_3U_3)$$

$$U_2 = U_3 \cdot (1 + \frac{R_2}{R_3} + \frac{R_2}{R_4} + sC_3R_2)$$

$$\frac{U_3}{R_3} + sC_2U_3 \cdot (1 + \frac{R_2}{R_3} + \frac{R_2}{R_4} + sC_3R_2) = -\frac{U_1}{R_1}$$

$$\frac{U_3}{U_1} = -\frac{R_3}{R_1} \cdot \frac{1}{1 + sC_2R_3 \cdot (1 + \frac{R_2}{R_3} + \frac{R_2}{R_4} + sC_3R_2) \cdot s^2C_2C_3R_2R_3}(1 + \frac{R_2}{R_3} + \frac{R_2}{R_4} + sC_3R_2)$$

$$\frac{U_3}{U_1} = -\frac{R_3}{R_1} \cdot \frac{1}{C_2C_3R_2R_3} \cdot \frac{1}{s^2 + \frac{R_2}{C_3} \cdot (\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}) \cdot s + \frac{1}{C_2C_3R_2R_3}} \tag{3-18}$$

$$\omega_0{}^2 = \frac{1}{C_2C_3R_2R_3}, \quad \omega_0 \cdot \xi = \frac{1}{2C_3} \cdot (\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}) \tag{3-19}$$

$$\xi = \frac{1}{2\omega_0 C_3} \cdot (\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}) \tag{3-20}$$

$v_0 \rangle\rangle 1 \quad R_3 \rangle\rangle R_2 \quad R_4 \rangle\rangle R_2$,

$$\xi \approx \frac{1}{2C_3} \cdot \frac{1}{R_2} \cdot \frac{1}{\omega_0} \tag{3-21}$$

$R_4 = 10 R_2$

$$\xi \cong \frac{1}{2C_3} \cdot \frac{1}{R_2} \cdot \frac{1}{\omega_0} \cdot 1.1 \tag{3-22}$$

$\xi_{Bessel} \approx 0.7$

$$\xi = \frac{1}{2} \cdot \sqrt{\frac{C_2}{C_3} R_2 R_3} \left(\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right) \cong \frac{1}{2} \cdot \sqrt{\frac{C_2 R_3}{C_3 R_2}} \cdot 1.1 \cong 0.7$$

$$\frac{C_2 R_3}{C_3 R_2} \cong \left(\frac{2 \cdot 0.7}{1.1}\right)^2 = (1.27)^2 \tag{3-23}$$

From the deduction above, the parameters of the electronic components should be determined as follows:

V_0 is given:

1, determination of R_3;

2, determination of R_1, $R_1 = \frac{R_3}{V_0}$;

3, determination of ω_0;

4, selection of R_2, according to current ratings of operational amplifier and load;

5, determination of C_3, C_2

$$\omega_0{}^2 = \frac{1}{C_3 R_2 \cdot (1.27)^2 \cdot C_3 R_2}, \quad \frac{C_2 R_3}{C_3 R_2} = (1.27)^2$$

$$\omega_0{}^2 = \frac{1}{C_3 R_2 \cdot (1.27)^2 \cdot C_3 R_2}$$

$$C_3 = \frac{1}{1.27 \omega_0 R_2} \tag{3-24}$$

$R_3 = 47\text{k}$

$$C_2 = \frac{1}{\omega_0{}^2 C_3 R_2 R_3} = \frac{1.27}{R_3 \cdot \omega_0} = 4.3\text{nF} \tag{3-25}$$

4 Establishment of the measurement system

Through the theoretical analysis for the measurement system in the chapters above, in this chapter we will set up the measurement system as the following steps:

1. Selection of the measurement signals,
2. Establishment of the measurement units and the power supply,
3. Extraction of the measurement signals,
4. Scaling of the measurement signals,
5. Collections of the measuring data,
6. Storage of the measuring data.

In this part, we will choose the signals which need to be measured, and then give the connecting mode for each signal, namely, how the original electrical signals in the furnace circuit could be lead out to measuring system, finally the signals will be processed, measured and stored.

Through the analysis for the voltages and currents in the induction furnace circuit, we have chosen 12 signals from the induction furnace circuit and 3 signals from the converter control as our measurement signals. Besides that, a reserve signal channel is also considered and will be realized in later time.

The 12 signals from the furnace circuit are indicated in the diagram below:

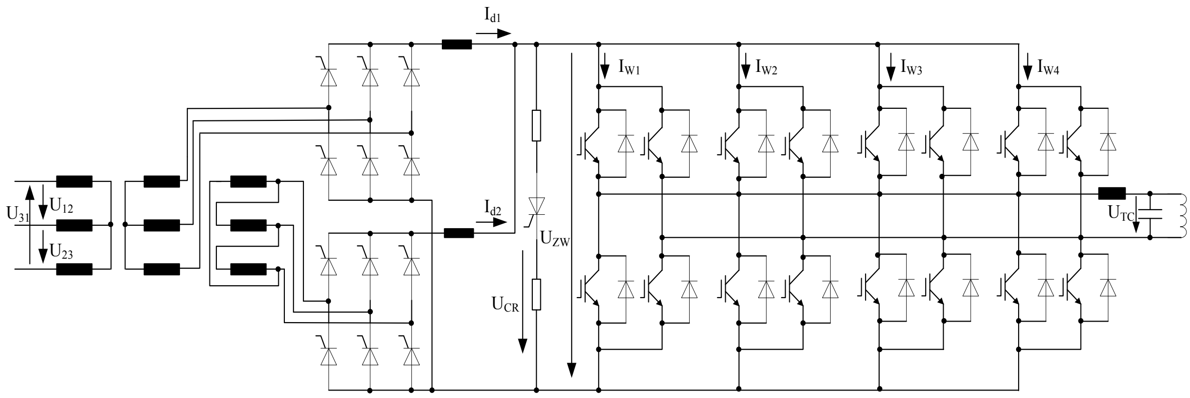


Figure 4.1 Furnace circuit with measurement signals

Table 4.1 overview of the 13 signals:

No.	Signal	Signification
1	U_{12}	Line voltage 20kV between phase L1 and L2 on the primary side of the transformer 20 kV/0.1 kV
2	U_{23}	Line voltage 20kV between phase L2 and L3 on the primary side of the transformer 20 kV/0.1 kV

No.	Signal	Signification
3	U_{31}	Line voltage 20kV between phase L3 and L1 on the primary side of the transformer 20 kV/0.1 kV
4	U_{ZW}	The DC voltage of the link between rectifier and inverter.
5	U_{TC}	The voltage over the capacitor parallel to the crucible
6	U_{CR}	The voltage over the resistor of crowbar equipment unit
7	I_{d1}	The direct current output from the rectifier 1
8	I_{d2}	The direct current output from the rectifier 2
9	I_{w1}	The current flows through the first inverter
10	I_{w2}	The current flows through the second inverter
11	I_{w3}	The current flows through the third inverter
12	I_{w4}	The current flows through the fourth inverter

The 3 signals from the converter control (Fig. 4.2) are:

U_{L1}: This is the supply voltage 230V of the converter control, Phase L(1) to the neutral conductor N.

U_{24N}: The output voltage of the power supply for the electronics of the converter.

U_{24B}: The battery-backed voltage of the power supply for the electronics of the converter. The power supply has a battery group as its reserve voltage. If the line or the power supply does not work properly, the battery group will be used to drive the electronics of the converter for a safe shut-down.

A reserve signal is described with U_{DSIGDA} at present and planned to realize at later time.

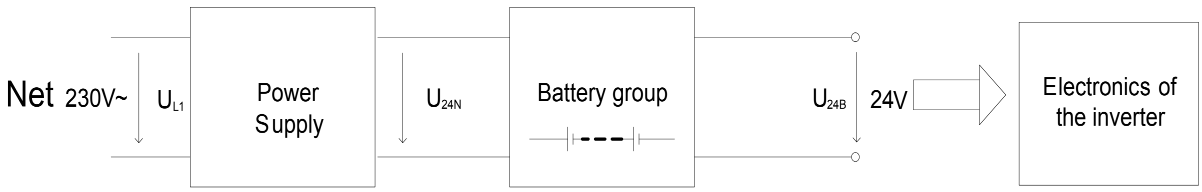


Figure 4.2 Power supply for inverter control

In order to collect and measure the signals by using of software in computer, we will nominate the 16 selected signals and give each signal a corresponding number. These names and corresponding numbers will be used in the software afterwards.

Table 4.2 Signal nomination in software

No.	Signal	Name	No.	Signal	Name
S1	U_{12}	U20L12	S9	U_{CR}	UCROWR
S2	U_{23}	U20L23	S10	U_{DSIGDA}	DSIGDA
S3	U_{31}	U20L31	S11	I_{d1}	ID1LEM
S4	U_{L1}	U230LN	S12	I_{d2}	ID2LEM
S5	U_{24N}	U24NGA	S13	I_{w1}	IWR1V5
S6	U_{24B}	U24BAT	S14	I_{w2}	IWR2V5
S7	U_{ZW}	UZWIKR	S15	I_{w3}	IWR3V5
S8	U_{TC}	UTIEGC	S16	I_{w4}	IWR4V5

4.1 Measurement system and power supply

Through the analysis and selection for the signals we have chosen 16 signals which are significant for the operation of the furnace. These 16 signals will be monitored in the measurement system. For a safe and accurate monitoring of the signals, we need to use voltage transducers, current transducers and difference amplifiers to adjust the original signals from the induction furnace circuit. Through the adjustment for the signals, the range of the new signals is suitable for the measuring and monitoring in the measurement system and by the measuring software of the computer.

The transducers and difference amplifiers should be supplied by certain voltages. Therefore, a power supply is also realized to supply the voltage transducers, current transducers and difference amplifiers.

4.1.1 Measurement system for voltages and currents

The measurement system is composed up of voltage transducers, current transducers and difference amplifiers. Due to the different types of the electrical signals in the furnace circuit, we use different methods to adjust the signals. For the voltage signals which are higher than 100V, we usually use voltage transducers to transfer them into low voltage, and then reduce them again through difference amplifiers; for big current signals, we usually use current transducers to convert them into small currents, and by using of a shut resistance the current signals will be transformed into voltage signals, then laid as input signals to difference amplifiers for further adjustment. For the low voltage signals and small current signals, they ould be input for the difference amplifiers directly, but the small current should be transformed into voltage through shunt resistance at first.

For a safe and stable measurement of the 16 signals, most of the measurement components are placed in a case and fixed inside. (Fig. 4.3)

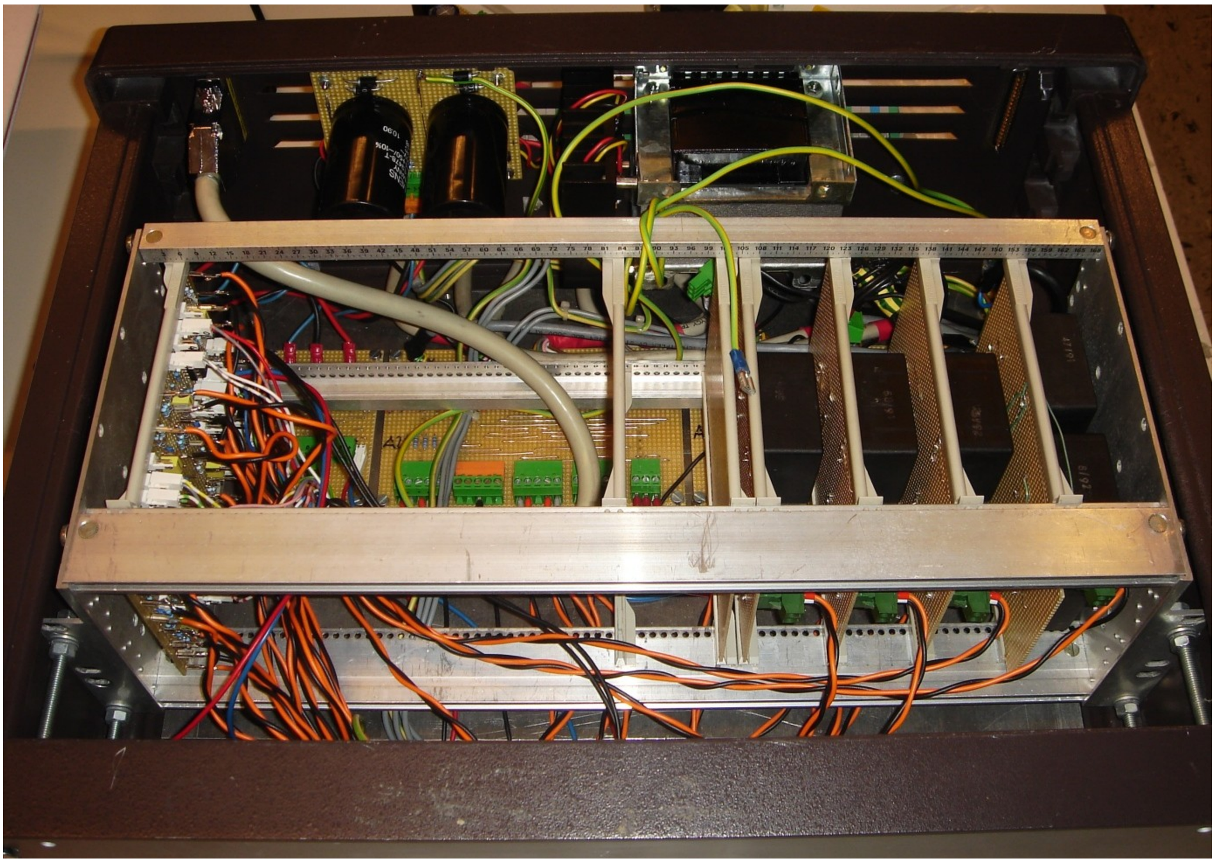


Figure 4.3 Measurement case with components

As shown in the picture above, most of the measurement components such as transformers, power supply and difference amplifiers are fixed in the case. Some measurement devices such as current transducers have to be installed in the furnace circuit because a change in the high-current circuitry is absolutely not feasible. The signals which are obtained from the secondary side of the transducers are lead to the difference amplifiers in the case with by shielded wires.

The 16 signals are processed with different methods. The table below gives us an overview of the processing methods for each signal. We will explain each processing method in detail in the following text.

Table 4.3 processing methods of the signals

number	single	Processing at furnace equipment	Processing in measurement case
S1	U20L12	Voltage transducer 20/0.1kV	2Transformer, Difference Amplifier
S2	U20L23	Voltage transducer 20/0.1kV	2Transformer, Difference Amplifier
S3	U20L31	Voltage transducer 20/0.1kV	2Transformer, Difference Amplifier
S4	U230LN	No processing	4Transformer, Difference Amplifier
S5	U24NGA	No processing	Difference Amplifier
S6	U24BAT	No processing	Difference Amplifier
S7	UZWIKR	LEM-Current Source	Difference Amplifier
S8	UTIEGC	LEM-Current Source	Difference Amplifier
S9	UCROWR	LEM-Current Source	Difference Amplifier
S10	DSIGDA	OP-Current Source	Difference Amplifier
S11	ID1LEM	OP-Current Source	Difference Amplifier
S12	ID2LEM	OP-Current Source	Difference Amplifier
S13	IWR1V5	VAC-Current Source	Difference Amplifier
S14	IWR2V5	VAC-Current Source	Difference Amplifier
S15	IWR3V5	VAC-Current Source	Difference Amplifier
S16	IWR4V5	VAC-Current Source	Difference Amplifier

4.1.1.1 U20L12, U20L23, U20L31

In the induction furnace circuit, first of all we choose the line voltages of the primary side of the transformers as our measurement signals. The RMS value of these voltages is 20kV (phase to phase). Due to the high value of the voltages, they are not suitable for direct measurement. Therefore, we use voltage transducers with the ratio of 20kV/0.1kV to convert 20kV into 100V. Then the 100V voltage will be sent to the measuring case by wires for further processing. (Fig. 4.4)

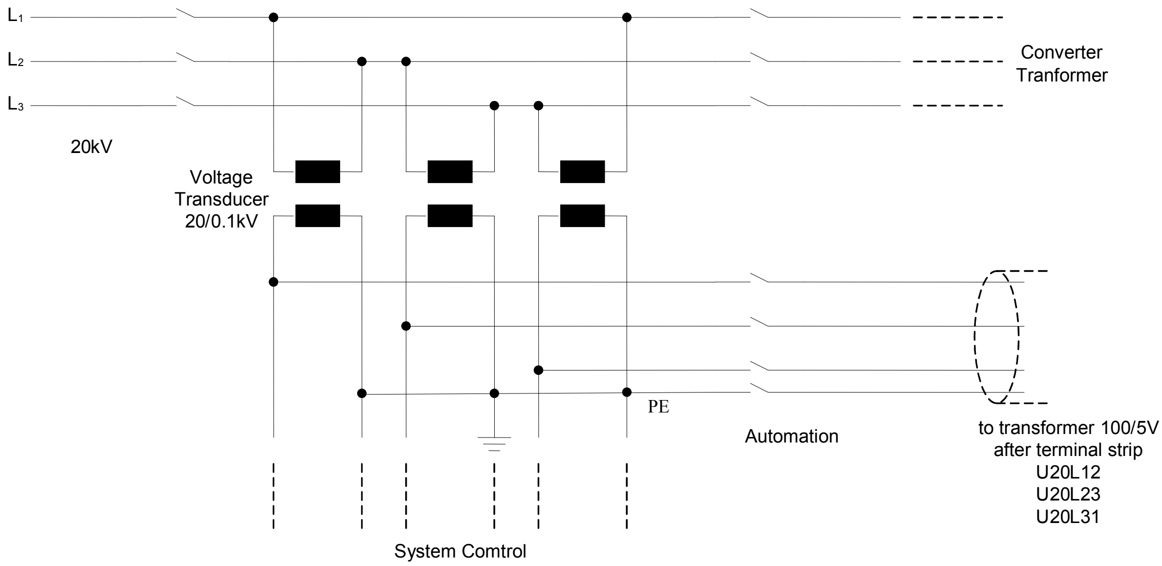


Figure 4.4 Measurement circuit of 20kV voltage

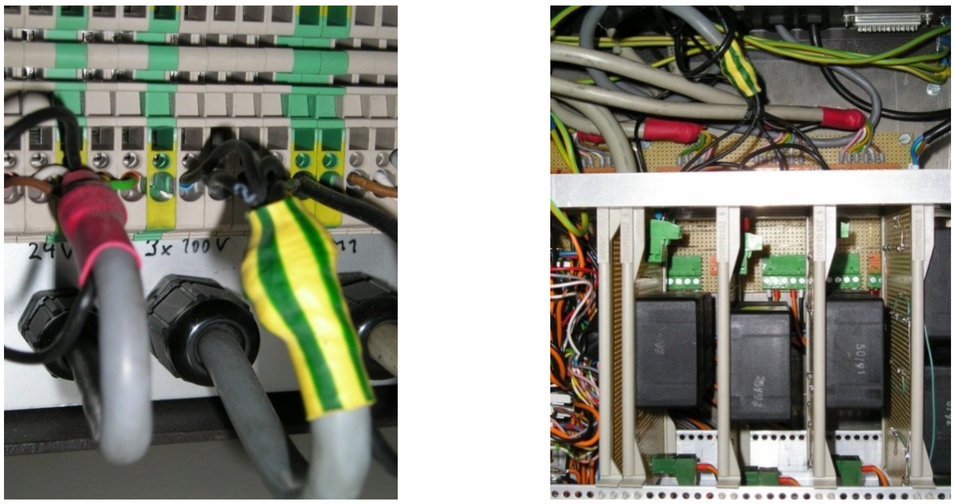


Figure 4.5 Wires and voltage transducers for 100V voltage

The three 100V voltages transformed from the 20kV are lead into the measuring case through wires and terminal strip (Fig. 4.5). In the measuring case, these three voltages are input signals for three transformer groups (Fig. 4.5). Each transformer group is made of two transformers. The ratios of the two transformers are all 220V/21V (Fig. 4.6). The two transformers are connected to each other in according to Fig.4.7, so that the voltage could be reduced from 100V to 5V.

Figure 4.6 Transformer group for 100V voltage

In order to obtain a reasonable voltage transducer (with continuous overload capability of 460V at input side) and get a voltage value which is suitable on the secondary side, the transformer group is connected in the following way: the primary windings of the two transformers are connected in series, the secondary windings are connect parallel (Fig. 4.7).

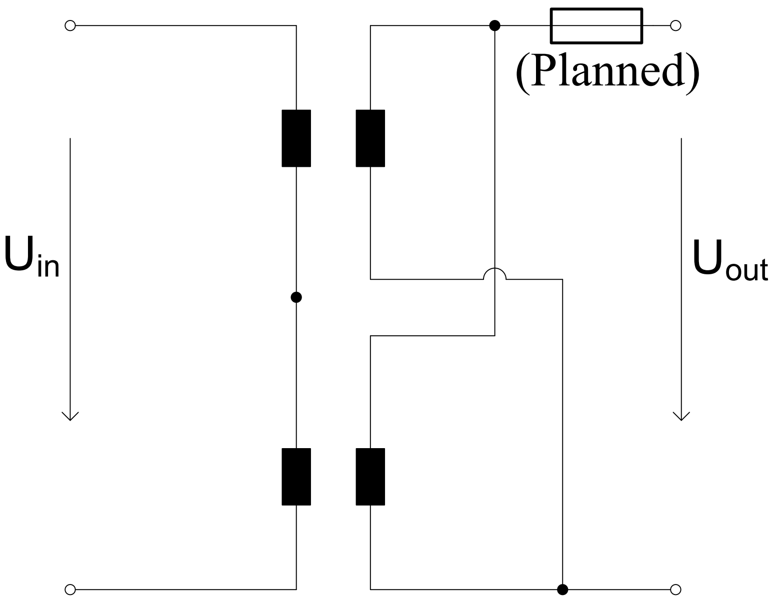


Figure 4.7 Connection circuit of transformer group for 100V voltage

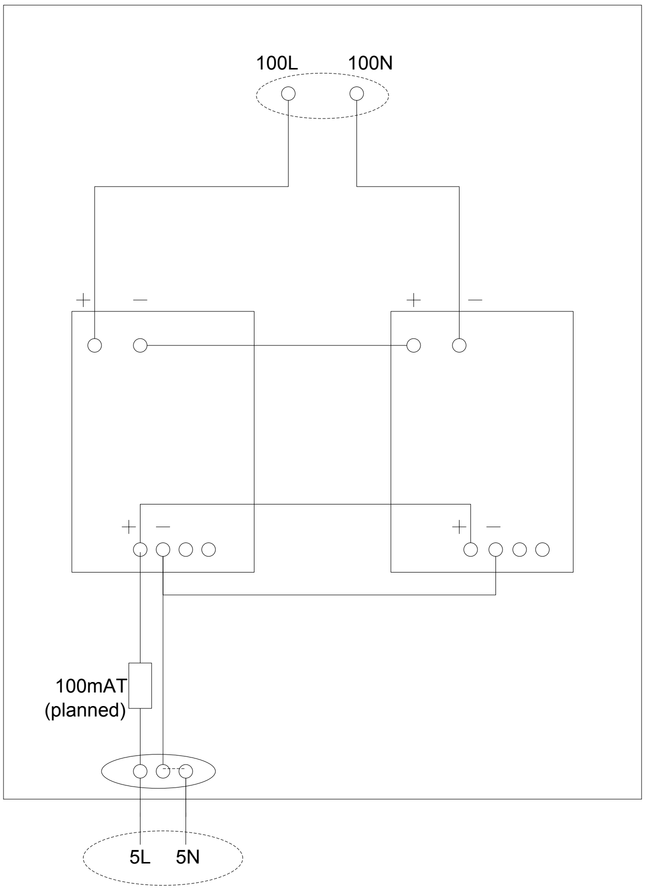


Figure 4.8 Cricuit layout of transformer group for 100V

Through the connecting mode above, the ratio of the transformer group is different with the original ratio of the signal transformer. The original ratio of the transformer is 220/21V, but the new ratio of the transformer group is 220/10.5V. When the 100V which comes from the 20kV is applied at the primary side of the transformer group, a voltage of 5.25V will be output from the secondary side.

By using the transformer group above, the voltage is reduced from 100V to 5.25V. This voltage will be sent to the difference amplifier for further processing. The difference amplifier has two main functions: first of all, the voltage could be adjusted again in the difference amplifier; secondly, if a short circuit happens on the output side of the difference amplifier, the difference amplifier could be used as an insulating unit which should protect the components on the input side of the difference amplifier from being destroyed by the short circuit current. After output from the difference amplifier, the voltage signal will be sent to other equipments for measurement, indication and further processing. Since finally all the 16 signal will be sent into 16 difference amplifiers for processing, we will discuss the 16 difference amplifiers together in section 4.1.3.

4.1.1.2 U230LN

For converter control we need a power supply with 230V AC input voltage and 24V DC output voltage. The signal U230LN is the 230V AC input voltage for the converter control. It must be also reduced for measurement, indication and storage.

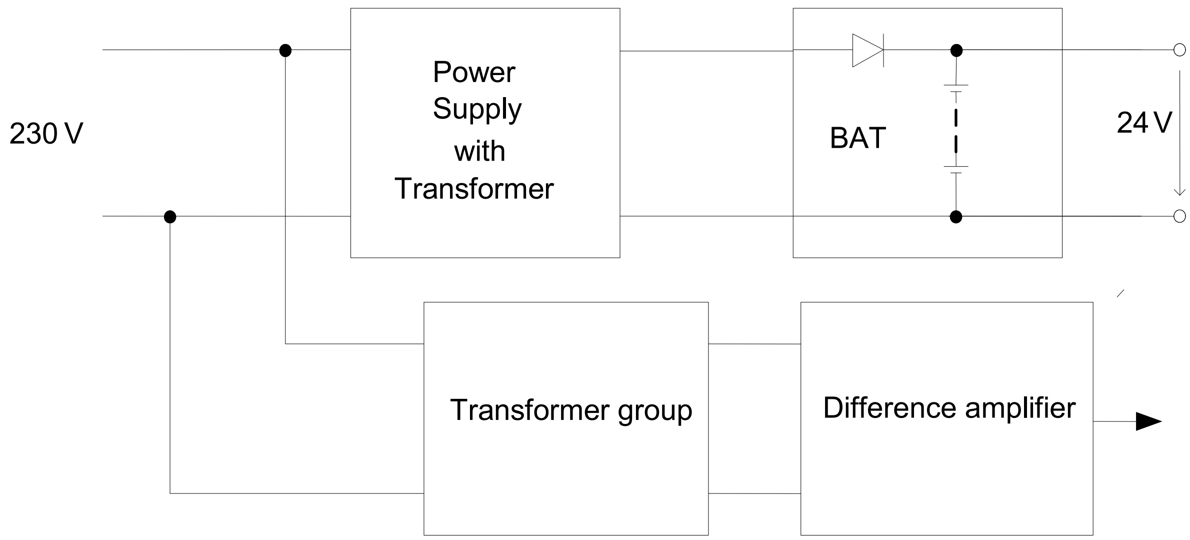


Figure 4.9 Measurement circuit for signal U230LN

Like the three 100V voltages above, this voltage is directly sent to the measurement case. In the measurement case, the voltage will be reduced by a transformer group which consists of four transformers, the ratios of the four transformers are all 230/21V. The four transformers are connected like this: the primary windings of the four transformers are connected in series, the secondary windings are parallel connected (Fig. 4.10), so that a new ratio of 230/6V is obtained while yielding a high continuous overload voltage capability of $920V_{RMS}$.

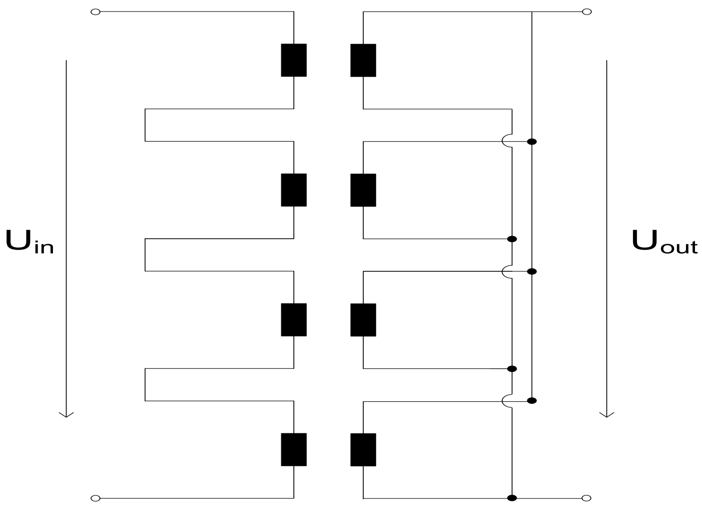


Figure 4.10 Connection circuit of the transformer group for 230V voltage

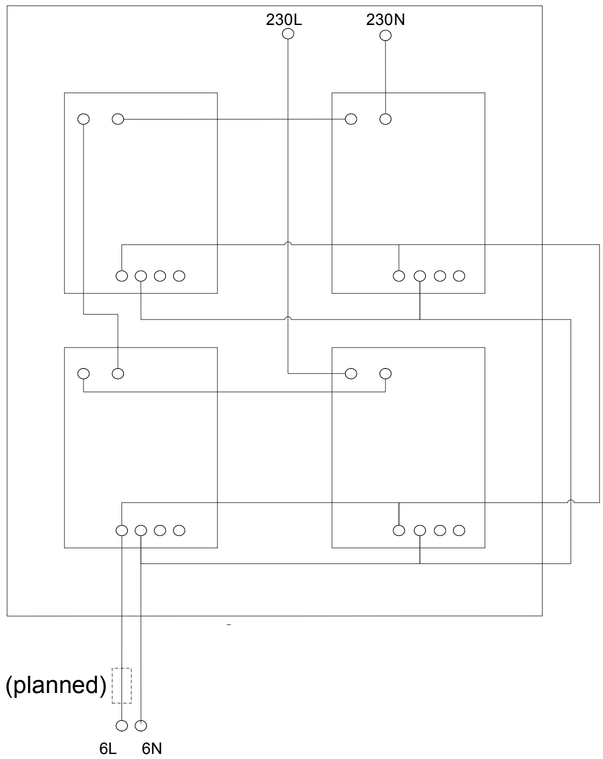


Figure 4.11 Circuit layout of transformer group for 230V voltage

By using the connecting way above, the following transformer group is set up. With this transformer group, we get the output voltage of about 6V on the secondary side of the transformer group. This voltage will be sent to the difference amplifier.

Figure 4.12 Transformer group for 230V voltage signal

4.1.1.3 UZWVWR, UTIEGC

These two voltage signals are the DC-link voltage of the between the rectifier and the inverter and the voltage over the capacitor parallel to the furnace coil. The values of the two voltages are about 1200V. This value is too high to measure directly. Therefore, it should be reduced at first, and then measured. For these two voltages, we use a LEM voltage transducer. The 1200V voltage is transferred into 60mA current, through a resistance of 90Ω, this current is transferred into a voltage of 5.4V. Finally, it is sent to a difference amplifier.

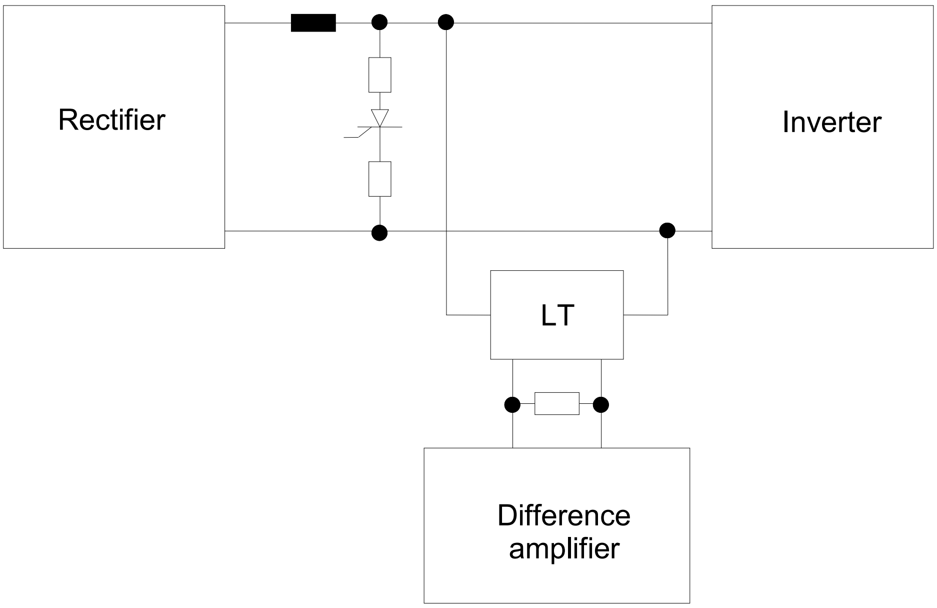


Figure 4.13 Measurement circuit for DC-link voltage

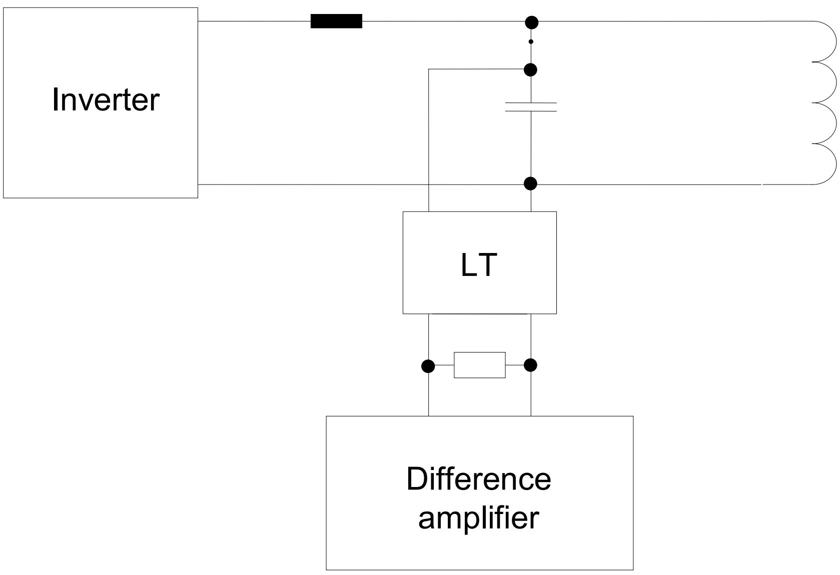


Figure 4.14 Measurement circuit for voltage over the capacitor

4.1.1.4 U24NGA, U24BAT

These two signals are the output voltage of the power supply for the electronics of the inverter and the voltage of the battery group. The value of the voltage is about 24V. These two voltages are directly sent to difference amplifiers.

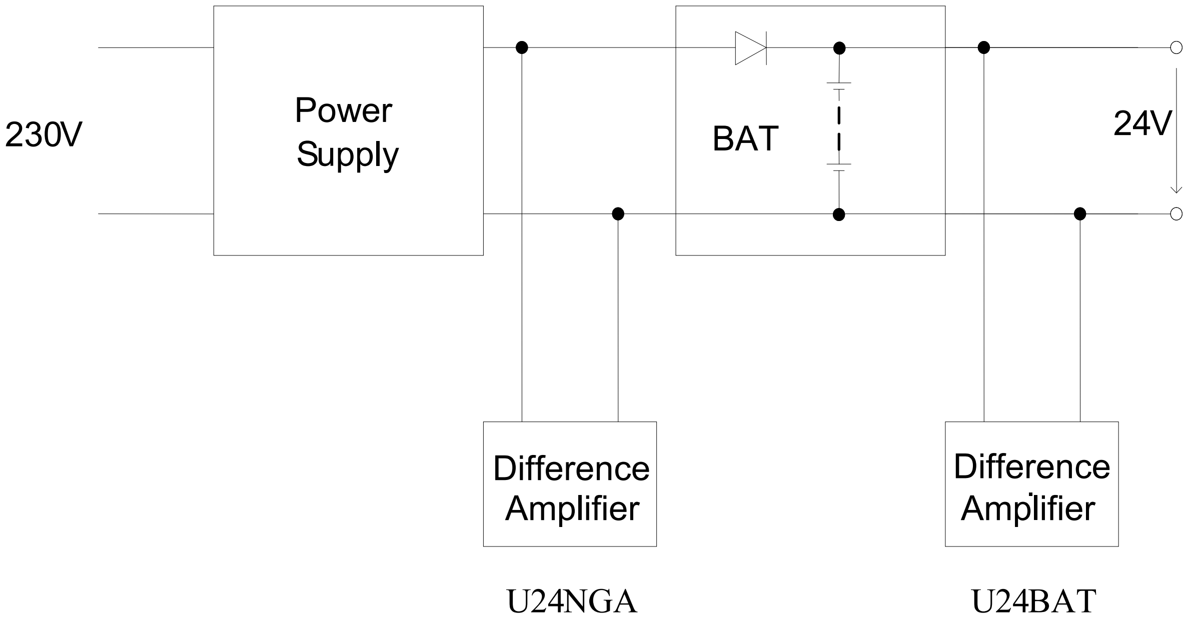


Figure 4.15 Measurement circuit for signal U24NGA and U24BAT

4.1.1.5 UCROWR

This signal is the voltage over the crowbar resistor. The crowbar is protection equipment against DC-overvoltage. In the furnace circuit, the crowbar is located between the rectifier and the inverter. If for any reason the DC-link voltage becomes too high and could damage the inverter, the crowbar equipment will be actuated and prevent the overvoltage from damaging the inverter. The voltage over the crowbar is about 600V. It should be adjusted with the LEM voltage transducer. The 600V voltage is changed into 80mA current, through a 750Ω resistance this current is changed into 6V voltage, and then the voltage is sent to the difference amplifier.

4.1.1.6 DSIGDA

This is a reserve signal at present. It is planned to realize at later time a combination of various error signals from the converter control and to establish an analog signal from these digital signals using binary weighting with a digital-analog converter.

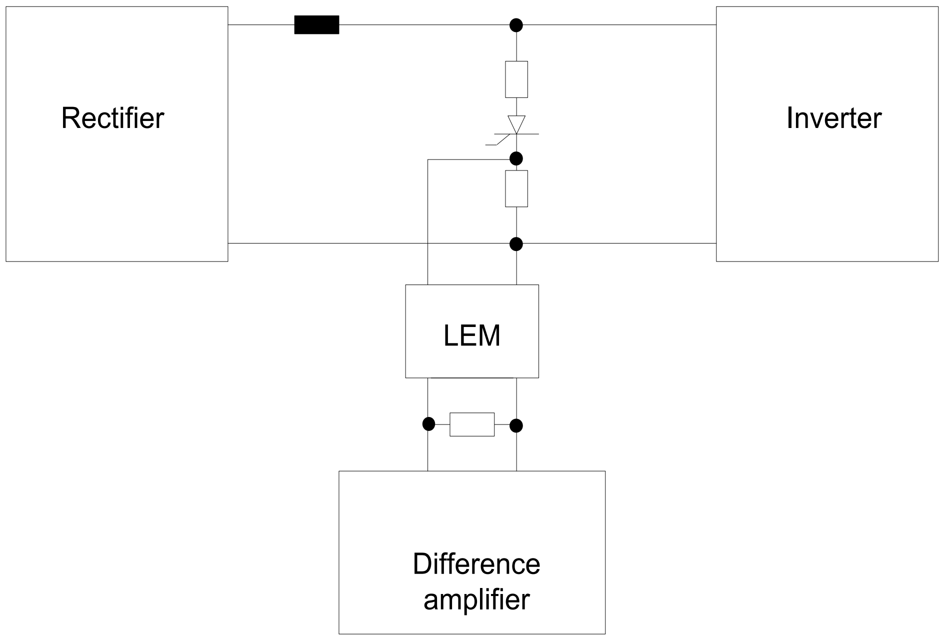


Figure 4.16 Measurement circuit for the voltage over the resistor of crowbar

4.1.1.7 ID1LEM, ID2LEM

The value of these two current is about 5000A. For a safe measurement, these currents must be reduced with transducers. The process is as follows; 5000A is reduced to 1A with a current transducer. By means of a 5Ω resistance the 1A current is transferred into a 5V voltage by the internal converter control. This voltage serves as a input for the added data acquisition arrangement and is then sent to an amplifier. The output voltage of the amplifier is connected with a voltage controlled current source. The output current of the current source is 3mA, this current flows through a 1.1kΩ resistor, so that we get a voltage of 3.3V over the resistor. This 3.3V voltage is sent to the difference amplifier in the measurement case.

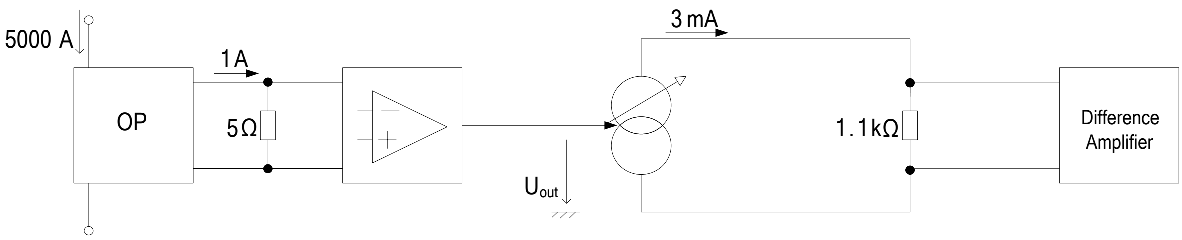


Figure 4.17 Measurement circuit for the currents output from rectifiers

4.1.1.8 IWR1V5, IWR2V5, IWR3V5, IWR4V5

These four signals are the currents which flow through the four inverters. They are processed mainly through the own current transducers of the inverter and the extra VAC current transducers. In the furnace equipment, the inverter has its own current transducer. The 4000A current is reduced to 5A with this current transducer, and then with the extra VAC transducer the 5A current is reduced again to 12.5mA. This current flows through a 100Ω resistor, and we get 1.25V voltage over the resistor. Finally, the 1.25V voltage signal is sent to difference amplifier in the case.

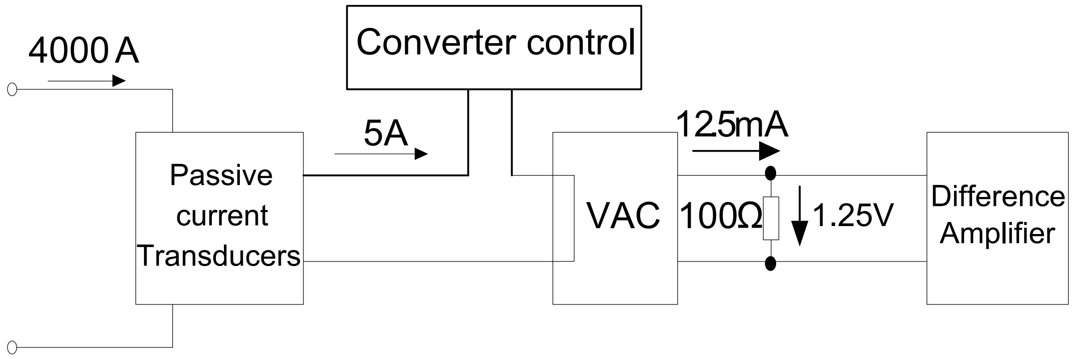


Figure 4.18 Measurement circuit for currents through the inverters

4.1.2 Interface of the measuring case

In chapter 4.11, we have described all the processing methods for the 16 signals. All the signals will be either sent to the difference amplifiers following voltage or current transducers or sent directly to the difference amplifiers. The difference amplifiers are located in the measurement case. Therefore, we need to send all the signals to the measurement case together. Here we use a terminal strip to connect all the signals with the difference amplifiers in the measuring case. The terminal strip has two rows of interface. One row is above, the other row is below (Fig. 4.19). Each of the two interfaces from the up-row and down-row are internal connected. We connect all the 16 signals from the furnace circuit and measuring circuit with the up-row interfaces, the down-row interfaces are connected with the measuring devices inside the case. Because of the internal connection of the up-row interfaces with down-row interfaces, all the measurement signals could be brought from outside to inside.

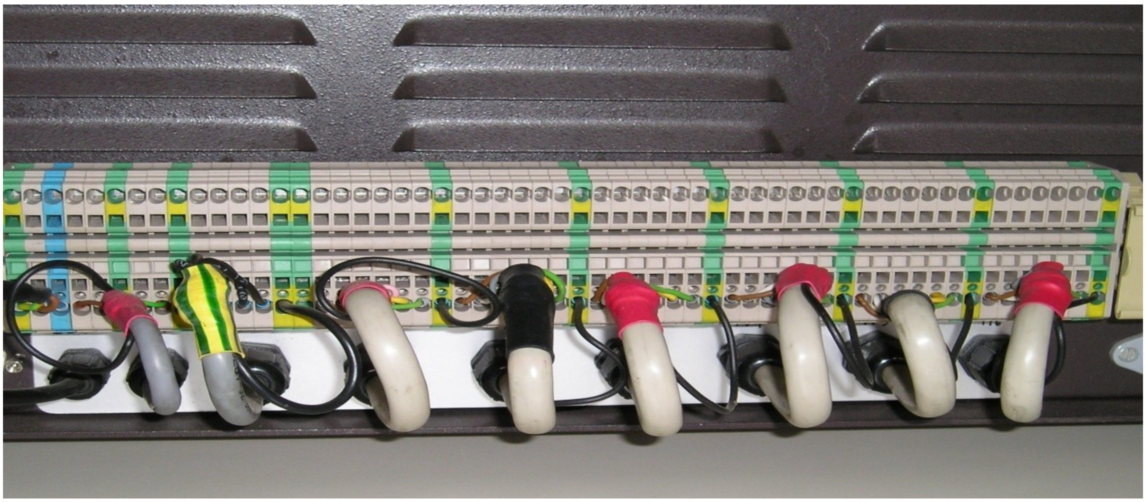


Figure 4.19 Terminal strip on the measurement case

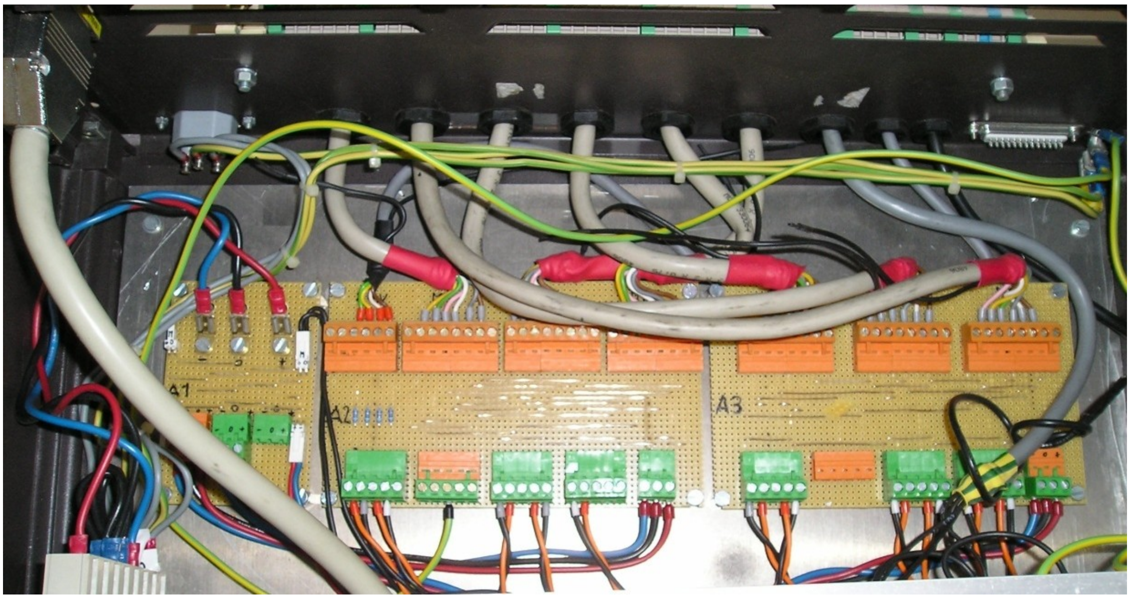


Figure 4.20 Signal distributors inside the measurement case

Inside the measurement case, the signals are not sent to the difference amplifiers directly, but they will be first of all sent to a signal distributor and through the distributor to the transformer groups or difference amplifiers. From Fig. 4.20, we could see that on both the input side (up) and the output side (down) of the distributor there are several plugs and sockets. The plugs are connected with cables and the sockets on both sides of the distributor are connected with wires on the back side of the board. The signals are transferred from outside to the distributor through the cables, plugs and sockets on the input side. Then the signals will be sent from the distributor to the difference amplifiers or the transformer groups through the sockets, plugs and cables of the output side. On the input side, each signal is connected with a certain plug. The following figures show us the arrangements of the plugs on the input side.

U20L12, U20L23, U20L31

These three signals are connected with the plugs as follows (Fig. 4.21), and then the plugs are connected with the sockets on the three transformer groups (Fig. 4.22). This plug group has the number M1.

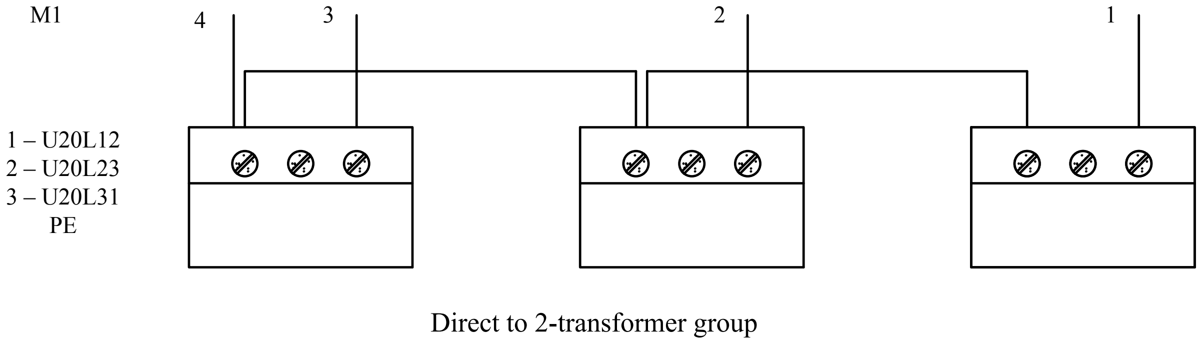


Figure 4.21 Connection of plugs for 100V voltage signals

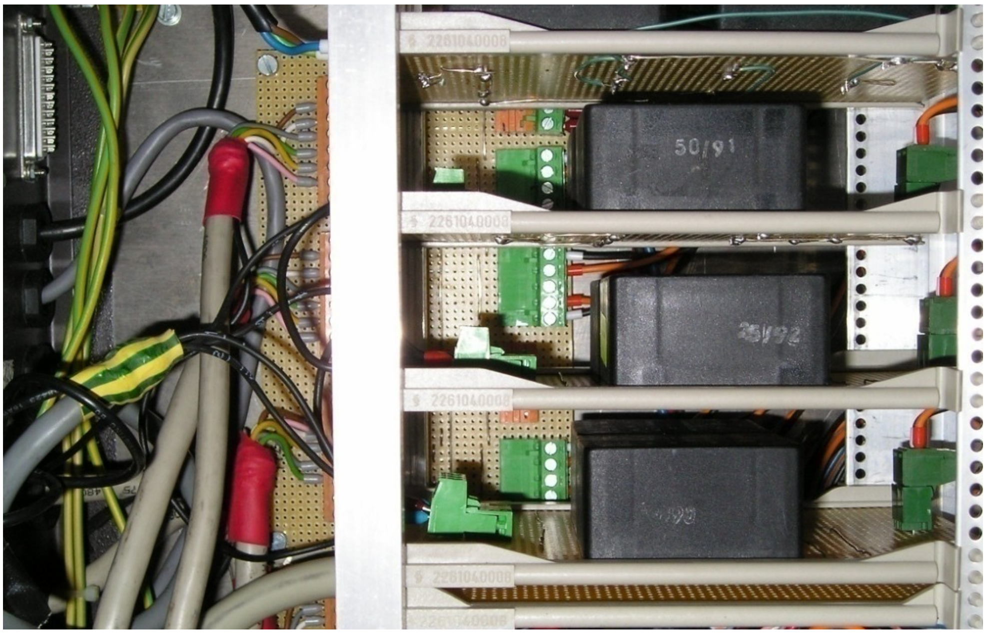


Figure 4.22 Connection of plugs with transformer group for 100V voltage signals

U230LN

This signal is connected with the plug as follows and this plug is then connected directly with the socket on the 4-transformer group.

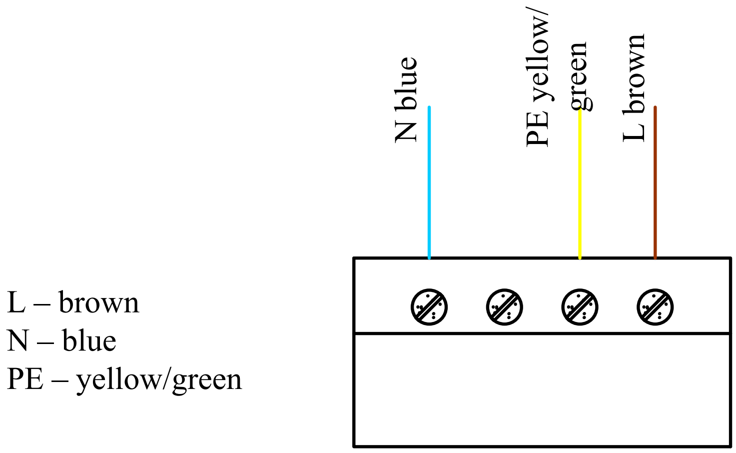


Figure 4.23 Connection of plug for 230V voltage signal

UZWVWR, UTIEGC

These two signals are connected as follows and have respectively the numbers of M2 and M3. Power supply wires for the LEM LV200 voltage transducers are included.

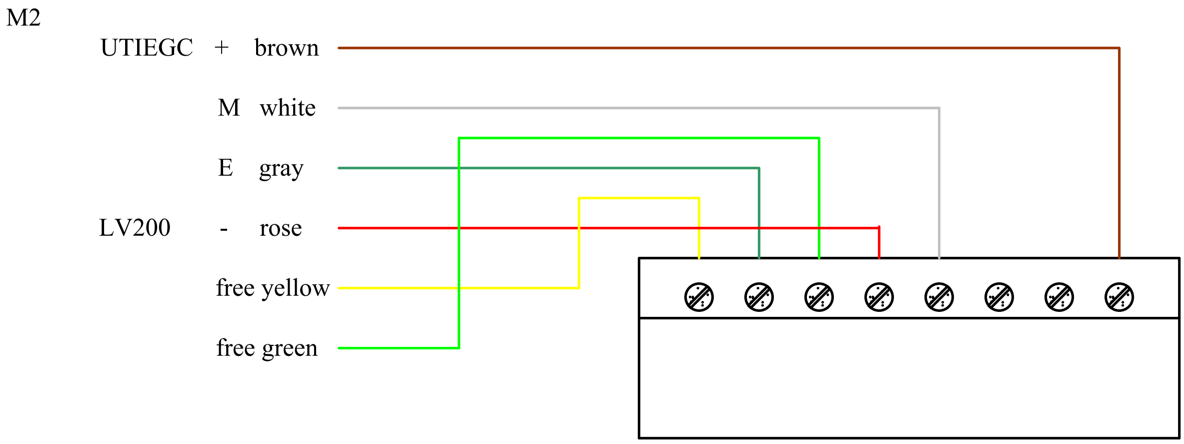


Figure 4.24 Connection of wires with plug for voltage over capacitor parallel to furnace coil

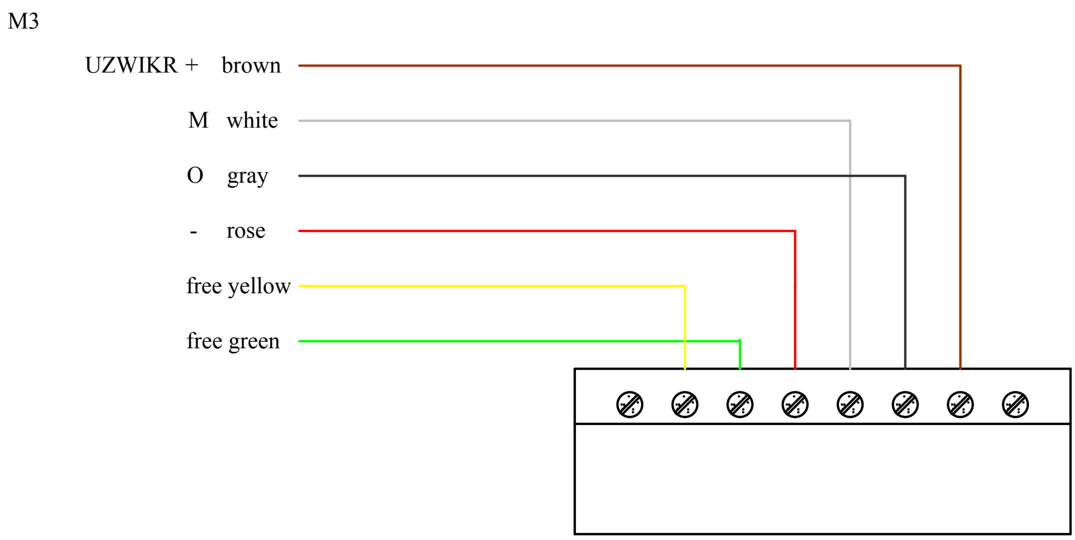


Figure 4.25 Connection of wires with plug for DC-link voltage

U24NGA, U24BAT

Following picture shows us the connection of the voltage of the power supply for electronics of the inverter and the back-up voltage.

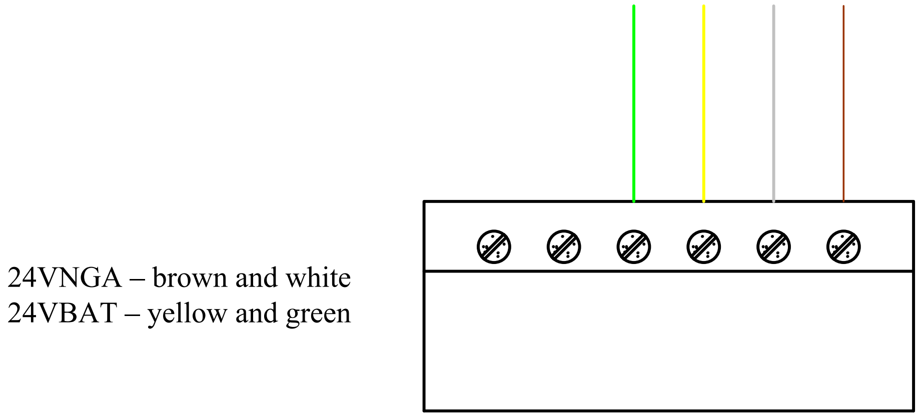


Figure 4.26 Connection of plug for signals U24NGA and U24BAT

ID1LEM, ID2LEM

These two signals of the current have the following connection with the plug and its number is M4. The wires necessary for supplying the amplifier and voltage controlled current source are included.

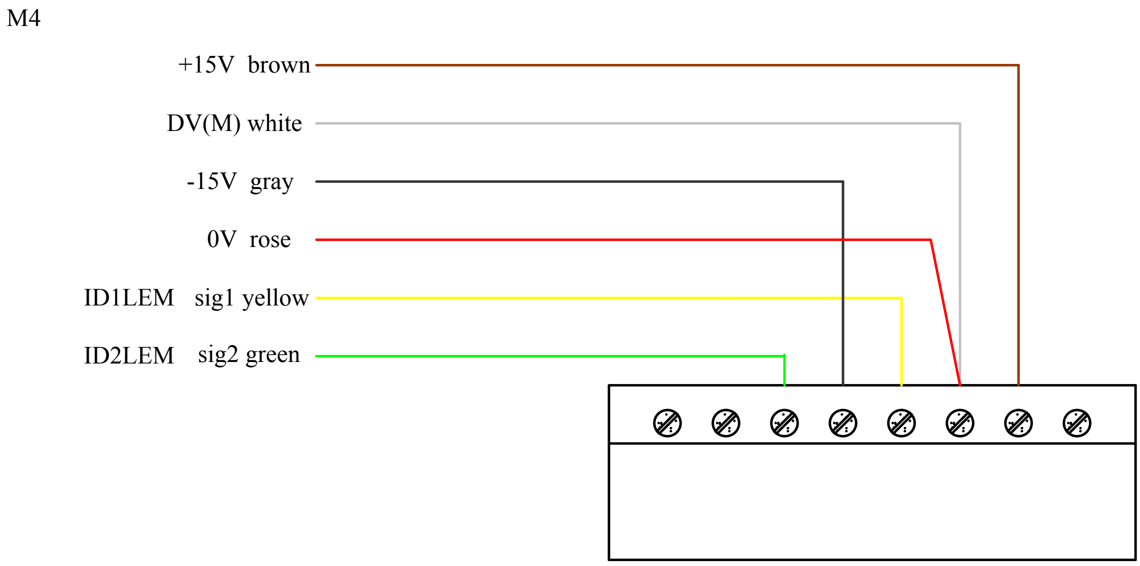


Figure 4.27 Connection of wires with plug for currents through rectifiers

IWR1V5, IWR2V5, IWR3V5, IWR4V5

The following two pictures show us the connection of the currents in the inverter and they have the numbers of M5 and M6. The VAC current transducer supply wires are included.

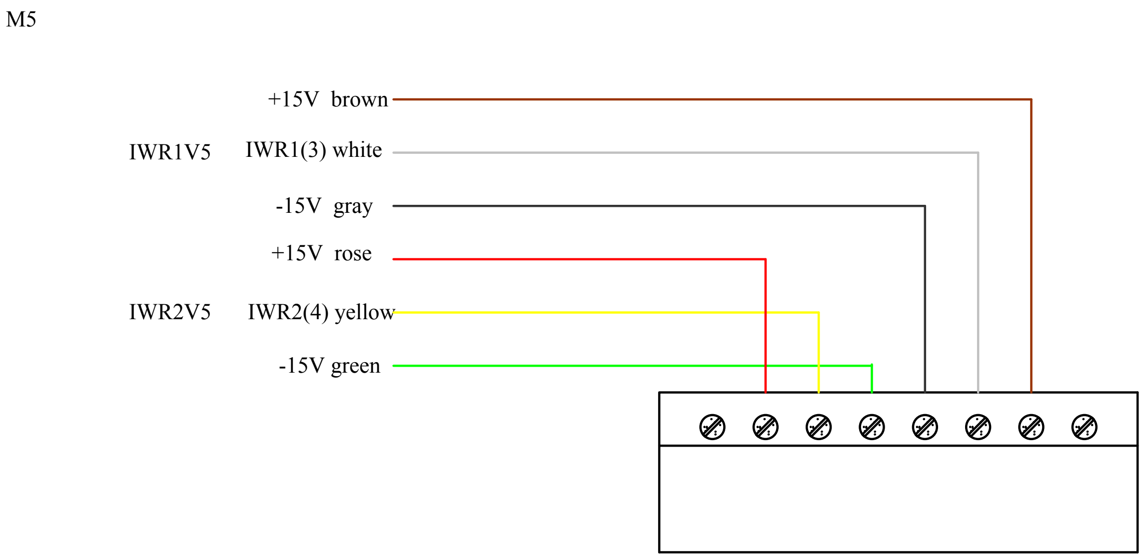


Figure 4.28 Connection of wires with plug for currents through inverter1 and 2

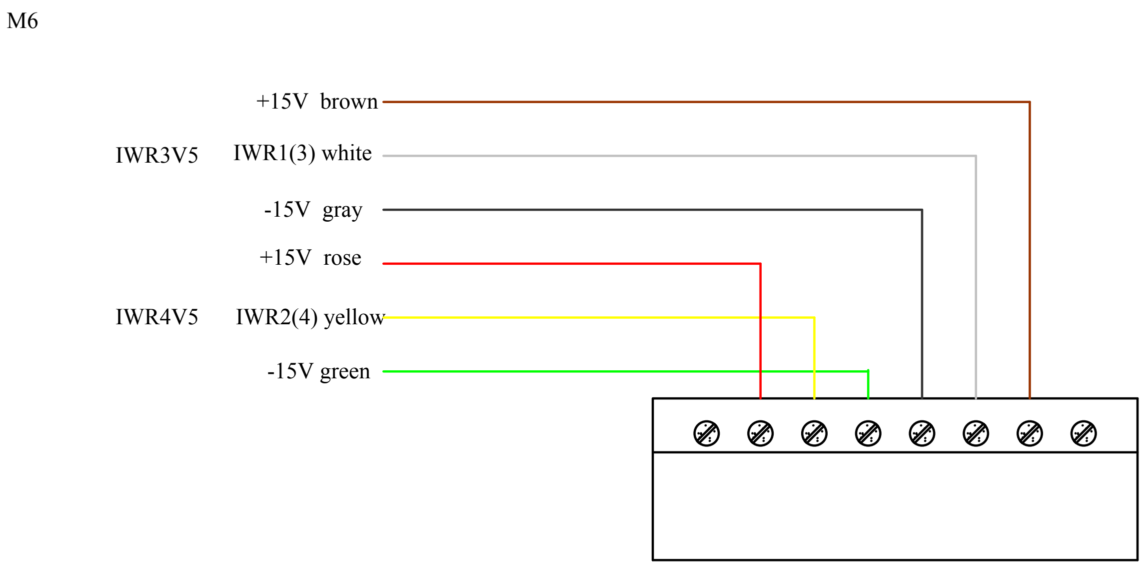


Figure 4.29 Connection of wires with plug for currents through inverter3 and 4

UCROWR

The plug M7 gives us the connection of the signal UCROWR which is the voltage from the crowbar equipment.

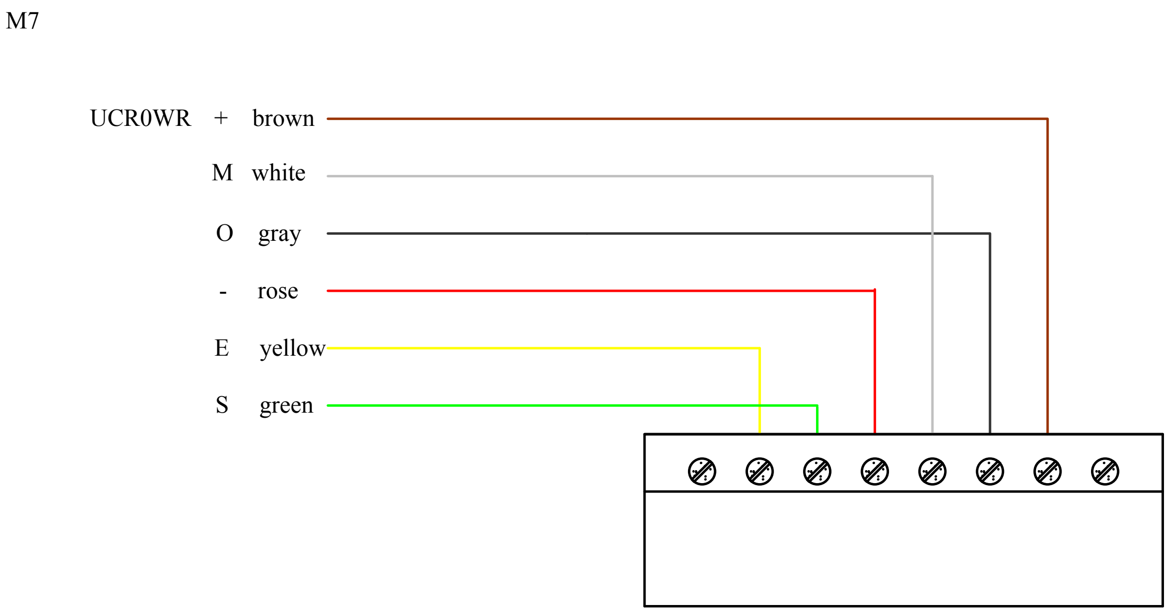


Figure 4.30 Connection of wires with plug for voltage over the resistor of Crowbar

With the pictures above, we have explained the connection of the cables with the plugs. The following two pictures show us the signal distribution on the distributor and the detailed connections of the plugs with the sockets.

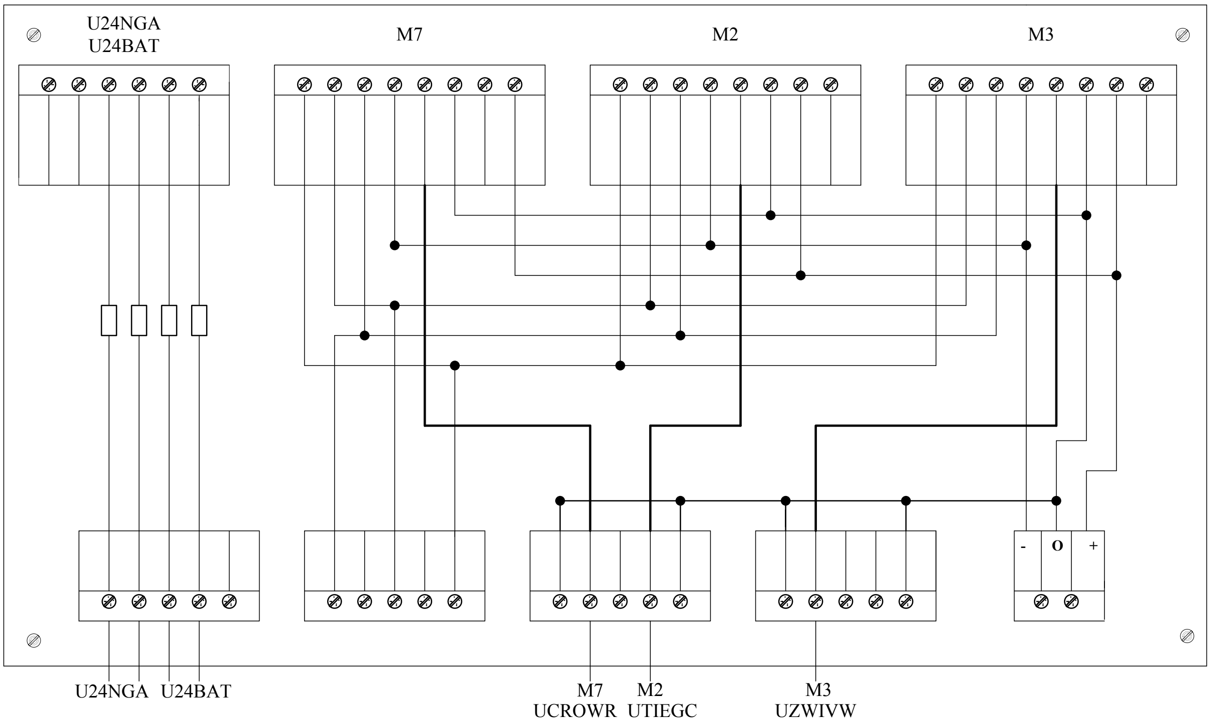


Figure 4.31 Board A for signal distribution inside the measurement case

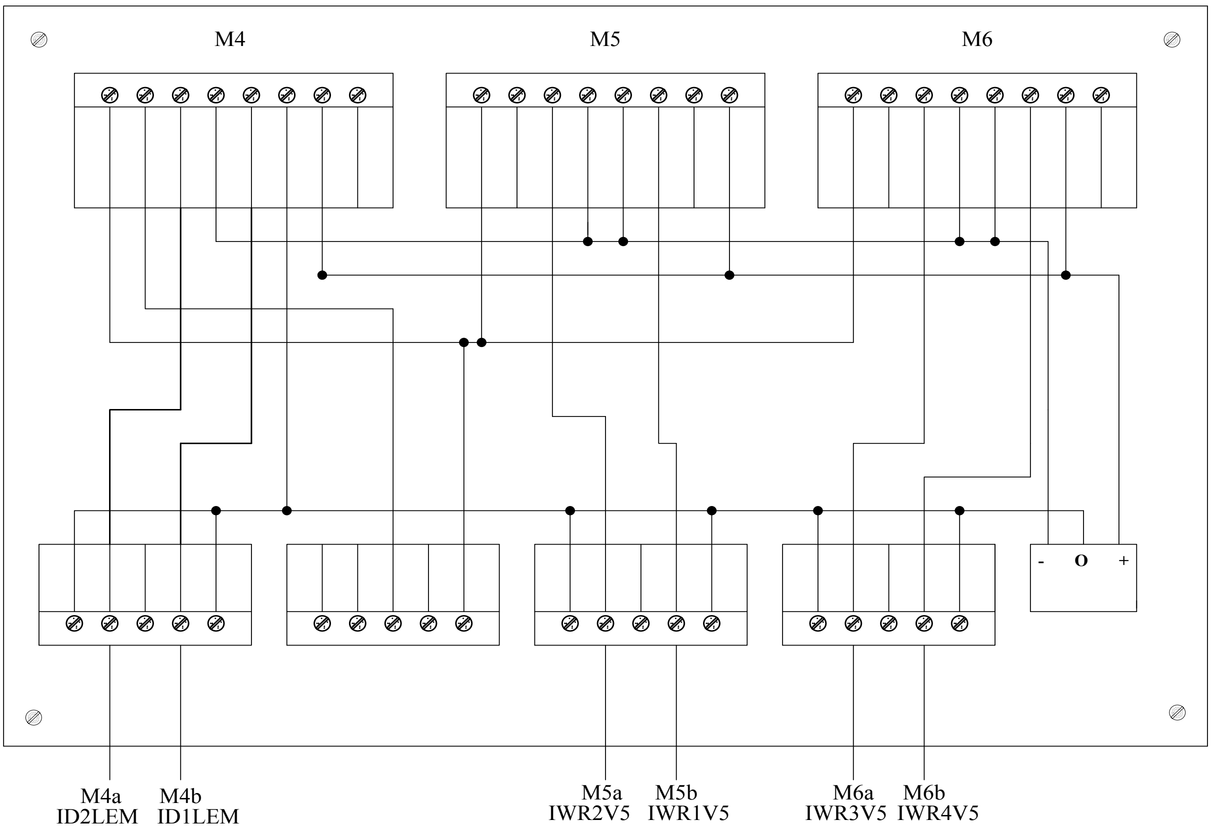


Figure 4.32 Board B for signal distribution inside the measurement case

4.1.3 Difference amplifier in measurement system

In the chapter 3 we have discussed the structure and operation principle of the difference amplifier. For all the measurement signals we need 16 different difference amplifiers. For different signals the external electronic components of the individual amplifiers such as resistors and capacitors are different, therefore, the amplification factors of the amplifier are not the same. By that the different signals could be adjusted in these difference amplifiers for further indication, measurement and other processing.

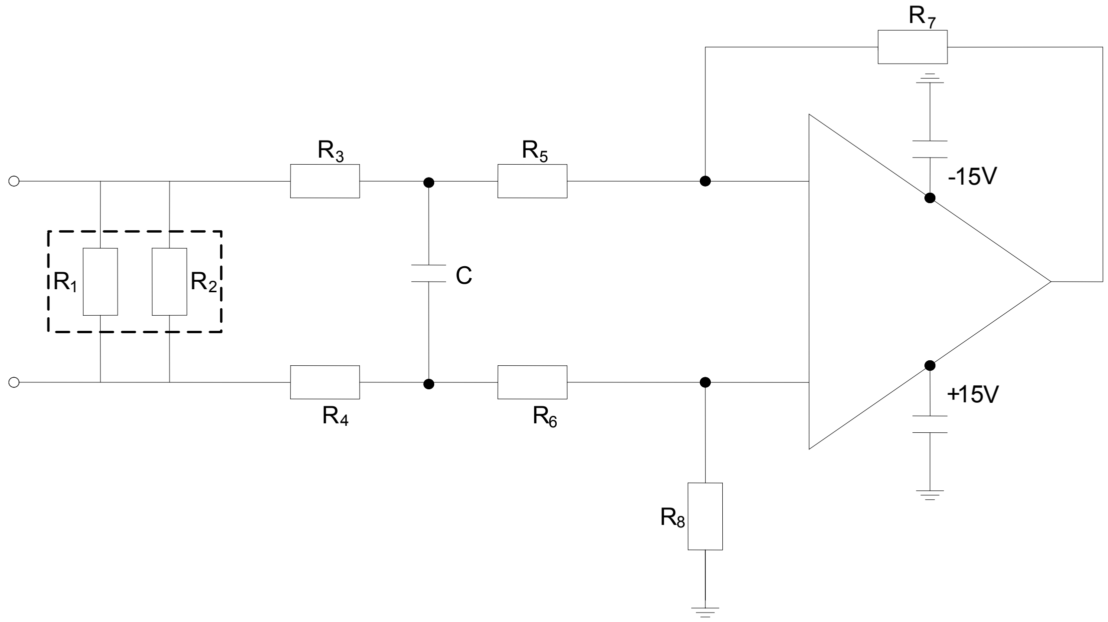


Figure 4.33 Circuit diagram of difference amplifier

The picture above shows us the circuit of the difference amplifier. The basic structure, this is the arrangement of the external components, is similar. But the values of the components are different in different amplifiers. The following table gives us a more detailed description of each difference amplifier.

Table 4.4 Parameters of difference amplifiers

No.	Single	R_1	R_2	C_2	R_3 R_4	R_5 R_6	R_7 R_8	V	C
0	U20L12				68k	68k	100k	0.7353	47p
1	U20L23				68k	68k	100k	0.7353	47p
2	U20L31				68k	68k	100k	0.7353	47p
4	UZKVWR	180k	180k		33k	33k	100k	1.515	100p
5	UTIEGC	180k	180k		33k	33k	100k	1.515	100p
6	U24NGA				180k	180k	100k	0.27	15p

No.	Single	R_1	R_2	C_2	R_3 R_4	R_5 R_6	R_7 R_8	V	C
7	U24BAT				180k	180k	100k	0.27	15p
8	UCROWR	150k	150k		33k	33k	100k	1.515	100p
9	FSIGDA				27k	27k	100k	1.852	100p
10	ID1LEM	2k2	2k2		27k	27k	47k	1.852	100p
11	ID2LEM	2k2	2k2		27k	27k	47k	1.852	100p
12	IWR1V5	100Ω		47nf	15k	15k	47k	3.333	220p
13	IWR2V5	100Ω		47nf	15k	15k	47k	3.333	220p
14	IWR3V5	100Ω		47nf	15k	15k	47k	3.333	220p
15	IWR4V5	100Ω		47nf	15k	15k	47k	3.333	220p

The figure 4.34 shows the difference amplifier unit in the measurement case.

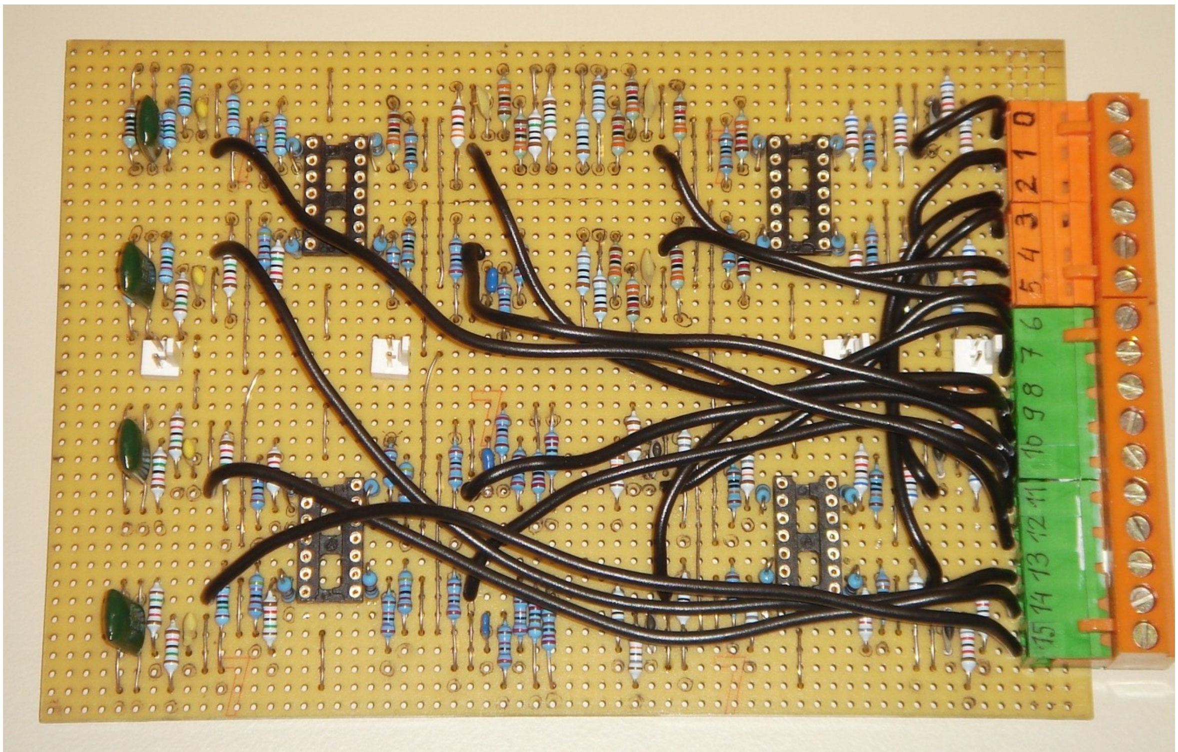


Figure 4.34 Difference amplifiers in the measurement case

The layout of the 16 difference amplifier is shown in Fig. 4.35.

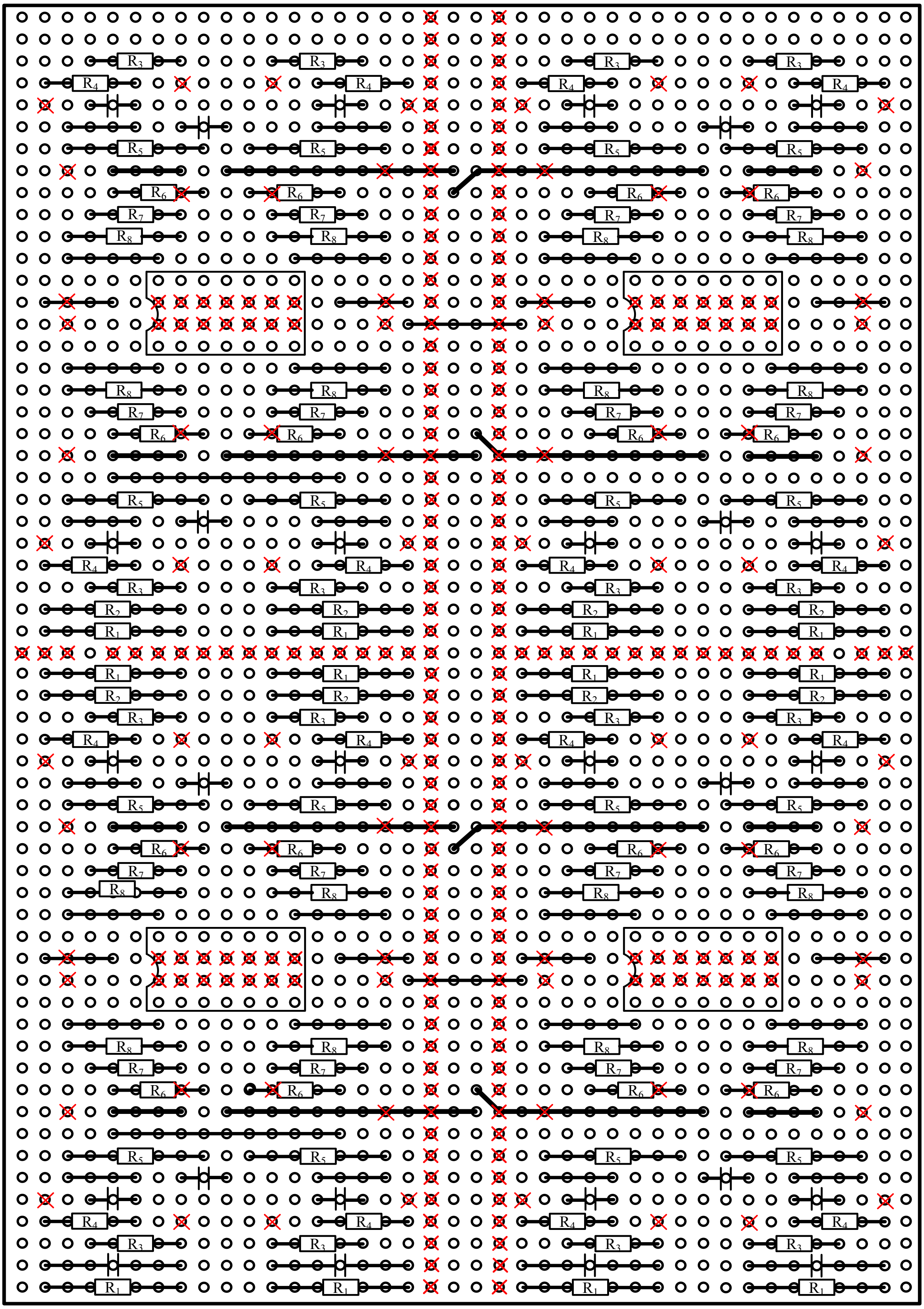


Figure 4.35 Layout of the difference amplifier unit in measurement case

4.1.4 Power supply for measurement system

The difference amplifiers and transducers in the measurement system above need ± 15 V DC operating voltage. DC voltage could be obtained through transformer and rectifier. But the voltage that we get from the rectifier always has some fluctuations which are harmful for the amplifier and will affect the accuracy in a bad way. These fluctuations could occur when the system voltage or the load changes. Therefore it is necessary to connect a voltage stabilizer so that the voltage could be stabilized.

4.1.4.1 Rectifier of the system voltage

There are many different circuits to rectify the alternating current, the simplest way is half wave rectifier (Fig. 4.36). The capacitor in the circuit is charged when the current flows through the diode. If there is no load at the output, in the positive half wave of the voltage, the capacitor is charged to $\sqrt{2}U_{Leff} - U_D$, U_D is the voltage over the diode. When the output voltage of the transformer reaches its peak value, the inverse voltage over the diode reaches $2\sqrt{2}U_{Leff}$.

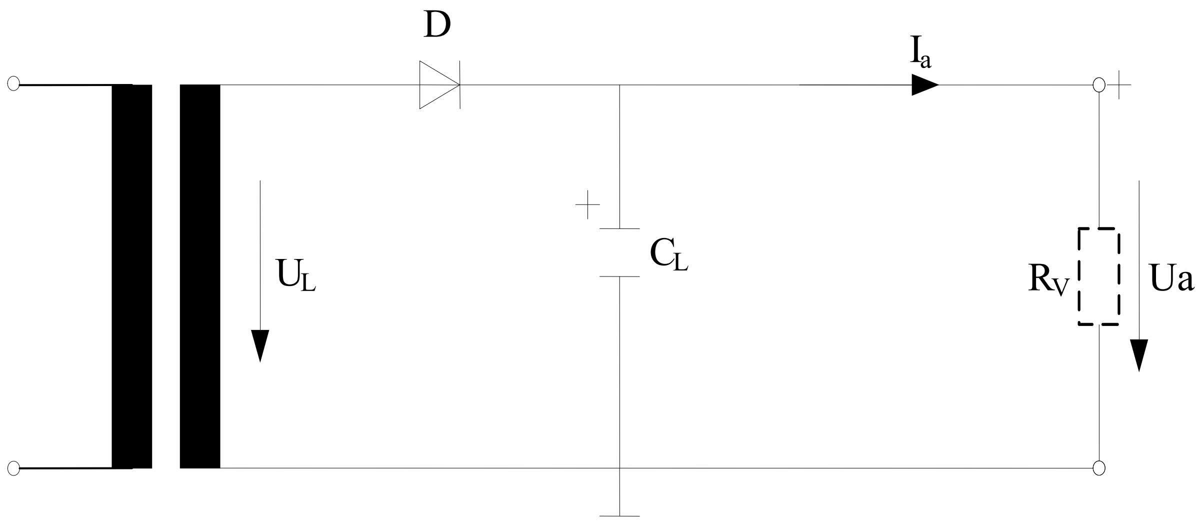


Figure 4.36 Circuit diagram of half-wave rectifier

The circuit in Fig. 4.37 is centre tap connection. With this circuit the full-wave rectification can be achieved. In this circuit the capacitor is charged both at the positive half-wave and the negative half-wave of the output voltage of the transformer. The midpoint of the secondary coil is connected to ground. The output voltage in no-load operation is given as follows:

$$U_{a0} = \sqrt{2}U_{Leff} - 2U_D \quad (4\text{-}1)$$

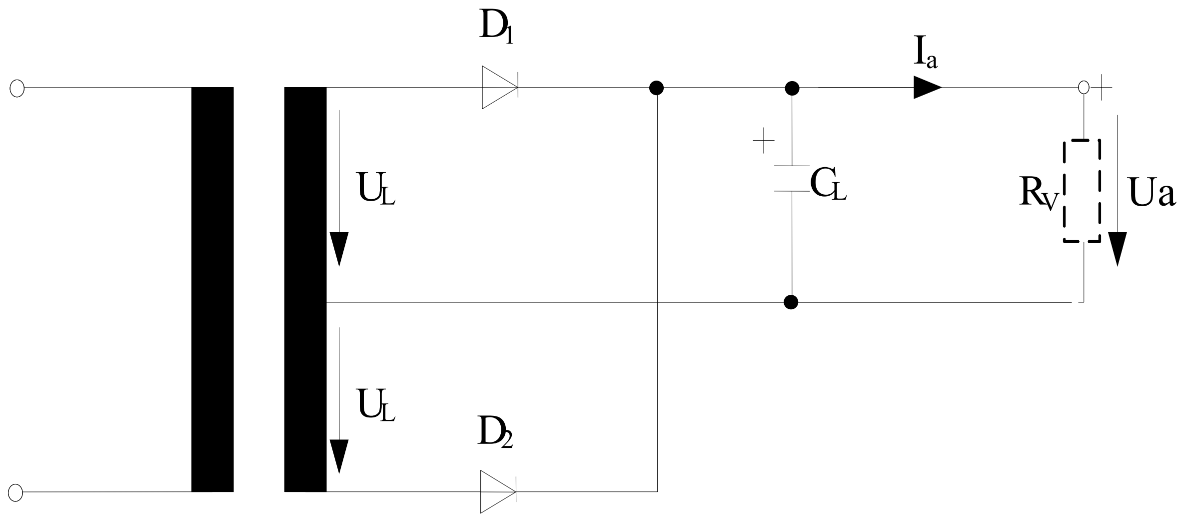


Figure 4.37 Circuit diagram of centre tap rectifier

The power supply needed should have an output voltage of ±15V in DC, for this reason we take the centre tap connection with symmetric output. (Fig. 4.38)

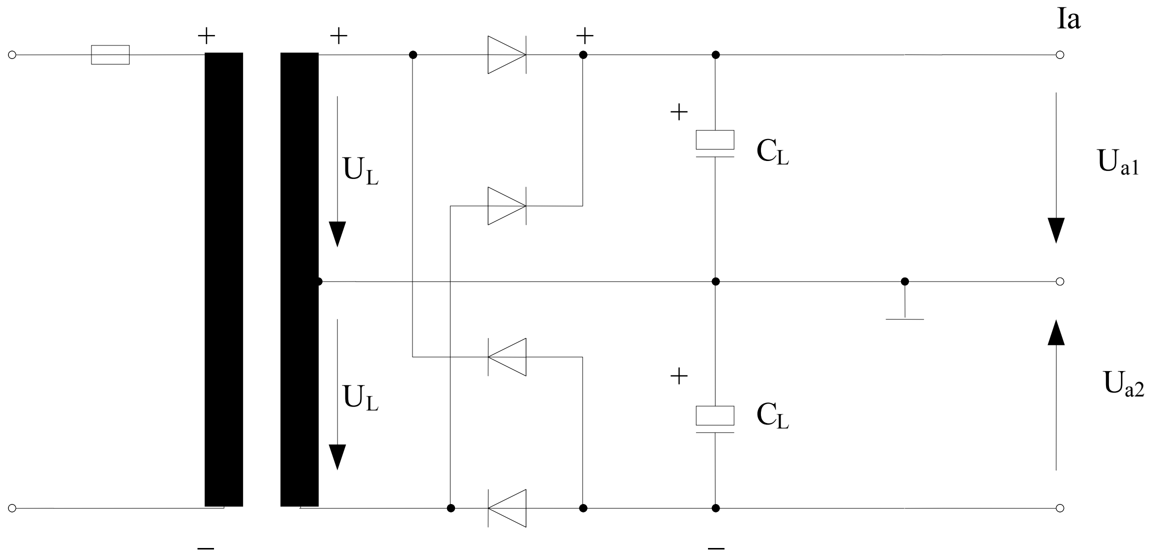


Figure 4.38 Circuit diagram of centre tap rectifier with symmetric outputs

In the circuit shown in Fig. 4.38, both the positive and negative half-wave output voltage of the transformer are used. With the help of diodes 1 and 2, we obtain the positive DC voltage, through the diodes 3 and 4, the negative voltage could be obtained at full-wave rectification.

In this power supply circuit, the primary voltage and secondary voltage of the transformer are respectively 230V and 15V. On the primary side of the transformer, in order to protect the circuit not to be damaged when the system voltage does not work properly, we connect a fuse into the circuit. The output voltages that we obtain are approximately:

$$U_{a1} = \sqrt{2}U_{Leff} - U_D, \quad U_{a2} = -U_{a1} = -\sqrt{2}U_{Leff} + U_D \tag{4-2}$$

In order to have stable output voltages of ±15V in DC, we need to connect voltage stabilizers following the capacitors in the circuit.

4.1.4.2 Voltage stabilizer

The amplifiers in the measurement sensor need operating voltages of ±15V in DC. But if the system voltage, the load or the temperature has some fluctuations, the fluctuations of the operating voltage for amplifiers should not exceed 10% of the standard operating voltage. Therefore, it is necessary to use a voltage stabilizer to create a stable voltage and then these voltages could be used as power supply. The following Fig. 4.39 shows the voltage stabilizer we use. For a better cooling effect they are fixed on the cooling.

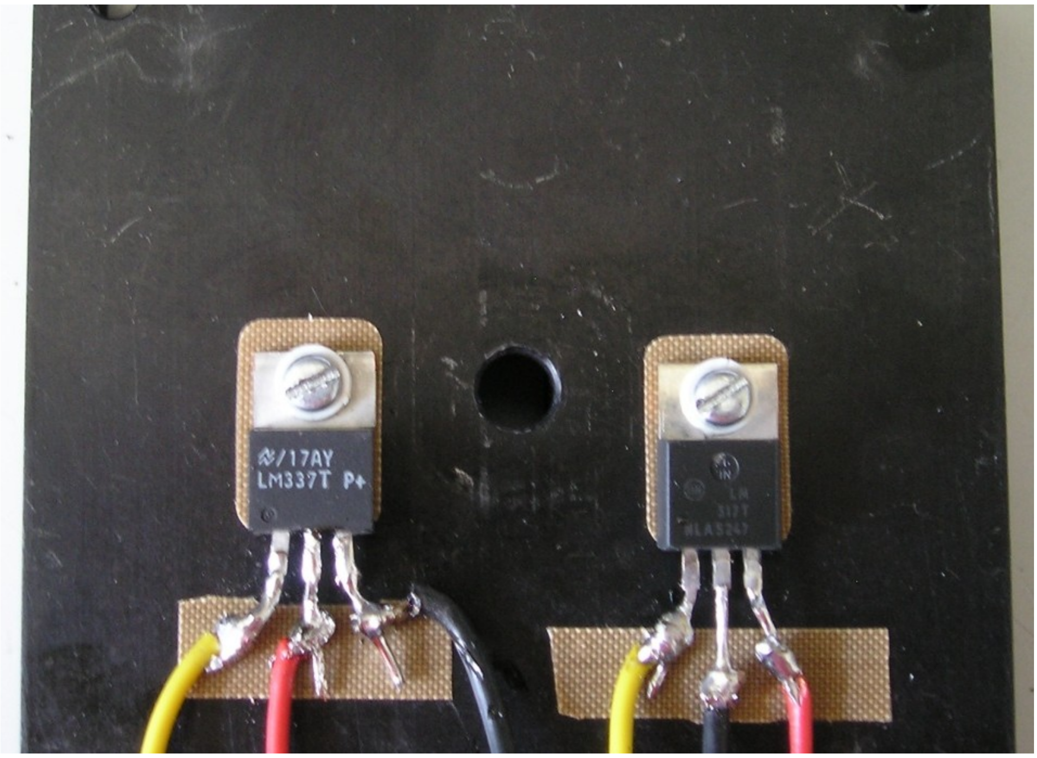


Figure 4.39 Voltage stabilizer LM337 and LM317

Usually the voltage stabilizer has following important parameters:

1. output voltage and tolerance;

2. maximal output current and short circuit current;

3. voltage drop;

4. line regulation;

5. load change influence.

Here, the internal structure of voltage stabilizer will not be discussed in detail. We choose the optimal voltage stabilizer for our circuit according to the parameters given above. This power supply need two voltage stabilizers, the output voltages of the two voltage stabilizer are respectively +15V and -15V. According to the table above, the voltage stabilizers LM337 and LM317 are chosen for our circuit. The output voltage of stabilizer LM337 is +15V and the LM317 output voltage is -15V. D5 and D6 in Fig. 4.40 are used as protection against voltage regulator defect in case of sudden DC input short circuits (at C1, C3; C2, C4 respectively).

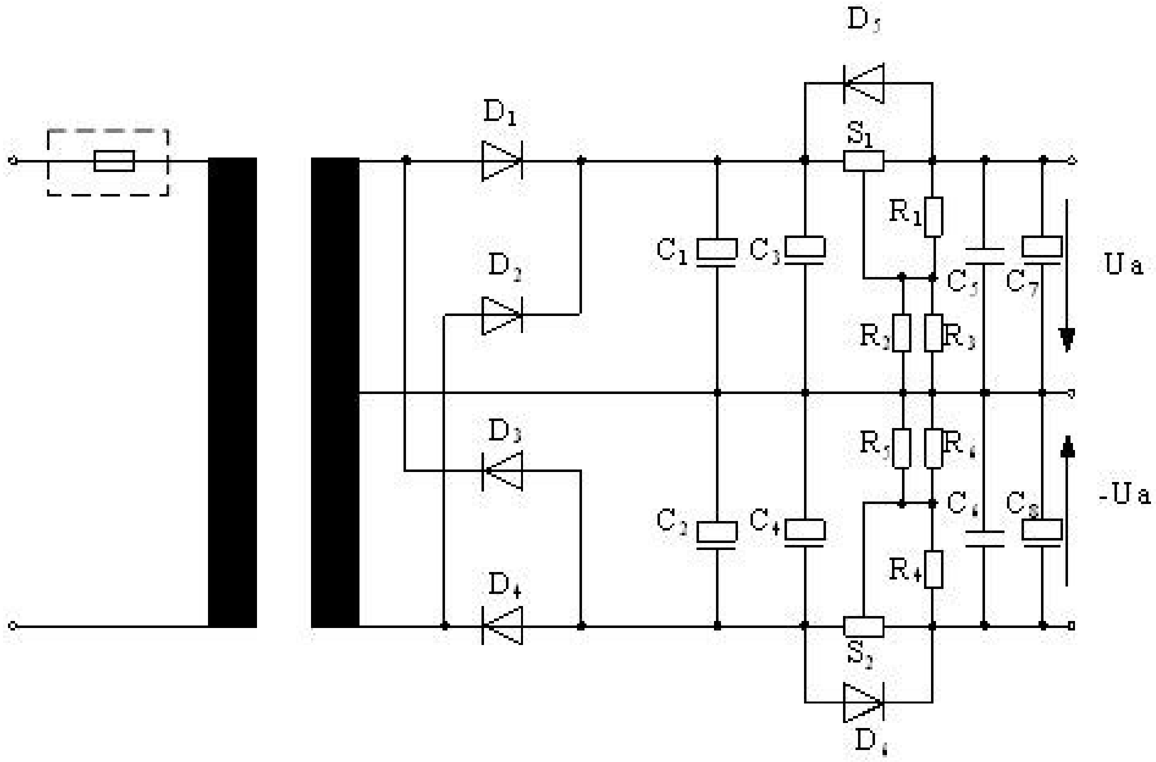


Figure 4.40 Circuit diagram of power supply for transducers and amplifiers

Table 4.5 parameters of the power supply for transducers and amplifiers

Component	Description (type/value)	Component	Description (type/value)
D_1 /D_2 /D_3 /D_4	N5408	$C_{7/}$ C_8	100μF
D_5 /D_6	N4007	R_1/ R_2	1kΩ
$C_{1/}$ C_2	4700μF	R_3/ R_4 /R_5/ R_6	22kΩ
C_3 /C_4	10μF	S_1	LM337
$C_{5/}$ C_6	1.0μF	S_2	LM317

Figure 4.41 shows the photo of the power supply for difference amplifier unit and transducers in the measurement system.

Figure 4.41 Power supply for transducers and amplifiers

4.2 Extraction of the processed signals

By using of the measurement system we get 16 signals from the difference amplifier unit. These 16 scaled (normalized) signals have been processed through the voltage transducers, current transducers and difference amplifiers. In this part, a signal splitter will be set up and all the 16 signals will be split into three groups of 16 signals, and then sent to the following three devices.

1 A/D converter: The A/D converter is installed in the computer. The signals will be transferred from analog signals into digital signals and then be stored in the computer.

2 Error recognition system: The 16 signals will be sent to another difference amplifier unit and then into an error recognition system. If some critical situations happen in the furnace circuit, the critical signals will be detected by this system and emergent measures will be taken to protect the furnace equipment.

3 Indicator: The signals will be also sent to a new difference amplifier unit and then to a low-pass filter. The signals from the low-pass filter will be indicated on indicator.

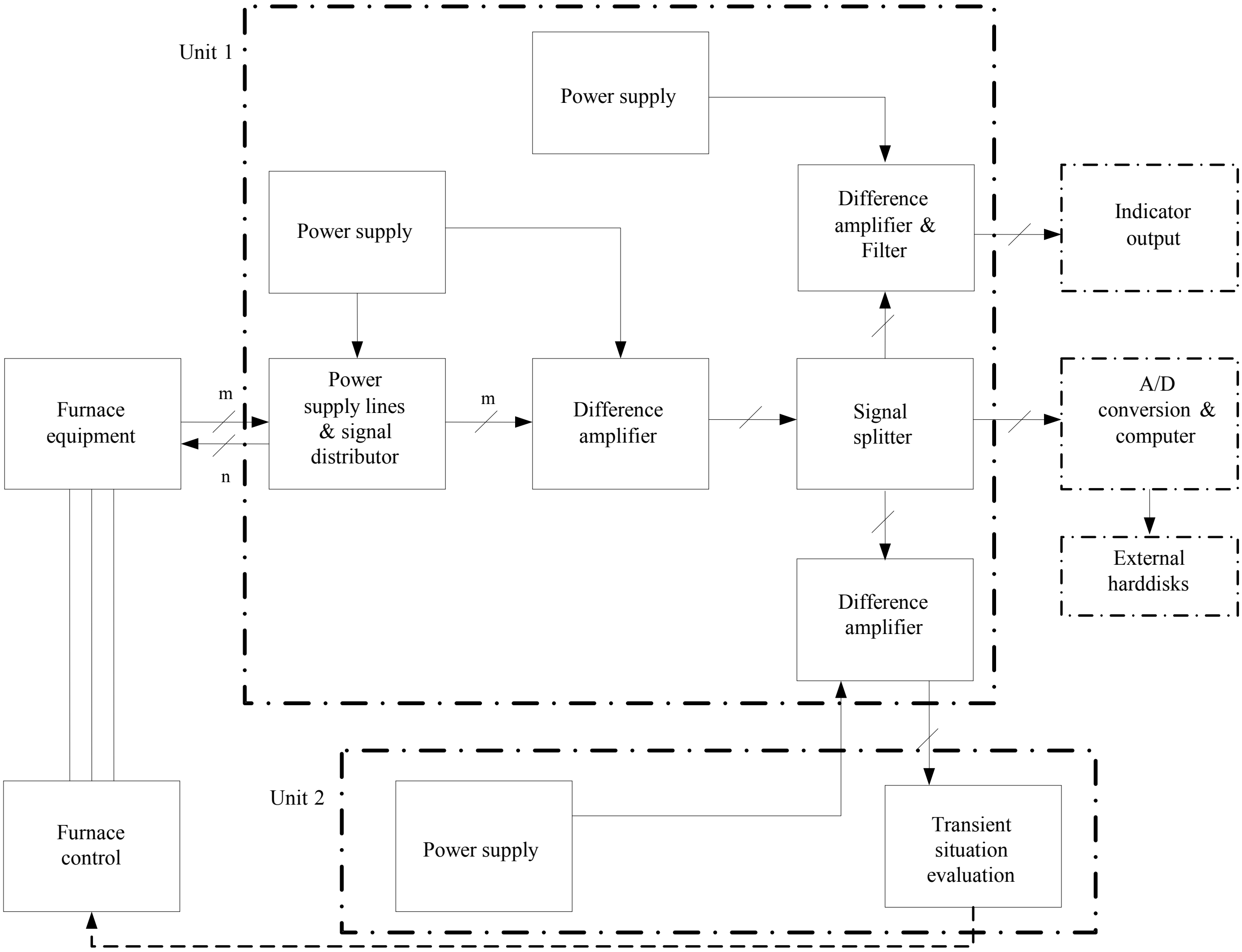
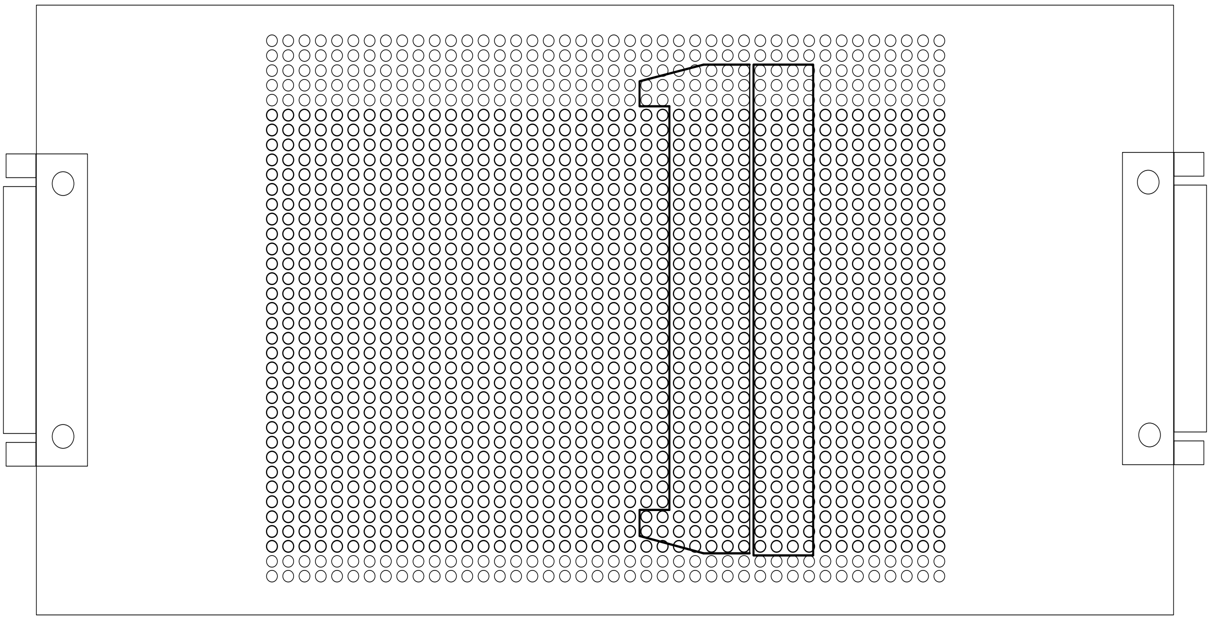


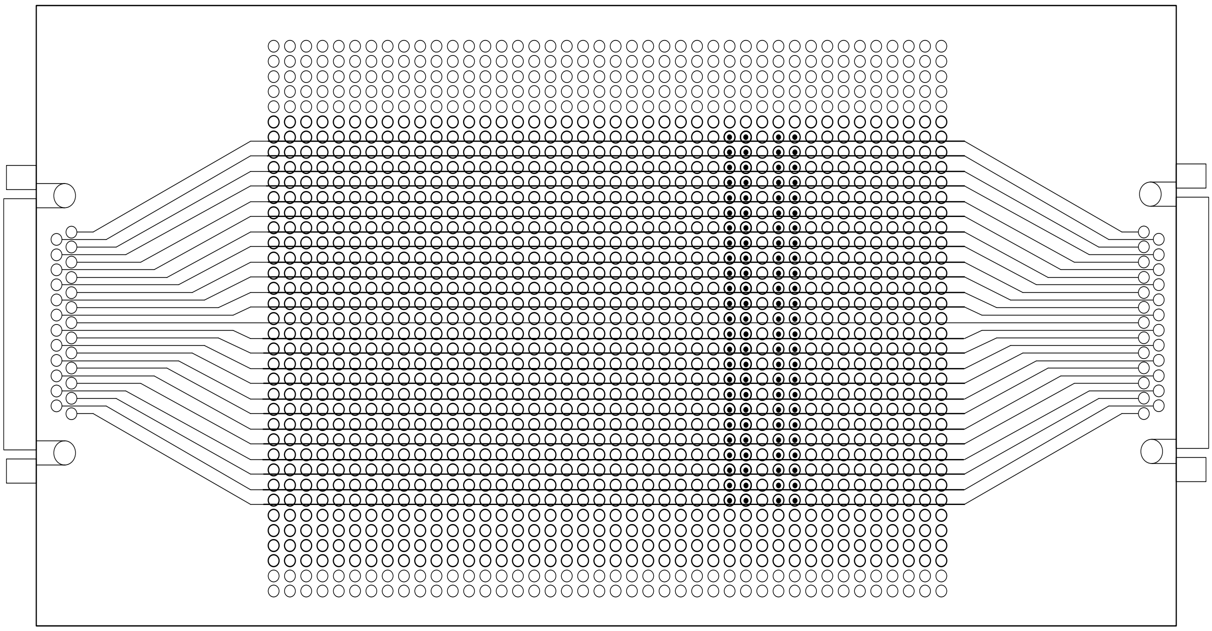
Figure 4.42 Block diagram of extraction system

4.2.1 Signal splitter

The 16 signals from the difference amplifier unit are sent to a signal splitter. In the splitter, the signals are split into three groups of 16 signals. The splitter consists of circuit board, BNC sockets and wires. Like the figure below, two 25-pole sockets are soldered on both sides of the circuit board, the two sockets are connected with wires. In the middle of the circuit, two 50-pole sockets are soldered on the board and connected with wires.

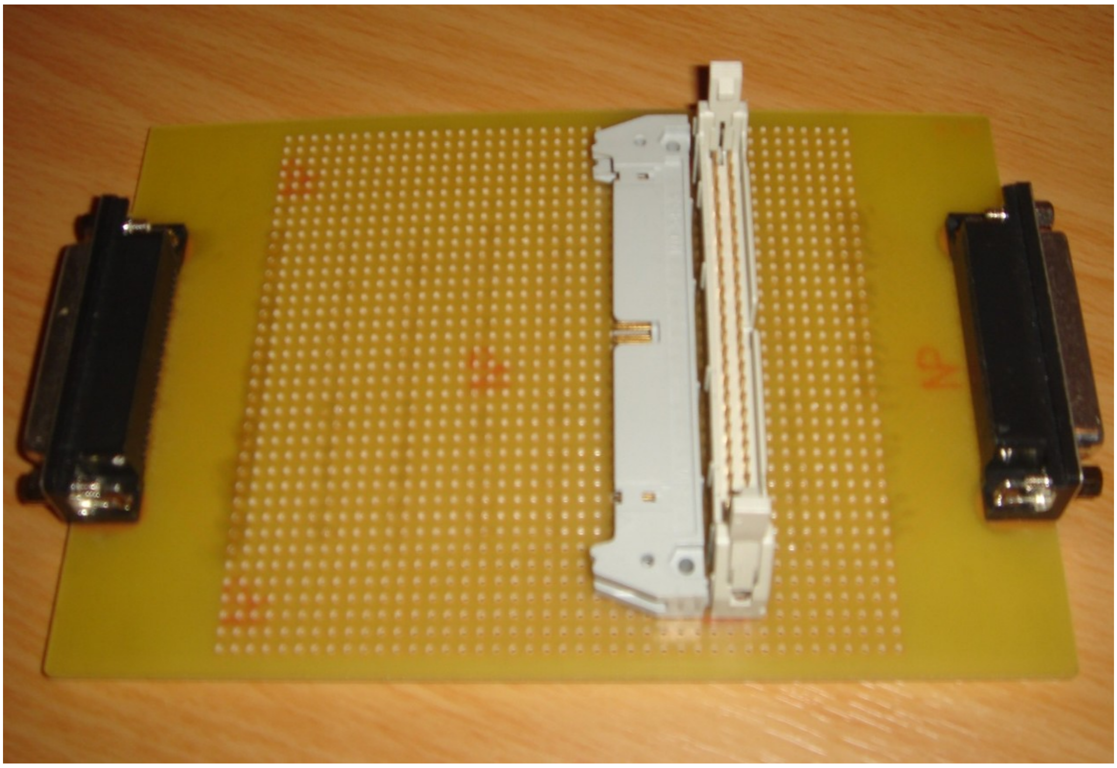


(a) Upper side of the layout

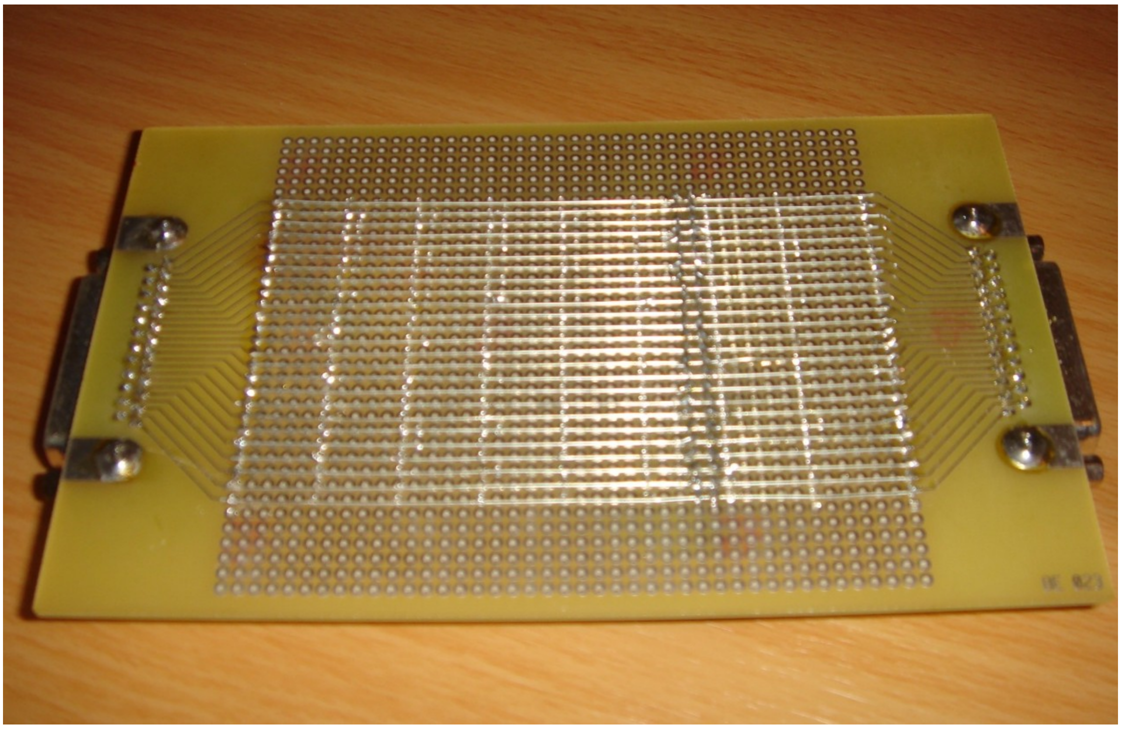


(b) Back side of the layout

Figure 4.43 Layout of splitter



(a) Upper side of signal splitter



(b) Back side of signal splitter

Figure 4.44 Signal splitter

With the splitter above the signals could be split into three groups with different directions, but a problem exists in this splitter. Part 1 in figure 4.45 shows this problem: all the pins on socket-1 are connected upside-down to the pins on socket-2, e.g. pin-1 on socket-1 is connected to pin-25 on socket-2 (Fig. 4.45) and pin-25 on socket-1 is connected to pin-1 on socket-2.

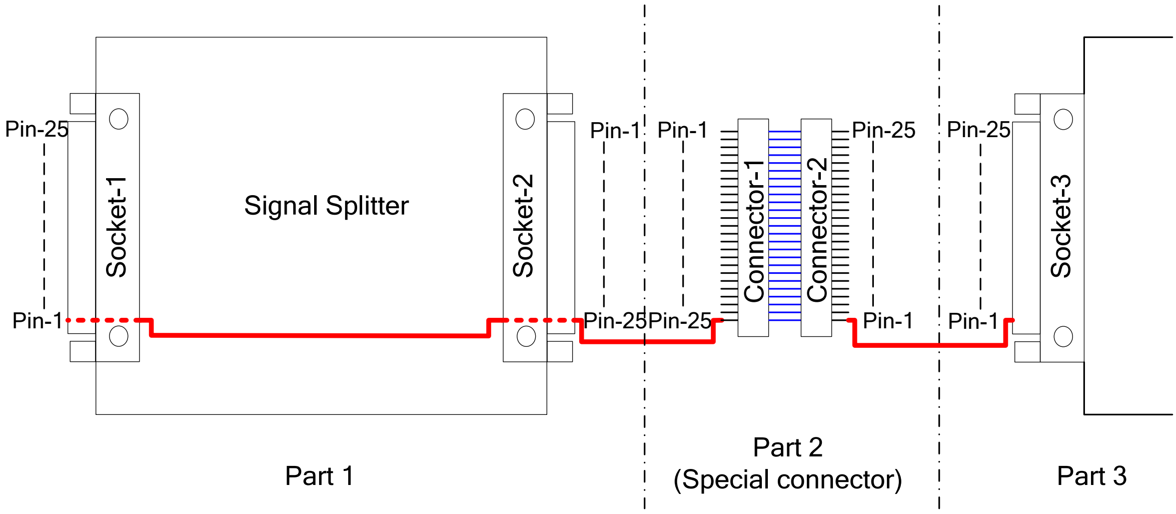


Figure 4.45 Special connector in signal splitter

In order to solve this problem a special connector unit made up of two connectors (part 2 in Fig. 4.45) can be used on the output side of the signal splitter. From part 2 in figure 4.45 we can see that the special connector unit consists of two identical connectors (connector-1 and connector-2). These two connectors have the same sequence of pins. We place the two connectors like figure 4.45 and solid the pins of the two connectors with wires (blue lines in Fig. 4.45), so that the pins on connector-1 are connected upside-down to pins on connector-2, e.g. pin-25 on connector-1 is connected to pin-1 on connector-2.

Through this special connector unit the sequence of the pins on socket-1 is identical with the sequence of the pins on connector-2. All the signals can be transmitted correctly through the signal splitter without change of the sequence. Figure 4.46 shows the photo of this special connector.

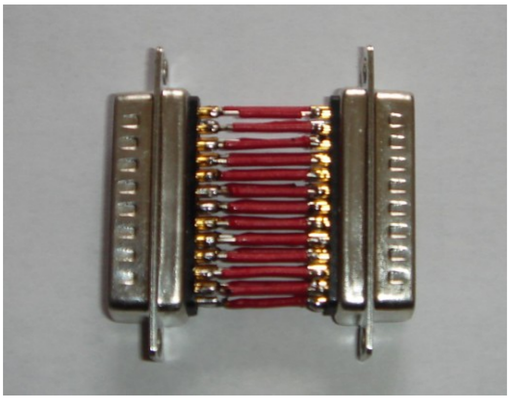


Figure 4.46 Photo of the special connector

4.2.2 Error recognition system

From the signal splitter, one group of 16 signals is transmitted into a new difference amplifier unit. This difference amplifier unit is the same as the one that we have described in section 4.1.3 and here it will not be discussed in detail. We have soldered a socket with 16 poles on one side of the circuit board of this difference amplifier unit and the 16 inputs of the difference amplifiers are connected with the 16-poles socket (Fig. 4.47). With this socket the 16 signals from the splitter can be sent to the difference amplifiers more easily.

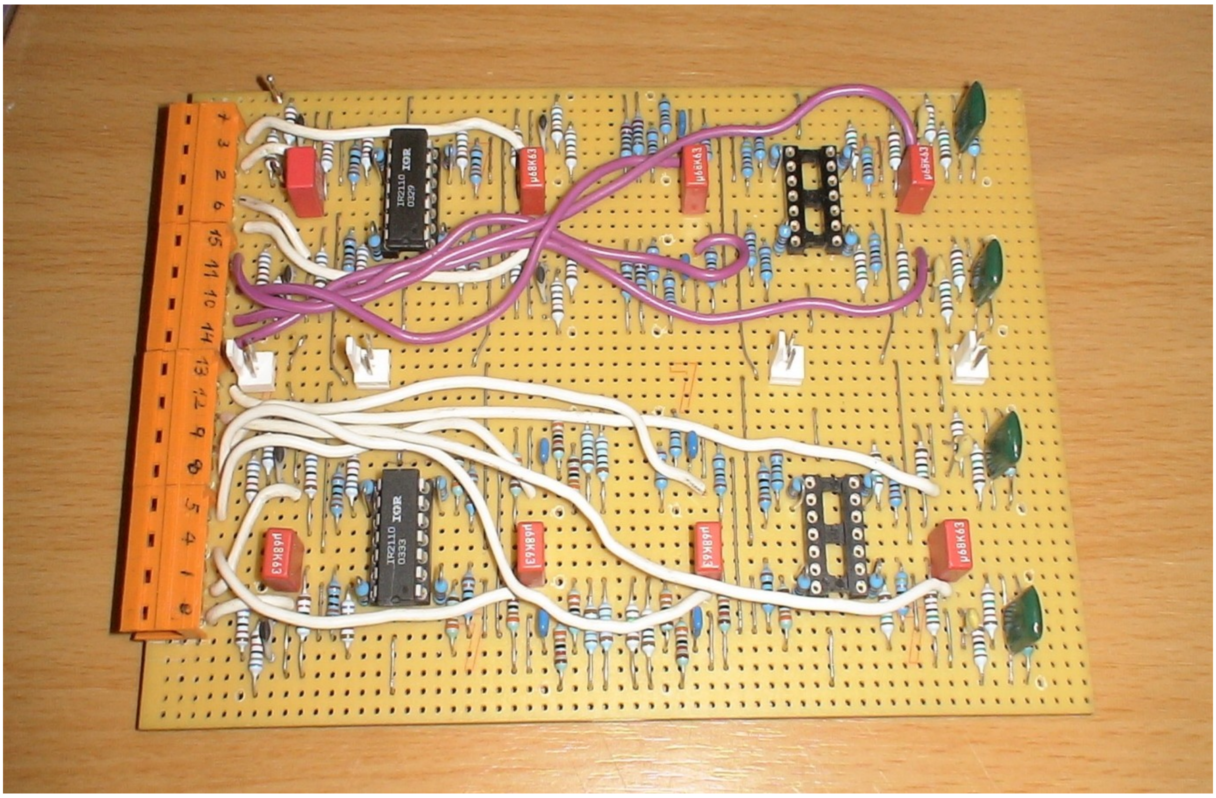


Figure 4.47 Difference amplifiers for error recognition system

This difference amplifier unit also needs ±15V power supply. The structure of the power supply is similar as the one we have set up in section 4.14. The circuit and the parameters of the components are given in figure 4.48 and table 4.6.

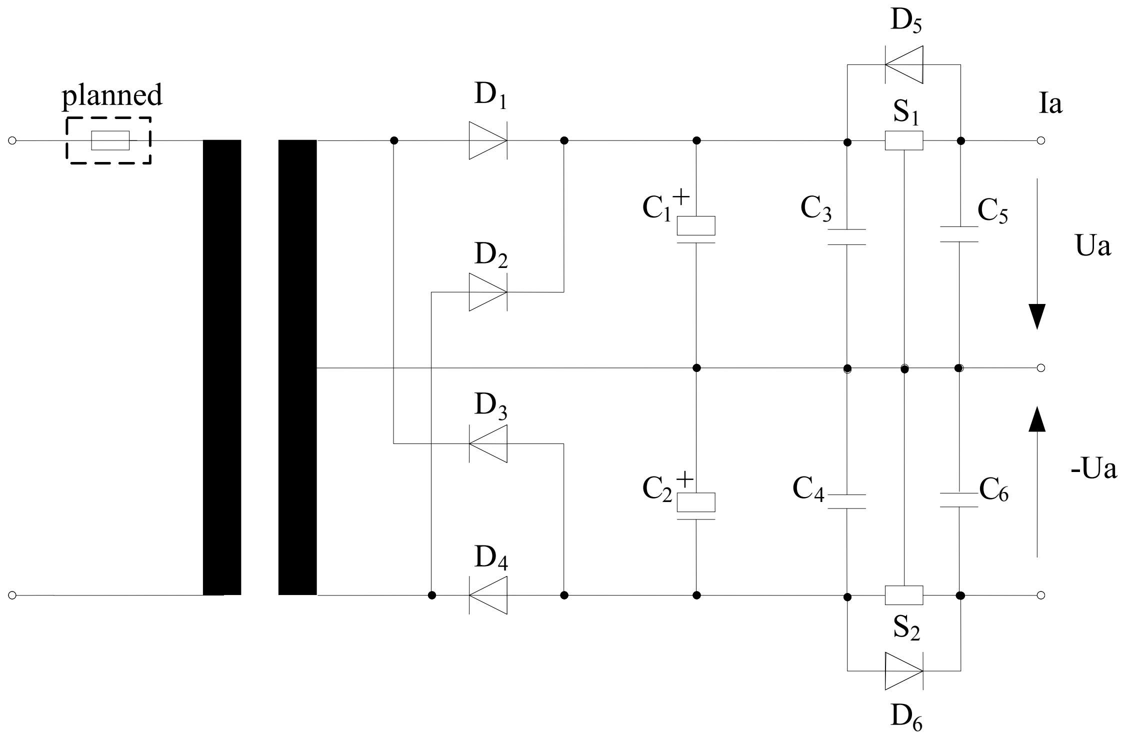


Figure 4.48 Circuit diagram of power supply in error recognition system

Table 4.6 parameters of power supply for error recognition system

Component	Description (type/value)	Component	Description (type/value)
D_1 ,D_2 ,D_3 ,D_4	1N5408	C_3 ,C_4 ,C_5, C_6	1.0µF
D_5 /D_6	1N4007	S_1	7815
C_1 /C_2	2200µF	S_2	7915

Figure 4.49 shows us the power supply. The output voltage will be connected with the difference amplifiers.

After being processed in the difference amplifiers, the 16 signals are sent to the error recognition system. The error recognition system is a kind of special protection equipment. It can protect the furnace equipment from being damaged in case of transient conditions. When the transient condition happens during operation of the furnace, this system could detect the transient conditions from the 16 signals which are sent into this system. If a critical condition occurs, but it disappears subsequently and the furnace continues to work, the system will not take measures. But if the same critical condition happens two times within a short period of time, the system will take measures at once and stop the operation of the furnace.

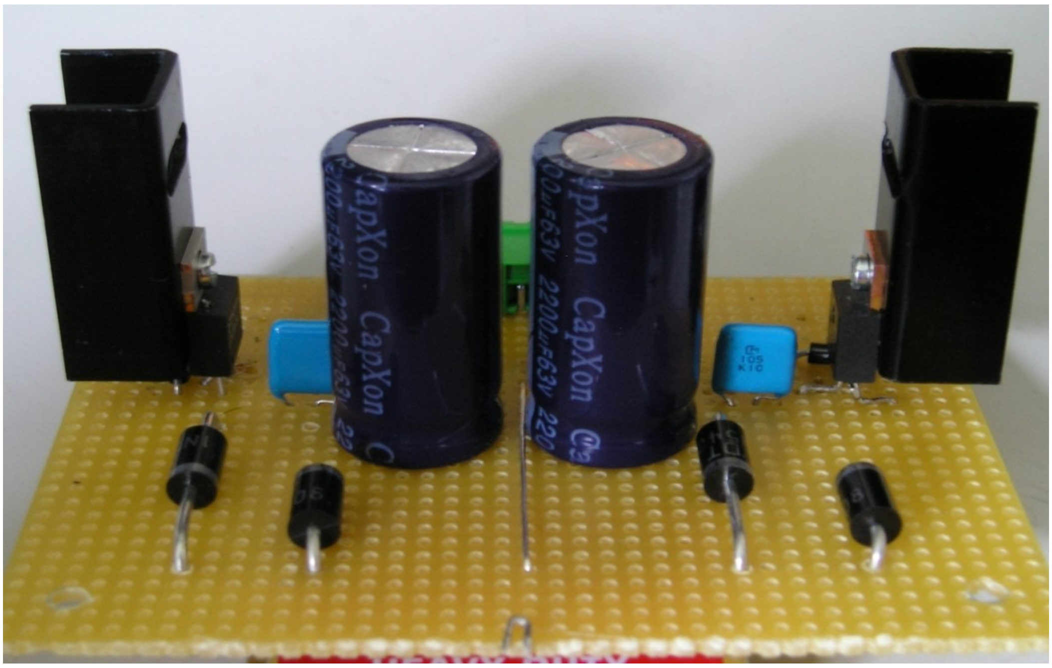


Figure 4.49 Power supply for error recognition system

4.2.3 Signals for indication

Through the 50-pole socket of the splitter, a group of 16 signals is transmitted to another new difference amplifier unit. This unit is totally the same as the one we use for error recognition system. From this difference amplifier unit, we get 16 new signals. We implement a special low-pass filter with output side parallel capacitor for immunity against certain capacitive loading.

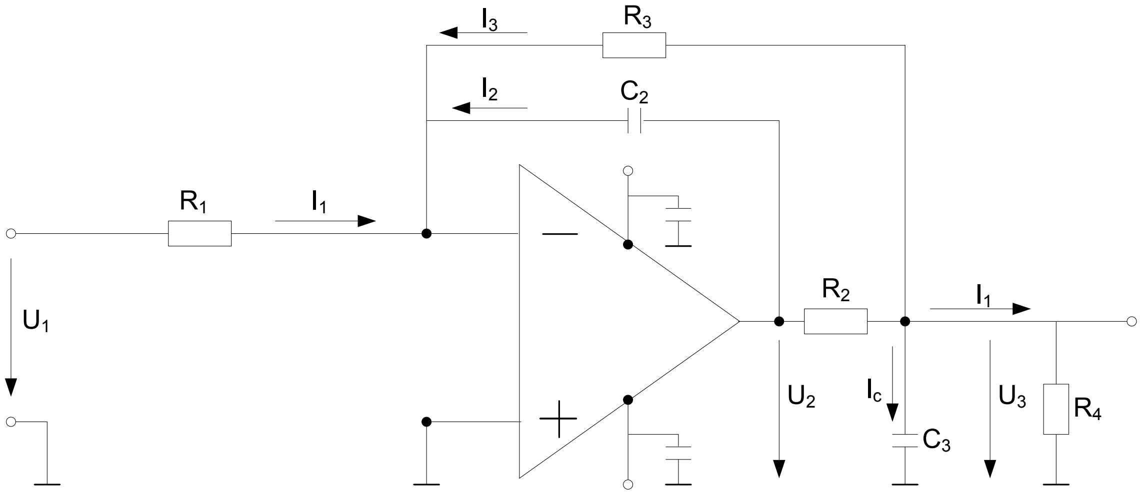


Figure 4.50 Bessel low-pass filter

Figure 4.50 shows the circuit of the low-pass filter. This low-pass filter is Bessel filter. In section 3.22 this filter has been described and the determination of the parameters has been discussed. Therefore, the parameters of the filter are given directly as follows. (Tab.4.7).

Table 4.7 parameters of the filter

Name	Value of the component	Name	Value of the component
R_1	10kΩ	C_2	1.0μF
R_2	1kΩ	C_3	18nF
R_3	10kΩ		

Here, 16 Bessel filters are needed for the 16 signals. The layout of the Bessel low-pass filter unit is planned to realize at later time. The 16 signals from the filters can be sent to the display device like an oscilloscope for indication.

The differential amplifiers and Bessel filters for indication also need a power supply of ±15V. The power supply has the similar structure as the ones we build above. But due to the different demand for the current, the components may be different. Figure 4.51 gives us the circuit and the parameter table is given subsequently.

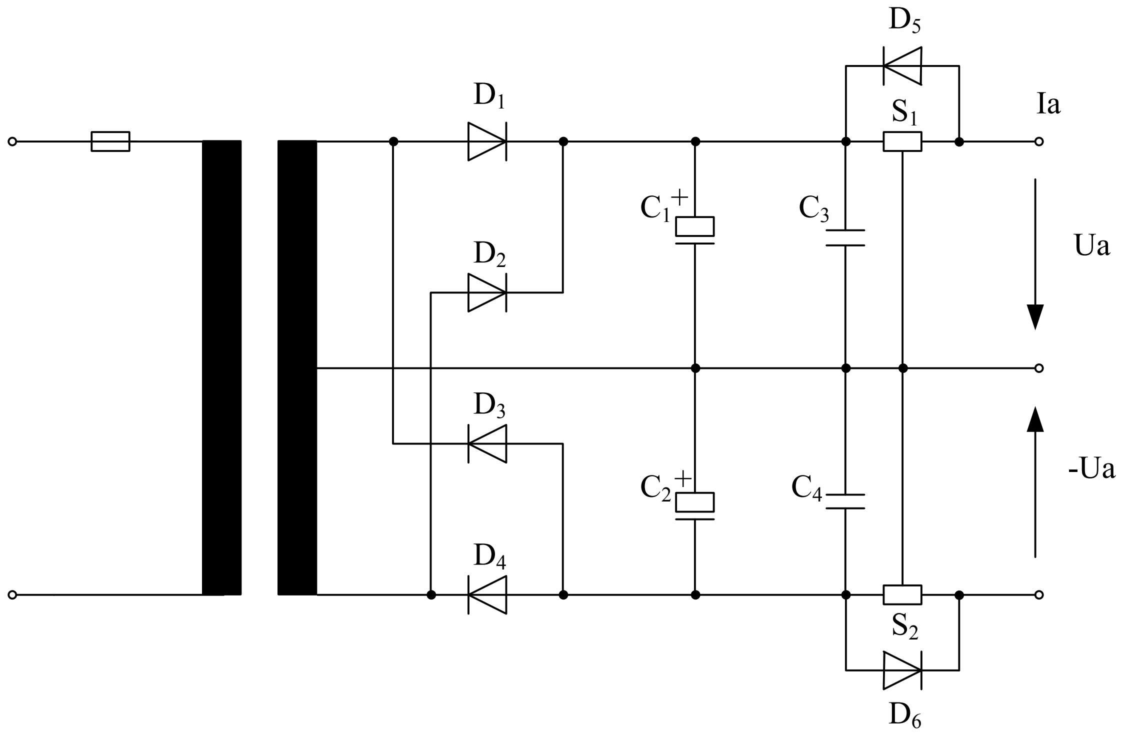


Figure 4.51 Circuit diagram of power supply for indication

Table 4.8 parameters of the power supply for indication system

Component	Description (type/value)	Component	Description (type/value)
$D_{1/}$ D_2 /D_3 /D_4	1N4007	C_3 /C_4	1.0μF
D_5 /D_6	1N4007	S_1	78L15
$C_{1/}$ C_2	470μF	S_2	79L15

The table above gives the parameters of the power supply. Figure 4.52 shows the power supply that we have established for the difference amplifiers and filters in the indication system.

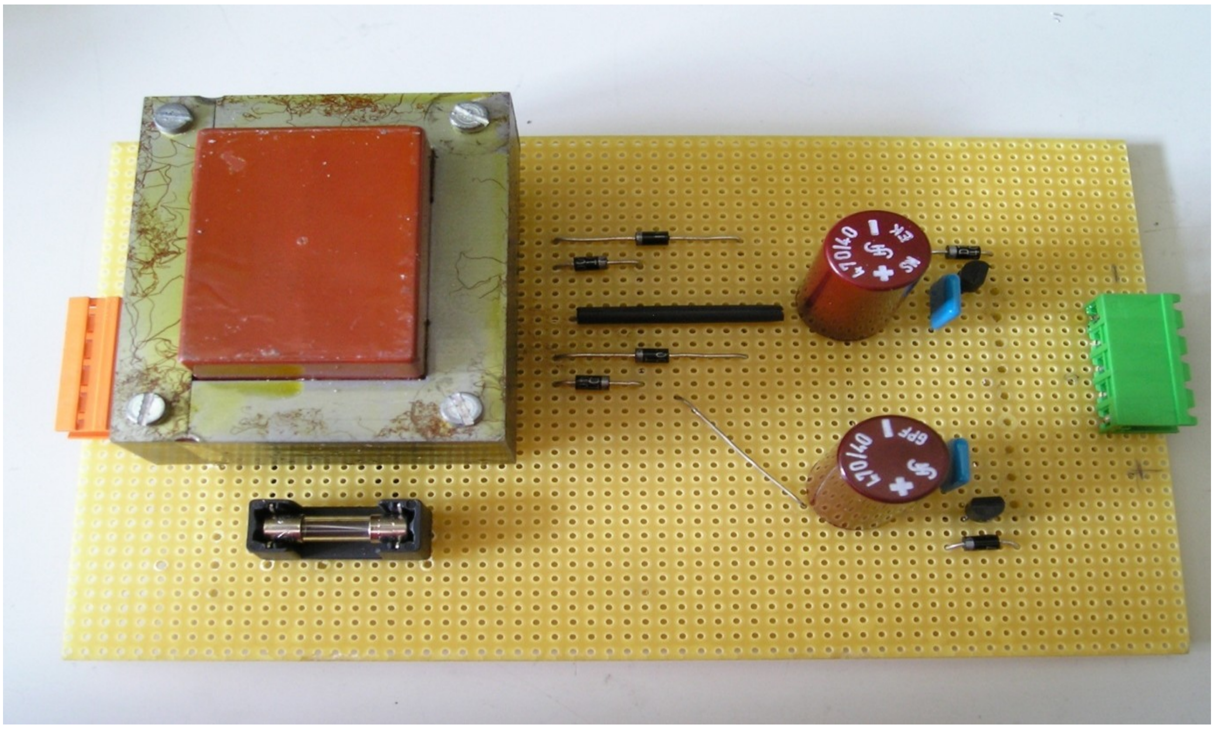


Figure 4.52 Power supply for indication

4.3 Scaling of the signals

Through the measuring system, the 16 original signals are processed and new signals are obtained. The range of these new 16 signals is between 0V and +/-10V, and they are suitable to be collected with the data acquisition card and measured with the software in computer. But these values are not the original values of the signals, they have been converted through transducers and amplifiers. Therefore, in order to reflect these original values of the voltage and current, we have to scale these values. The following table shows us the procedure of the conversion of these values from original signals to the new signals in the computer.

Table 4.9 conversion process of the measurement signals

number	signal	conversion in transducer	conversion in difference amplifier	
0	U20L12	100V→5.96V	V=0.7353	5.96V→4.38V
1	U20L23	100V→5.96V	V=0.7353	5.96V→4.38V
2	U20L31	100V→5.96V	V=0.7353	5.96V→4.38V
3	U230L1	230V→6.85V	V=0.6098	6.85V→4.18V
4	U24NGA		V=0.25	24V→6V
5	U24BAT		V=0.25	24V→6V
6	UZKVWR	$1200V \rightarrow 60mA \xrightarrow{90\Omega} 5.4V$	V=1.515	5.4V→8.182V
7	UTIEGC	$1200V \rightarrow 60mA \xrightarrow{90\Omega} 5.4V$	V=1.515	5.4V→8.182V
8	UCROWR	$600V \rightarrow 8mA \xrightarrow{750\Omega} 6.0V$	V=1.515	6.0V→9.091V
9	DSIGDA			
10	ID1LEM	$5000A \rightarrow 1A \xrightarrow{5\Omega} 5V \rightarrow 3mV \xrightarrow{1.1k\Omega} 3.3V$	V=1.852	3.3V→6.11V
11	ID2LEM	$5000A \rightarrow 1A \xrightarrow{5\Omega} 5V \rightarrow 3mV \xrightarrow{1.1k\Omega} 3.3V$	V=1.852	3.3V→6.11V
12	IWR1V5	$4000A \rightarrow 5A \rightarrow 12.5mA \xrightarrow{100\Omega} 1.25V$	V=3.333	1.25V→4.17V
13	IWR2V5	$4000A \rightarrow 5A \rightarrow 12.5mA \xrightarrow{100\Omega} 1.25V$	V=3.333	1.25V→4.17V
14	IWR3V5	$4000A \rightarrow 5A \rightarrow 12.5mA \xrightarrow{100\Omega} 1.25V$	V=3.333	1.25V→4.17V
15	IWR4V5	$4000A \rightarrow 5A \rightarrow 12.5mA \xrightarrow{100\Omega} 1.25V$	V=3.333	1.25V→4.17V

From the table above, we get an overview of the conversion procedure for each signal. The following conversion table below gives us the scaling and standardization of each signal in the DEWEsoft software.

Table 4.10 scaling in DEWEsoft program

No.	Signal name	Real value (pro V in DEWEsoft)	No.	Signal name	Real value pro V in DEWEsoft
0	U20L12	22.8V	8	UCROWR	66.0V
1	U20L23	22.8V	9	DSIGDA	
2	U20L31	22.8V	10	ID1LEM	818.3A
3	U230L1	55.0V	11	ID2LEM	818.3A
4	U24NGA	4.0V	12	IWR1V5	959.2A
5	U24BAT	4.0V	13	IWR2V5	959.2A
6	UZKVWR	146.7V	14	IWR3V5	959.2A
7	UTIEGC	146.7V	15	IWR4V5	959.2A

From the conversion table above, we could read the original value of the signals from the processed value in the computer.

4.4 Collection of measuring value

From the measurement units and difference amplifiers, we have got 16 processed signals. It was already mentioned in section 4.2 that these signals are sent to three different directions. One of them is A/D data acquisition board. This board coupled with the DEWEsoft software forms the data collecting system.

4.4.1 Data acquisition board

The data acquisition board that we use is PCI-6070E. This DAQ board has 16 channels for analog signals and digital signals. We input the 16 analog signals into the 16 analog terminals and from the output the 16 digital signals are obtained. Through the data cable they are sent to the CPU of the computer.

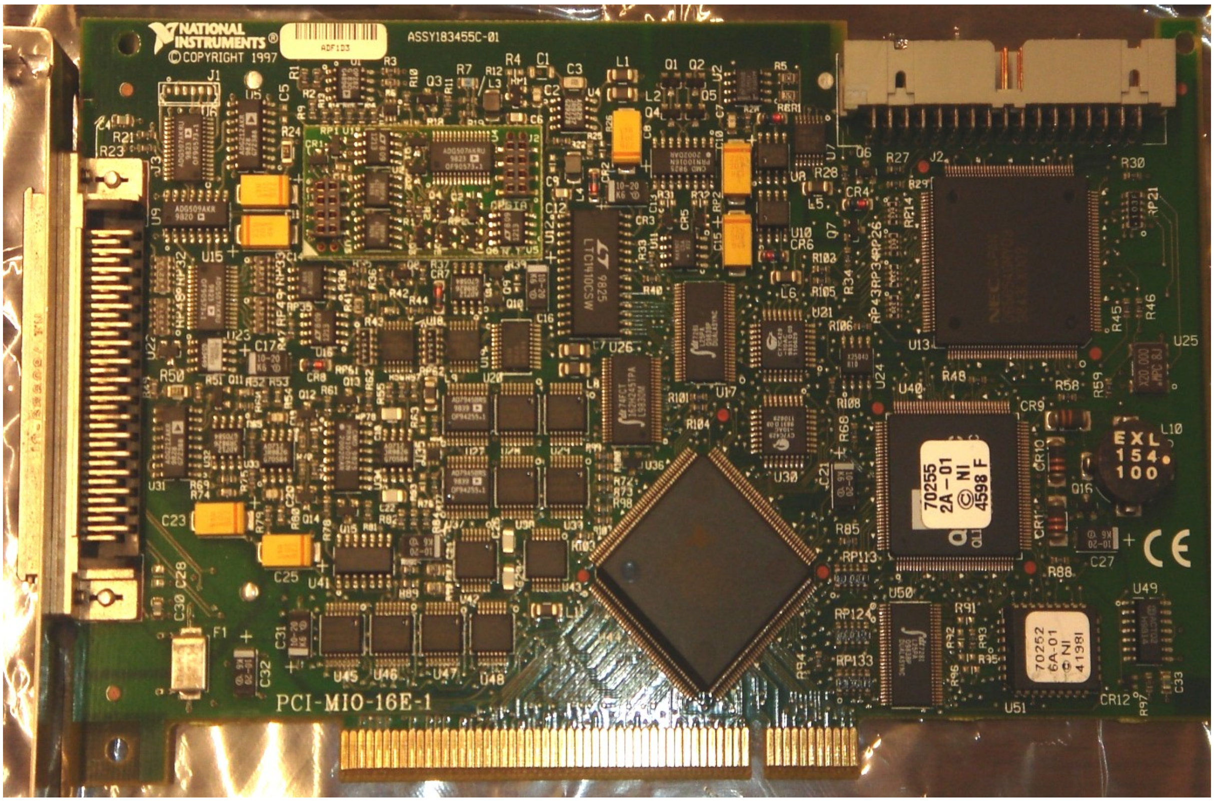


Figure 4.53 Data acquisition board PCI-6070E

4.4.2 Data acquisition software

From the DAQ board inside the computer we get digital data. These signals should be monitored and displayed in the computer. In the computer, these signals should be processed by means of software. The most popular software is LabVIEW. However, LabVIEW is a programming language and a lot of work (e.g. several months) is required to learn and use LabVIEW. Realizing a LabVIEW-based data collecting and monitoring program would take several months to years in addition. Here, we use the DEWEsoft program from Austrian company DEWETRON to process the 16 digital signals in computer. DEWEsoft is a very easy-to-use popular software for data processing. Combined with the DAQ board, it could measure the analog signals in computer and store the signal data in hard disk. There are many models of monitoring and measuring in the software. We need only to install the DAQ board in the computer and select the corresponding functions for monitoring and measuring, then the monitoring and measuring of the signals will become possible. The table below gives an overview of all the 16 signals with corresponding NI-signal in DEWEsoft program.

Table 4.11 overview of the measurement signals with corresponding NI-signal in DEWEsoft

Signal-Nr.	Signalname	NI_Signal	Signal-Nr.	Signalname	NI_Signal
S1	U20L12	AI0	S9	UCROWR	AI8
S2	U20L23	AI1	S10	DSIGDA	AI9
S3	U20L31	AI2	S11	ID1LEM	AI10
S4	U230LN	AI3	S12	ID2LEM	AI11
S5	U24NGA	AI4	S13	IWR1V5	AI12
S6	U24BAT	AI5	S14	IWR2V5	AI13
S7	UZWIKR	AI6	S15	IWR3V5	AI14
S8	UTIEGC	AI7	S16	IWR4V5	AI15

The following figures (Fig.4.54, Fig. 4.55, Fig. 4.56) show the screen shots of the Setup, Scope and Recorder in DEWEsoft program separately.

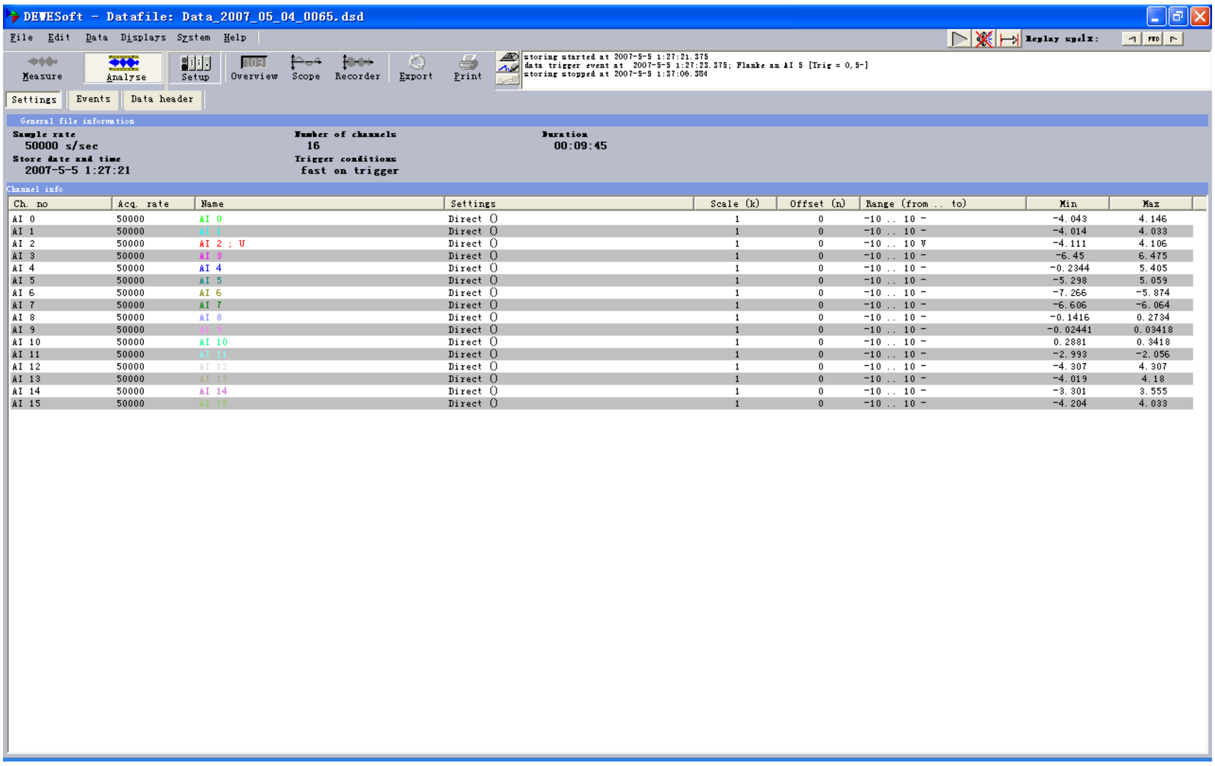


Figure 4.54 Screen shot of Setup

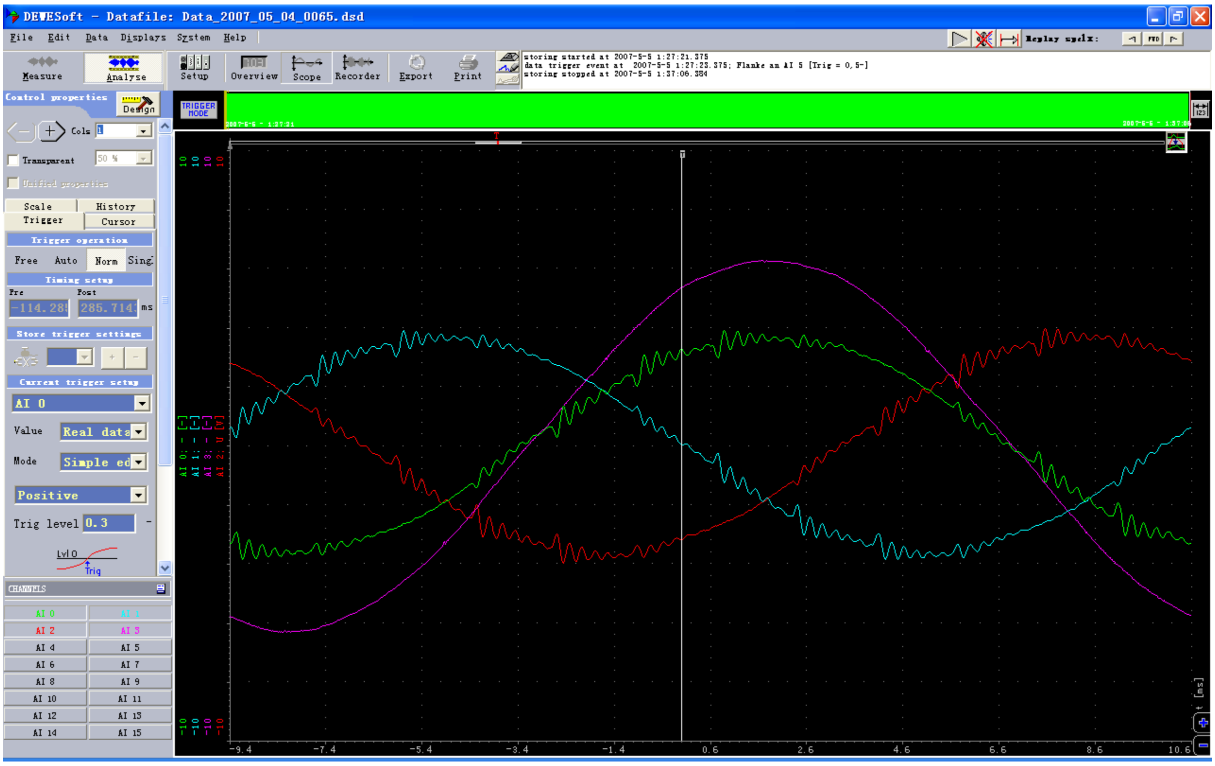


Figure 4.55 Screen shot of Scope

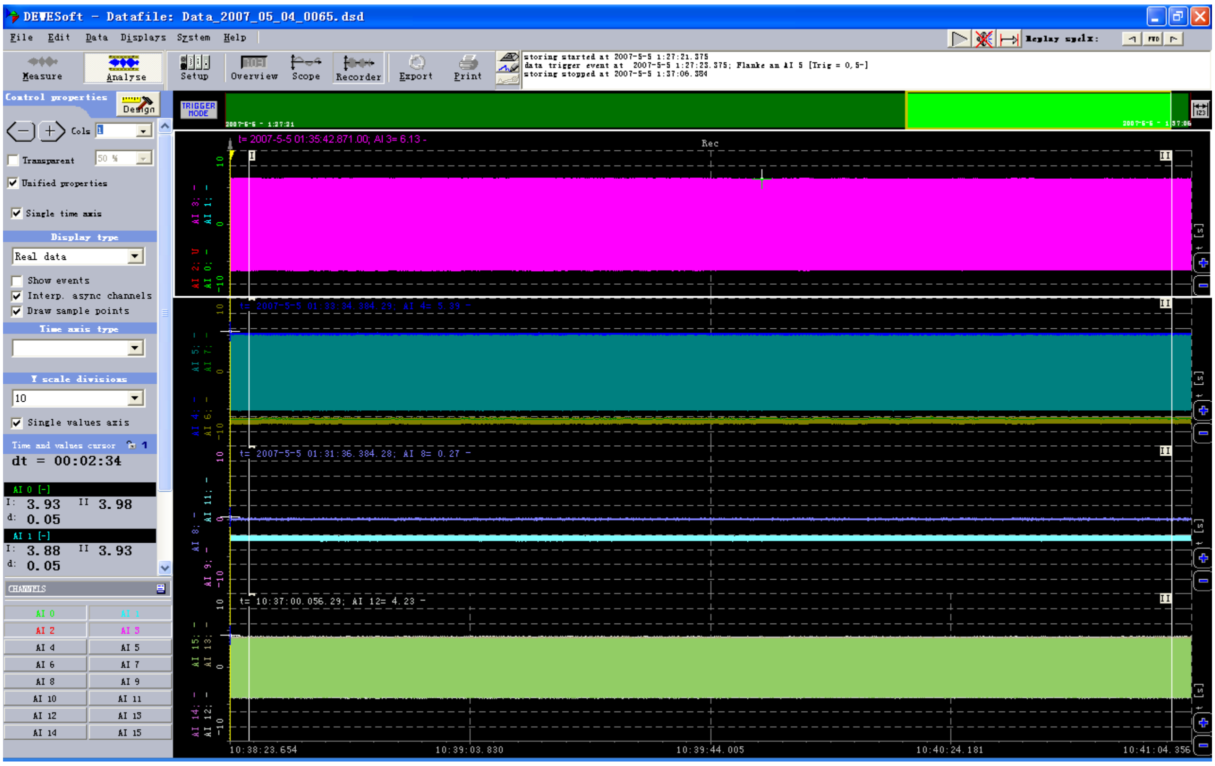


Figure 4.56 Screen shot of Recorder

4.5 Data storage

In the last part, all the signals are processed through voltage transducers, current transducers and difference amplifiers, and then transferred in A/D converter and finally measured. But for further improving of the furnace performance, it is necessary to analyze the operation data of the furnace in detail afterwards. Therefore, all the operation data of the furnace during a certain period can be recorded and stored in hard disks and keep available as a quality documentation about the process for a certain metallurgy melting activity. We have already used the DEWEsoft software in computer to monitor and measure the working of the furnace, and it is also possible to store the operation data by means of the DEWEsoft. But as we know, most of the hard disks inside the computer have a certain capacity, but we need to record the data of a long-term operation of the furnace. For this reason, a great number of external hard disks (30 disks) are used to store the operation data of the furnace.

Figure 4.57 External hard disks for data storage

The external hard disks are connected with the computer through USB interface. In DEWEsoft, the directory of the storage is set as external hard disk. By changing the hard disk regularly, a long-term storage of the operation data could be realized.

We used a high-speed-recording at a data rate of 5.5 Giga-Byte per hour, a standard “500GB” (actually 465GB) hard disk is full after more than 3 days.

5 Analysis and estimation of operational performance

Through the procedures above, the measurement system for monitoring and measuring of the signals is set up. With this system, we could monitor the long-term operation of the furnace continuously. This measurement system is installed at Boehler Company for a limited time. All the measurement signals are connected with the corresponding interface, and the output terminals are connected with the A/D converter in the computer. After all the analog signals are changed into digital signals, they are measured and then stored in the external hard disks with the DEWEsoft software.

We have used the measurement system to monitor the operation of the furnace for several months. Through the analysis for the operation data in the hard disks, standard operation and problems usually hidden during the operation of the furnace can be seen. Several examples are given as follows.

Figure 5.1 and figure 5.2 indicate separately the standard starting process and stopping process of the melting in induction furnace unit. During the starting process the RMS values of the currents through rectifiers and inverters and the voltages of the power supply and battery group for converter control increase from zero to their operational values and during the stopping process they decrease to zero again. The RMS values of the other voltages do not change.

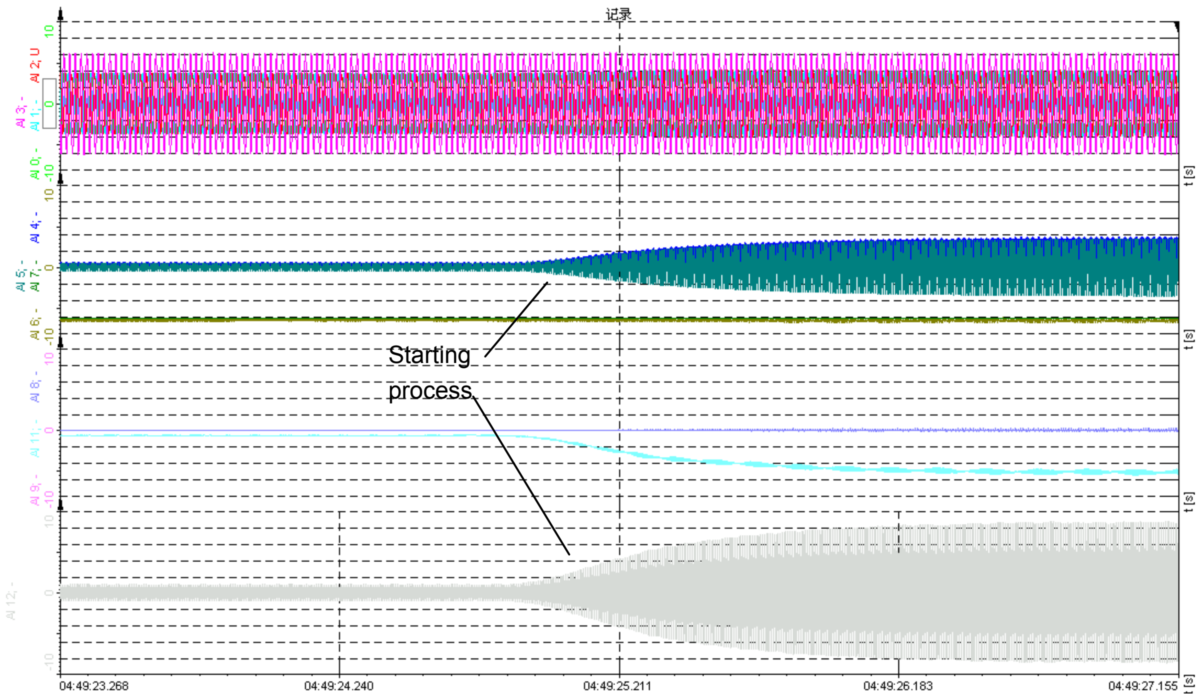


Figure 5.1 Starting process of the melting

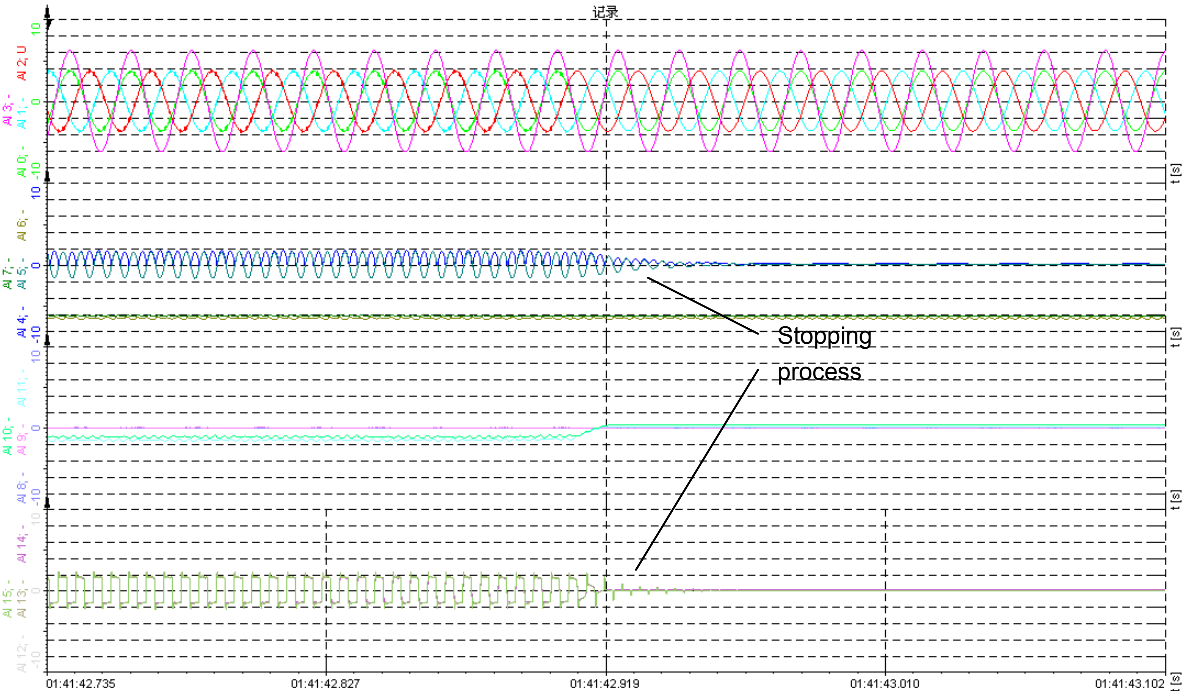


Figure 5.2 Stopping process of the melting

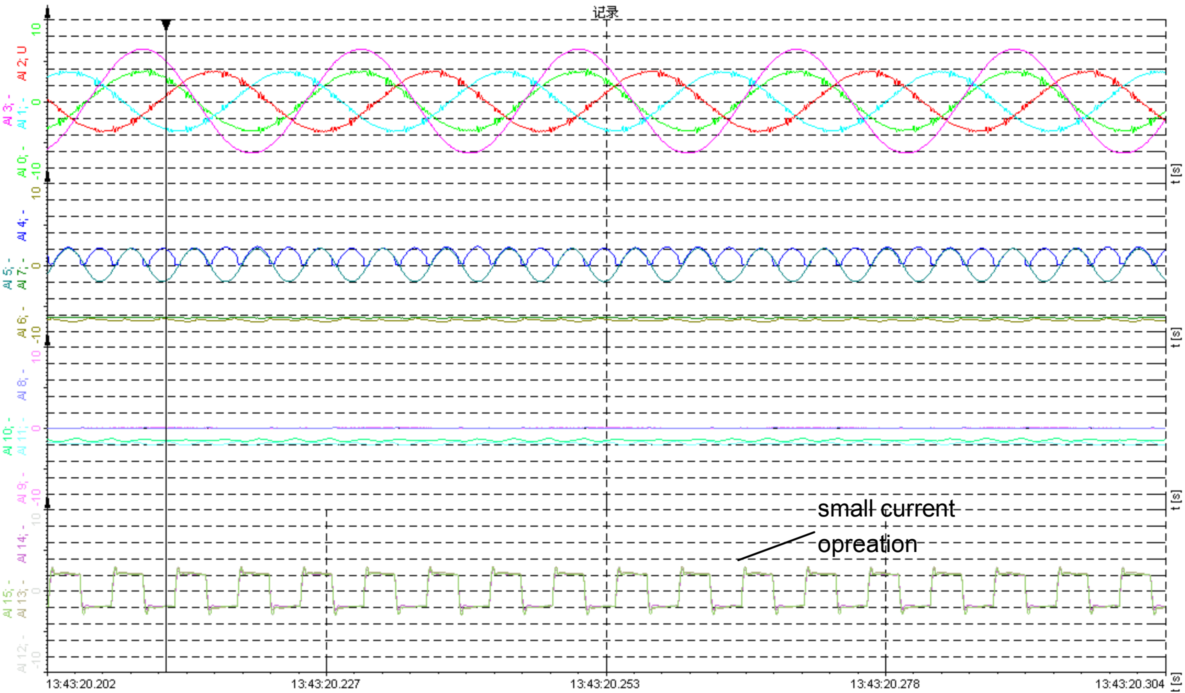


Figure 5.3 Standard operation with small current

Figure 5.3 and figure 5.4 show separately the standard operations of the melting with small current and big current. In small current operation (Fig. 5.3) the RMS value of the currents through the inverters (rectangular signals) is only half of the value in big current operation (Fig. 5.4).

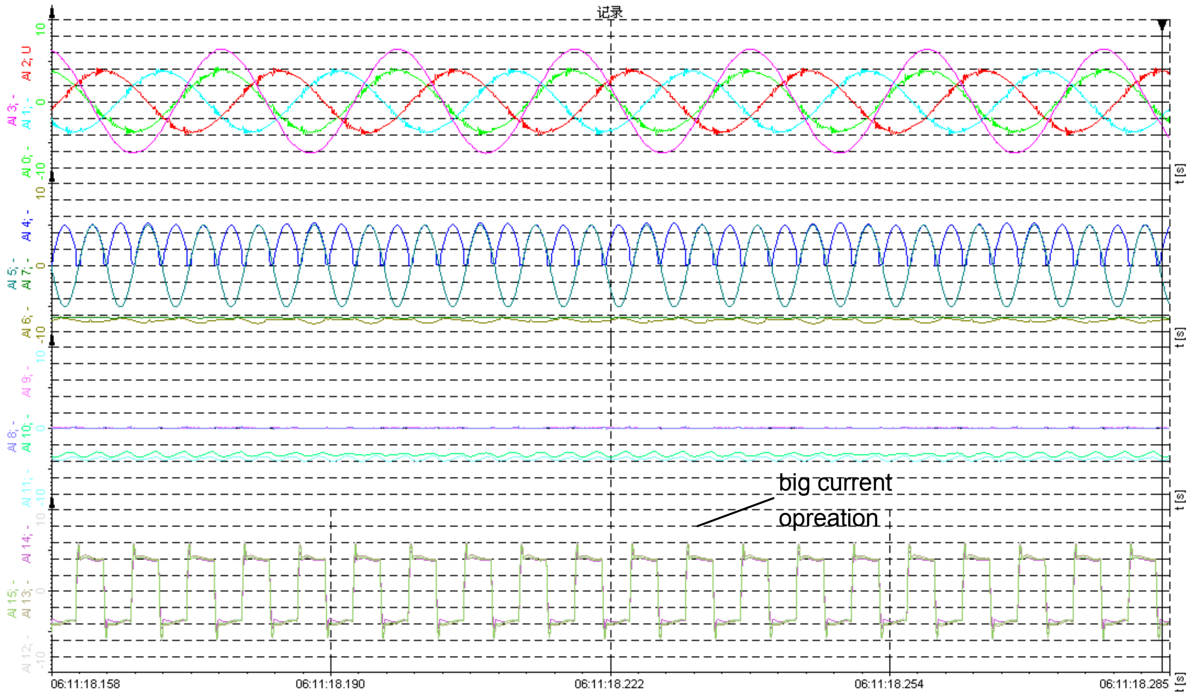


Figure 5.4 Standard operation with big current

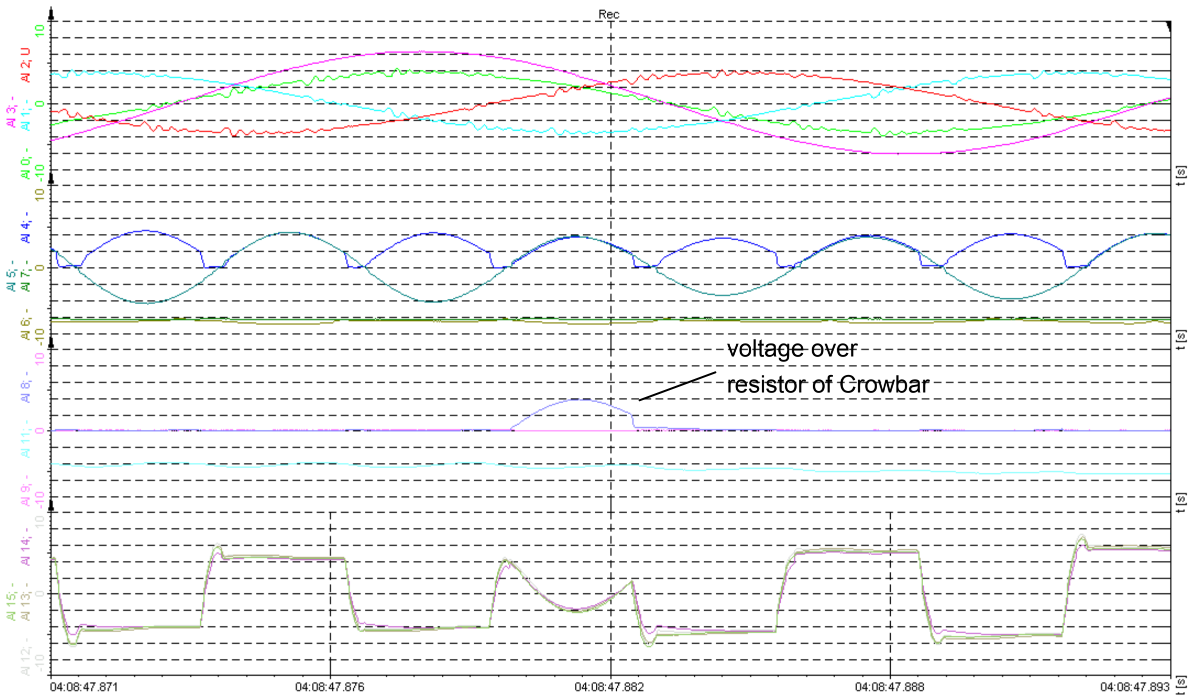


Figure 5.5 Critical situation during operation

Figure 5.5 shows the critical situation which occurs during the operation of the induction furnace. In Figure 5.5 we can see that when the critical situation happens, the crowbar protection unit is actuated and the voltage over the resistor of the crowbar unit increases. The currents through the IGBT-inverters reduce. After several ms the voltage over the resistor of the crowbar reduces to zero again and about 30 ms later the furnace unit comes back to stationary operation.

In the passages above, we have analyzed the standard operation and certain non-steady-state situation during the operation of the furnace by means of several examples. Through a detailed checking for the operation data which are stored on the hard disks, we have found out situations to be checked and evaluated. The record of these transient situations belongs to the secret of the company, for this reason the complete report of the transient situations will be given in appendix.

Through a long-term monitoring and measuring of the operation of the furnace equipment, we have found that the operation of the induction furnace at Boehler Company includes several transient conditions. The over-current and over-voltage appearing during the commutation could cause a turning off of the furnace. Therefore, components such as IGBTs may be damaged by the transient conditions and stop the operation of the furnace. Then the production program could not run as scheduled. More energy is consumed and the production efficiency is reduced. Due to this, based on the operation data on the hard disks, the hardware and control software of the furnace might be improved to avoid that the transient condition happens again.

6 Conclusion

According to the operation reports of the induction furnace from Boehler Company, we take the transient conditions of the induction furnace during running as our starting point, analyze the possible reasons for these faults, and determine the tasks of this thesis. The base of the induction furnace is electrical inductive heating. Therefore, electrical signals such as voltage and current play very important roles in the stable operation of the furnace. In this thesis, a partially existing measurement system has been adapted and documented. With this measurement system the electrical signals in the furnace circuit could be monitored and measured continuously for a long time and finally stored in hard disks. Main use is a documentation of the production process.

In this thesis, first of all we have analyzed the theoretical basis of the measurement system, and simply explained the principles of difference amplifier, low-pass filter and analog/digital conversion, and then chosen 16 electrical signals which are important for the furnace operation for measurement. Finally, we have built up a measurement system successfully. This measurement system is mainly made up of voltage transducers, current transducers and difference amplifiers. In the measurement sensor the high voltage and big current signals have been transferred into small signals which are suitable for measuring. The signals are monitored and measured continuously for several months, and then stored in hard disks. Finally, all the transient condition voltages and currents during this period are found out and recorded. Since all the transducers and amplifiers need to be driven with power supply, we have also produced reliable DC power supplies to drive the transducers and amplifiers.

All the 16 signals are output from a difference amplifier group. Using a signal splitter the original 16 signals are split into three groups of 16 signals. The three groups of 16 signals are sent to three terminals for different use: 1) computer terminal, the computer is embedded with data collecting card and A/D converter. In the converter, the electrical signals are transferred into digital signals, with the help of the DEWEsoft software which is installed in computer, the signals could be displayed at the computer screen and the signal data would be stored in the external hard disks; 2) indicator terminal, one group of 16 signals from the splitter has been input into a difference amplifier again and then subsequently into a low-pass filter, design accepting capacitive loading. These signals will be available for indication at an external device; 3) critical condition recognizing system: One group of 16 signals will be sent into a difference amplifier again and then into a critical condition recognizing system. This system has the function of critical condition recognizing and could take emergent measures such as cut off when the critical conditions happen. With these measures, the induction furnace could be protected immediately in case transient conditions.

By use of the measurement system which we have built up above, we have monitored and recorded the running performance of the induction furnace during the period from May 2007 to July 2007 in Boehler Company, and found out all the appeared critical voltages and currents. With these data we can easily know that when the faults occurred during the operation of the furnace, which voltages and currents are not correct. It offers to us the foundation and basis to improve the operation performance of the furnace and to enhance the working efficiency of the furnace. In this thesis, the main task is to develop a system to measure and find out the abnormal electrical signals, the improving of the furnace circuit has not been discussed.

In summary, in this thesis we have developed a measurement system which is suitable for the induction furnace in the Boehler Company, and achieved a long-term monitoring and measuring for the running of the furnace. Finally we have analyzed the data which are stored in the hard disks, found out several critical voltages and currents during this period. These critical signals will be very helpful in improving the operation performance and enhancing the operation stability of the induction furnace in the future.

7 Directory

7.1 Literature

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7.2 Tables

7.3 Figures