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TAPIO NIEMI

DC -FURNACE CONTROL PFILOSOPHY IN FERROALLOYS APPLICATIONS

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Tässä työssä tutkitaan DC-uunin ohjausjärjestelmän kehittämistä ferrokromisovelluksessa. Sulattojen sähköuunin kehityksessä on tapahtumassa käänne maailmanlaajuisesti, sillä yhä useammin päädytään asiakkaiden toimesta DC-uunien valintaan perinteisten AC- uunien osalta. Lisääntyvät ympäristösäännökset puoltavat osallaan DC-uunien rakentamista kuten myös se, että hyvin usein sulatot sijaitsevat varsin kaukaisissa paikoissa, joissa sähköverkot ovat hyvin epävakaita, mikä puolestaan puoltaa DC-uunien käyttöönottoa.

Työ jakaantuu kahteen osaan: Kirjallisuustutkimusosassa käydään pinnallisesti läpi sähköuunien historiaa sekä niiden jakautumista kahteen eri toimintatapaan, joista DC uunit ovat alkaneet nostaa suosiotaan helppokäyttöisyydellä, alentuneilla käyttökuluilla sekä joustavuudellaan. Osiossa käydään läpi myös DC-uunin ohjauksen osalta keskeisimmät näkökohdat, joiden pohjalta on lähdetty kehittämään Porin ORC:ssä kehitettävän pilotti-tyypin DC-uunin ohjausfilosofiaa ferrokromi sovelluksissa. Markkinat ovat pienet ja niillä toimii varsin isoja yrityksiä, joilla on DC-teknologia ollut käytössä jo pitemmän aikaa ja näin ollen kyseisistä uuneista on jo paljon kokemuksia maailmanlaajuisesti.

Työn toisessa osiossa käydään läpi toimintakuvausta ja tarkastellaan lyhyesti Porin tutkimuskeskuksessa olevaa laitteistoa sekä analysoidaan testiajon tuloksena saatuja tuloksia graafisesti. Tarkastelussa keskitytään vain logiikan toimintaan ja pois suljetaan muut mekaaniset ja prosessiteknisten asioiden tarkastelu.

ABSTRACT

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In this Master thesis is investigated the development of control system for ferroalloys applications. In the DC EAF technology is about to having a break through due to treason that more of the customers are ending up to invest in DC furnace instead of traditional AC furnaces. Also the continuously increasing environmental emission regulations are favoring the DC furnaces in addition to the fact that at mostly the smelters are located in very remote areas where electrical networks are often unstable.

The work is divided into two parts. In the literature survey is firstly considered the history and comparing the difference of EAF furnaces which has been divided to AC and DC furnaces. In the chapter also the most common control practices and the function of DC furnace control philosophy is studied which then has work as the basis for developing the Pori ORC DC-furnace pilot project. Global markets for the electric arc furnaces are very small and few major companies has been developing DC furnaces continuously and therefore also lot of experience has been gained from these applications.

In the second part of the thesis functional description and the equipments of Pori ORC are taken under the loop. At the end, final conclusions of the test trial are presented only from logic and control point of view and all the mechanical and metallurgical results are excluded.

ALKUSANAT

Diplomityön teko alkoi jo vuonna 2012, jolloin sain mahdollisuuden osallistua varsinaisten työtehtävieni lisäksi uuteen tuotekehitysprojektiin. Olen kiitollinen tästä sekä muista haastavista tehtävistä, joita olen yhtiössä ollessani saanut kokea. Haluan kiittää myös Outotecin henkilöstöä, jotka ovat olleet tämän Pilot-projektin osalta olleet kanssani tekemisissä sekä heidän pitkäjänteisyydestään Diplomityön loppuun saattamisessa.

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Tapio Niemi

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TERMIT JA NIIDEN MÄÄRITELMÄT

α	Alfa
A	Amber
AC	Alternating current
Db	Desibel
DC	Direct Current
EAF	Electric Arc Furnace
Flicker	Disturbances in the electrical network
I	Current
K	Kelvin
kA	Kiloamber
kW	Kilowatt
Mintek	South Africa’s national mineral research organisation
MVA	Mega Volt Ampere
ORC	Outotec Research Center
P	Power
PCS7	Siemens automation system
Proscon	Automation system by Outotec
R	Resistance
V	Voltage

1 INTRODUCTION

Electrical Arc Furnaces are not a new invention since the first furnaces were patented already in 18th –century. ASEA was the first company who developed the very first DC arc furnace in 1885. From that point on, the development of EAF technology has been going through various changes and steps in history. Still, it took a rather long time until DC-furnaces had their break through and the real development work started. The actual breakthrough in furnace development started in 1970's when ABB started to develop DC-furnace control systems. This was mostly affected due to rapid development of semiconductor devices, like thyristors. Big steps in development were taken at end of 1980's when component prices were coming down and rectifier technology with thyristor control systems were becoming more cost effective. [1]

Currently environmental solutions and economical scales from operating point of views are getting a more and more important role when choosing the technology to be used in smelting industry. In some areas of the world electrical grids are quite weak and are always fluctuating which are not optimal for operating with AC furnaces. Instead, DC technology would be ideal for this type of locations, since with DC technology, flicker effect on electrical grid is not as critical as with AC technology.

Finding new mineral resources is becoming more difficult and normally they are located in very harsh environments, which is affecting to the economical scale as well. Because of these particular reasons among others, smelting companies are continuously improving old technologies and seeking new for improving the recovery of minerals from ores. [1]

High capacity AC furnaces are often requiring agglomerations which are expensive investments. In this kind of furnaces, recovery of minerals is lower because a higher capacity is needed for off gases and slags. A DC furnace would be an ideal solution for handling all the slag and all the fine dust that generates from agglomeration processes to recover minerals from. Besides, since it does not require any agglomeration, particle sizes can be extremely small and operating costs are much smaller than those of AC furnaces. [1]

DC furnaces are operated with open arc principle which means that the electrode is above the slag level and the arc is generated between the arc and the slag. The arc that is generated is actually plasma that has high velocity and force, which are affecting positively to the string effect in the furnace. Control philosophy differs quite much from AC technology. Voltage levels are much lower; however, adjusting has to be done fast enough and under control since plasma arcs are very difficult to handle. [1], [2]

DC technology is currently an approved technology from the smelting companies' point of view and for this reason; it is an interesting market area for the future. Only a few manufacturers are offering furnaces based on DC technology nowadays; thus, there is a great market potential in this area with new design and innovations. [1]

DC furnaces are flexible and can be operated with different type of materials. There are many variations of this furnace but the most commonly used furnace designs are the bottom bin anode and the conductive bottom refractory design. Different variations exist also form the electrode point of view. Furnaces may be supplied with a solid electrode, a hollow electrode or the furnace might even have two electrodes, both working independently from each other. [1]

DC furnaces are most often round furnaces due to equal heat distribution which is achieved by round mantle design. Since DC-furnace normally has a single electrode in the middle of the furnace, round mantle design provides ideal heat balance to the liquid. By using round furnaces so called, cold pockets, can be reduced or eliminated in the smelting process. For example, using a square type furnace with in-line electrodes, causes always cold pockets to each four corners and overall the furnace is difficult to control due to unbalanced heat distribution.

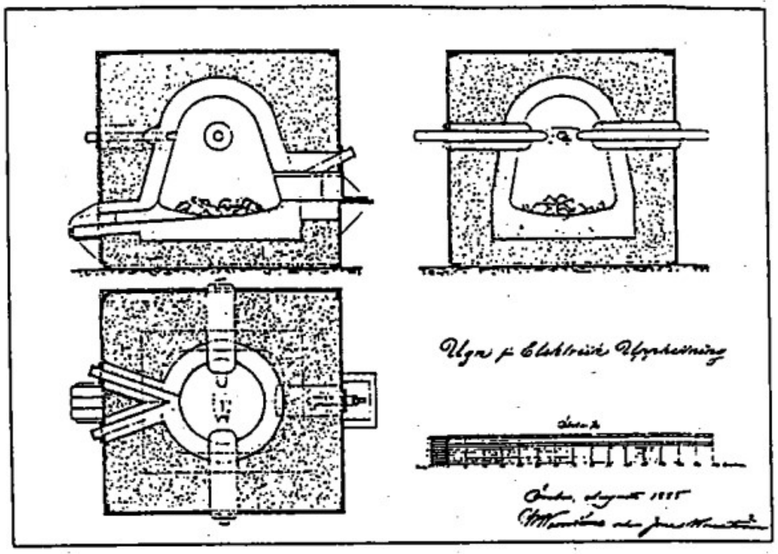


Figure1. First DC-furnace by ASEA [1]

As the Figure 1, presents the first patented DC-furnace by ASEA in 1885, Figures 2 and 3 on the other hand presents the latest development of the modern DC-furnace. Currently there are four pieces of this type of DC-furnaces been built in Kazakhstan on the time of writing this thesis by SMS-Siemag. Indeed, the technology has made some large steps forward since the year 1885. [18]

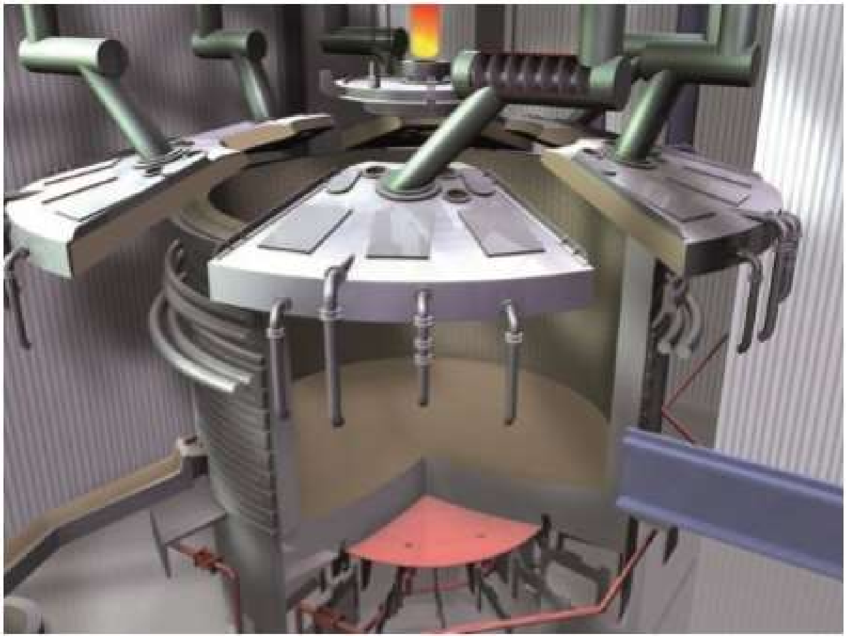


Figure 2. Modern DC-furnace by SMS-Siemag [18]

In Figure two, it can be easily noticed the basic construction of a DC-furnace. Key elements such as, water cooled mantle, material feed tubes which are going through the furnace roof which is also water cooled, single electrode in the middle of the roof are easily visible. The cut away type of illustrated picture shows also the conductive bottom structure nicely, through which the electric current shall travel during the smelting process. [5], [18]

Under the conductive refractory layer is round bottom anode to which the bus bars are connected under careful evaluation and modelling, in order to avoid unwanted torsion of magnetic fields which are affecting to the direction of plasma arc. The arc is very sensitive for the magnetic fields that the high current bus bars are producing. If design in routing the bus bars are done poorly it might lead to bend the arc permanently. [5], [18]

Figure 3. Modern DC-furnace by SMS-Siemag [18]

Actual water cooled roof structure can be seen in Figure 3 where the large water cooled duct is a raw gas duct which is been used during the heat up phase and maintenance period to guide the excessive hot CO gases out safely. This same duct is also connected gas scrubbers which function is to wash and clean the process gasses. Round cylindrical type of barrel is over pressure relief valve which open in case the pressure inside furnace is raising too high. [5], [18]

2 COMPARING AC AND DC TECHNOLOGY

2.1 Alternating electric arc furnace

Alternating current electric arc furnaces have been the most popular furnaces for decades. Technology for these kind of furnaces was published already 1950´s and it has remained nearly the same till these days. It can also be seen at the moment that a technology peak for the AC EAF has been reached. Nowadays these furnaces are using three phase power.

AC furnaces are having a good production capacity per ton and are hence considered to be the best or even the only option for large scale production of ferrochrome and other steels. Furnaces are operated with different operating principles depending on the applications like submerged, brush arc or open arc principles, depending of the process material. In submerge arc operation mode, electrodes are inside the raw material and the actual heating happens under the material where molten metal and slag forms. This method is commonly used in ferrochrome applications. In open arc mode, the electrodes are not touching the raw material or the slag layer when the arc is formed. In brush arc mode, electrodes are partly submerged in the slag but the flame is not visible. In open arc mode, the flame is easily visible above the molten slag. These two latest mentioned application principles are used for ilmenite and iron for example. [1], [2]

2.1.1 Electrode applications

AC furnaces are using as electrodes Söderberg type graphite paste electrodes. This electrode paste is supplied in solid cylindrical form from Elkem to the final user. Electrode constructions in the AC furnaces have two main features, steel casing and the actual electrode paste. Since the graphite paste is in the form of cylindrical cubic it cannot be used as such in the melting process. Paste is melted from solid into form of liquid, and from liquid back to solid thorough so called baking process. This baking process is essential from the process point of view since it gives for the electrode its final strength. Since electrode paste is required to be changed in form of liquid the steel casing around the electrode is providing the base, and the form for the actual electrode. [3], [4]

This is very critical stage in the process and operators has to be experienced and validate knowledge how this is to be done in order to achieve strong and homogeneous graphite electrode. Steel casing and hardened graphite are then melted in to the liquid bath of metal. [4], [5]

2.1.2 Electrical circuit in AC furnace

Normally AC furnaces are designed as a round circular shape having three graphite electrodes that are equally distributed from each other in the furnace central area but also several different variations are existing such as six in line systems, where six electrodes are located evenly distributed in rectangular shape of furnace. However, Figure 4 illustrates the normal basic configuration of this particular furnace. Each electrode has own transformer which are supplying single phase voltage to electrodes and transformers are connected together with delta connection. Before transformers bank of capacitors are preventing the supply network fluctuations and reducing the flicker effect. This type of furnace solution is providing huge phase change effect which can be realised very well next to the running furnace. [2]

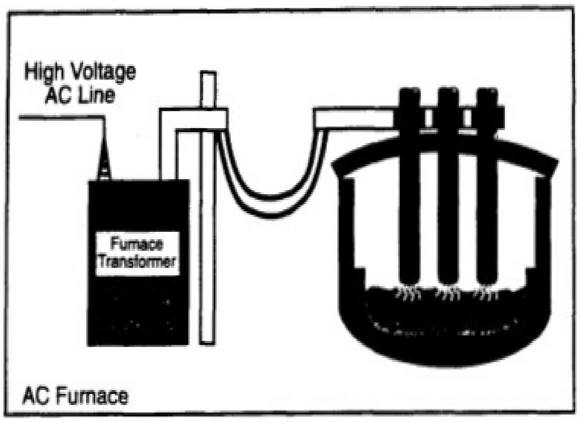


Figure 4. Typical AC circuit layout in EAF applications [2]

In Figure 5 is shown typical AC-furnace design and how it is being operated in ferroalloys applications. Electrodes are submerged in to the molten slag and ferrochrome and on top of the slag is a pile of agglomerated pellets which is fed continuously through charging tubes. On top of the pellet bed or piles is gas space where the CO-gas is sucked and through the off-gas duct to gas scrubber or to raw gas stack.

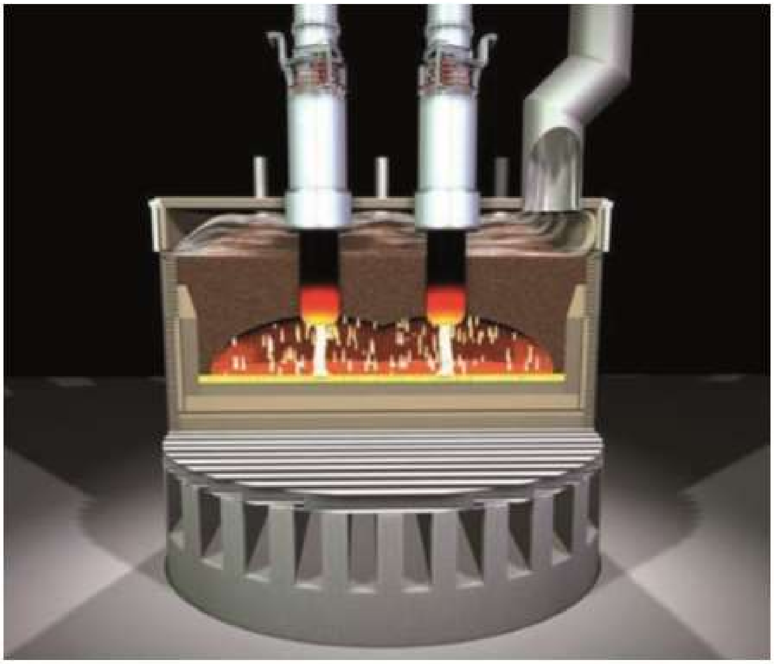


Figure 5. Modern AC-furnace in ferroalloys application [18]

AC furnaces do require a large capacity electrical network and the electrode diameters can be more than 2,0 meters and the current carrying capacity of the graphite electrodes is around 2,5A/mm^2. Electrodes of this size require large scale transformers and reactors in order to provide a stable load without fluctuations and flicker effect. It is critical to have a proper electrical network for the operation. In non developed countries, where the steel plants are often located, this is the most critical issue. [2]

These kinds of furnaces are operated with high voltage, which eventually affects to the current carrying capacity. Usually, voltage may vary between 600-1000V whereas transformed power can reach up easily to 25 MVA per transformer, depending on the furnace size and total power design.

AC furnace requires also often an agglomeration process before ferrochrome applications can be run. This is a major cost impact process for the plant and its purpose is only to produce raw material in a form in which it can be fed into the smelting furnace. [5]

2.1.3 Operating principle

Depending on the applications, submerged or open arc, the furnace is controlled differently from operator point of view. As a basic operational principle the operators are controlling the furnace power factor (cos fii), which is the ratio of resistance and reactance. [6] According to H. Lagendijk in his article [6] furnaces can be operated without problems having cos fii value > 0,8. If operating value with power factor values from 0,65 to 0,8 interaction effect starts to create operational problems.

2.2 Direct current electric arc furnace

A direct current furnace has started to become a very interesting alternative for the steel making industry and therefore, there are a lot of investigations ongoing globally. Technology is still considered to be rather new, hence globally there are approximately 20 large scale DC furnaces commissioned or under construction. The largest of these DC furnaces are achieving up to 72MW [9] electrical power outputs (ferroalloys applications) and 80MW in the ferronickel applications while the smallest, pilot furnaces, vary in a range from 100kW to 1MW in laboratory conditions around the world. [1], [8]

2.2.1 Electrode applications

Normally DC furnaces are provided with one graphite electrode which is located in the centre of the furnace roof providing then equal heat deviation to the melt. Furnaces can be operated with open arc or brush arc control principle and applications with double or triple electrode have also been commissioned. Mostly DC furnaces are provided with one electrode which is also influencing to the current carrying capacity of the electrode. Electrodes are prebaked which means that extension pieces can be directly fastened and baking phase which is typical for Söderberg paste electrodes can be skipped. For example if an AC furnace is having three electrodes, it would be possible to convert it into a DC furnace having one or two electrodes without a reduction in the production capacity. However, for this purpose, the electrodes in the DC furnace would have to be much larger that it would not be wise to manufacture any electrode arms that would stand the heavy load caused by the substantial increase in the weight of the graphite electrodes.

Prebaked electrodes exists several different variations and sizes. Two most typical types of electrodes are solid and hollow type. In hollow type electrode applications it is possible to feed charge material in to furnace though the electrode. However this causes the reduction in the power since current carrying capacity for is not as good as with solid electrode and mainly the hollow electrodes are not any more used. [4], [10]

2.2.2 Electrical circuit in DC furnace

The basic principle in DC furnace operation is varying widely from AC furnace circuit. In DC applications, the part of the electrode in the furnace steel structure that is connected to the positive side of the electrical circuit is called as anode; whereas the graphite electrode which is located in the roof section and is in the middle of the furnace and which is having minus side and called as cathode. These two electrodes are forming the interface of the closed electrical circuit with a rectifier and a DC reactor where the intermediate material, the slag is functioning (also the liquid metal and bottom refractory layer working) as the resistor of the circuit, Figure 6.

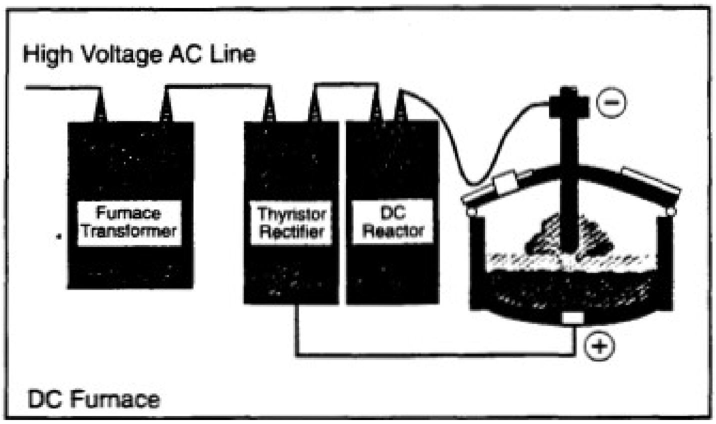


Figure 6. Typical DC circuit layout [2]

There are several different types of applications for the bottom electrode: From bin type to pillet type and water cooled electrodes. In the majority of the furnaces (40%) that are having a bottom electrode configuration the electrodes are fin type, pin type or pillet type and they are supplied with conductive refractory. As for the roof electrode, there are two main designs: Solid electrodes and hollow electrodes as mentioned earlier. Hollow electrodes are used when the material feed is wanted to be directly in the middle of the furnace. This way it is possible to guide the feed material in the middle of the plasma arc, to the hottest spot of the melt. [1], [2]

The reactor is one of the most important electrical circuit components in DC applications and its function is to balance the electrical circuit from the high speed current fluctuations. It can be considered as a filter for the electrical circuit that balances the current peaks in the system, caused by the short time shortages between the melt slag and the roof electrode. The reactor is always connected on the plus side before anode. [1]

In the past, the major slowing factor has been the high costs of rectifiers which recently have come down due to an increase of the demand and technology breakthroughs in thyristor development. Nowadays the latest rectifiers are supplied with latest thyristor control system and are therefore ideal for the type of applications that require fast control. [1]

DC applications do not need an agglomeration process as AC furnace requires in ferrochrome melting process. Fine dust from the off gas handling process can be fed back to the smelting process without any problems. Therefore, this is bringing clear benefit from the operation point of view for DC applications.

2.2.3 Operating principle

DC furnaces are operated with open arc principle. Different alloys and slag's have different type of conductivities and therefore depending on the material characteristics, correct operating values have to be defined during the process. Material batches are fed in to furnace through material openings in the furnace roof by vibrating feeders. Furnace is operated by constant power control mode, which adjusts then material feed accordingly to requested power. Arcs length is in remarkable role in the process. By adjusting the length of the arc the current and voltage is being also adjusted, current effects to the thrust force and to the actual stirring effect. [1], [7]

Arcs have lot of thrust force which helps the arc to penetrate through the slag layer to the molten metal. This thrust force pushes the material downwards which causes material to flow sideways and back to the surface, which then results on better metallurgical process, more reliable sampling and better control in tapping temperatures. [1], [7]

Regular tapping intervals are in essential part of the operation since increasing the slag layer affects increasingly to electrical conductivity and makes the accurate control of the furnace more challenging. The thinner slag layer the more accurate control operators have on the overall system. [1]

2.3 Benefits with DC EAF compared to AC EAF

Several aspects favour DC furnaces from operational point of view as well from economical point of view. However, there are also several aspects which favour the use AC furnace. Choosing the right furnace for a specific application is always a decision that combines pros and cons.

2.3.1 Electrode consumption

The major cost impacts for the steel smelting plants are the electricity and the electrode consumption. It has been confirmed that the major benefit with DC furnaces is low electrode consumption. In fact, the electrode consumption has been reported in several cases to be at least 50 % smaller than with AC furnaces [1]. The fact of using only one electrode instead of three naturally reduces the electrode consumption. Furthermore, having the graphite electrode (cathode) above the slag level and the hot spot being located in the melt itself, influences in having a cooler electrode cathode and this also reduces the electrode consumption. The three different most common reasons for the electrode consumption are: side oxidation, tip consumption and breakage of electrodes. It has been rectified that electrodes in DC furnace applications are lasting longer. Different types of electrode breakages are also rarer in the DC processes compared to AC processes, mainly related to prebaked electrodes which are ready to use as it is not the case in AC EAF applications. [1], [2]

A reduction in the electrode consumption is a major cost saving factor for the operating plants where the electrode consumption in a year can be several hundreds of tons and the price per tonnage can be more than $1400.

2.3.2 Equal heat distribution

Equal heat balance is much more stable when operating with DC furnaces rather than in AC furnaces. In DC applications the electrode is vertically and centrally located (single electrode applications) in the furnace and the arc expands vertically down towards molten bath. Even when using a twin electrode configuration in DC furnace, the arcs are still working independently and the heat balance is equally divided in the furnace. This provides uniform heating pattern over the bath and therefore the melting is more efficient. [1], [7], [14]

AC furnaces however are suffering from the twisting of the arc since three different electrodes each with a different phase are forcing the arc to bend outwards from each other’s due to magnetic fields. The heat distribution is more unstable because the arc is bending in a 45 degree angle outward from the furnace centre. Hence, it is not possible in AC furnaces to achieve a similar type of balanced heat distribution as in DC furnaces. Besides, using only one electrode in DC furnace has a better result for sealing the furnace roof since there is only one opening compared to the three that have to be sealed gas tight in an AC furnace. [10]

2.3.3 Noise hazard

DC furnaces are very quiet compared to AC furnaces where the noise level can exceed 90db to 100db depending from the application. DC furnaces are not making so much noise hazard unlike the AC furnaces, because there is no frequency change happening in the electrical circuit. Overall, AC transformers working at a three phase sequence and having high capacity are always considered to be noise hazard equipments. [1], [10]

2.3.4 Reduction of fines

One of the most important advantages for the DC furnace is that it does not require any separate and expensive agglomeration plant to be built in order to operate. In fact, not even a preheating of the brackets is necessary. The furnace can be loaded directly with scrap metal and material feed even with very fine dust and it can be started immediately when a small amount of molten metal has been formed. [10], [17]

DC-furnaces can be considered to be a more economical solution since high recovery of alloys can be achieved without any additional auxiliary pre-processes. The furnace can be loaded even with the dust that has been collected from previous processes via bag filters, directly, without having this dust undergo any other processes. This waste form bag filters would otherwise be considered to be useless waste which would not be used further without expensive agglomeration processes. [10], [17]

2.3.5 Electrical circuit

Power surges in an AC furnace are causing lot of disturbances in the supply line; this is called as flicker effect. This effect is an unwanted phenomenon which is tried to be kept as small as possible by dimensioning a strong enough supply line. Even in the DC circuits the flicker effect and harmonic variations are not strange phenomenon’s but because of the rectifier and the thryristor control system, the flicker effect is kept much efficiently under control due to fast reaction time of control system. [1], [2], [13]

DC furnaces do not require a similar type of strong power network as AC furnaces and are therefore are considered as better solutions in areas where power supply is known to be weak. Large frequency changes in supply network are affecting directly to the AC furnace power output and also to the production rate whereas a DC furnace can be operated with full power with a minimal reactance, while being able to provide the full power output and production rate required. The reason for this is that DC furnaces are equipped with a reactor (see Figure 3) that dampens the flicker effect in the electrical circuit and therefore, a stable load can be achieved. [13], [14]

2.3.6 Stirring

Stirring is a phenomena taking place as a result of the electromagnetic forces that effect to the slag path. In this phenomenon, the arc hits the slag bath and the current can flow through the slag to the bottom side of the anode. During this process, the melt interacts with these electromagnetic forces that result from the current penetrating the slag and the metal layer. The magnetic forces and velocity of the arc are forcing the melt into a rotating movement (see Figure 7); this is something that does not happen in AC furnaces. Since the plasma arc is having a strong thrust force downwards, this thrust pushes the melt to flow first downwards and then towards the furnace walls. Additionally, the electromagnetic forces in the bottom anode results rotating movement and forcing the melt to rotate in the furnace. [1], [9]

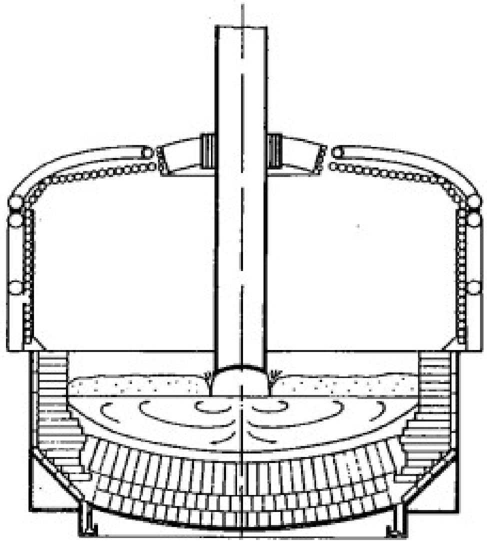


Figure 7. Stirring effect of the arc in the DC furnace [1]

2.3.7 Energy savings

DC furnaces are consuming less electrical power compared to AC furnaces. Experiences are demonstrating that approximately 5-10% electric consumption decrease has been achieved. This percentage reduction is not as remarkable as the electrode consumption decrease but considering this decrease and the current electrical prices at the stock markets it will play a significant role when planning to reduce the operating costs. The reduction in the electrical consumption is related mainly to a better design of the furnace structure when only one electrode is used. The fewer electrodes used in the furnace, the lower the losses in the electrodes. This implies having less chances to have leakages and also, having a better sealed roof. Moreover, in DC furnaces there are no inductive losses in the electrical circuit as it happens in AC applications. [1]

2.3.8 Service

DC furnaces have less maintenance costs than AC furnaces. This is due to the fact that AC furnaces have more electrodes and consequently, more mechanical equipments which require a planned maintenance. Also, the spare part costs are higher with AC furnaces due to the larger stock of spares required at the plant. In addition, hydraulic systems are simpler in DC applications compared to AC furnaces because of the amount of electrodes that are used. [1]

Refractory costs for DC furnaces are a little bit higher compared to AC furnaces; however, the refractory repairing costs in the slag line area of DC furnaces are less than those in conventional AC applications. The reasons for this are lower stress and wears at the slag line levels caused by the vertical thrust force of the arc. [1]

Service costs for the main electrical components are also smaller in DC EAF applications due to smaller component quantities than in AC application. Some of the components do not require any specific service such as reactor and rectifier. Rectifier can be maintained by changing printed circuit boards and updating the software in case malfunctions. [1], [16]

2.4 Disadvantages of DC furnace compared to AC

Despite the fact that there are several advantages (smaller flicker effect, reduced electrode consumption, reduced electricity costs) in DC-furnace processes over AC-furnace processes, there are also some disadvantages.

Refractory consumption in DC furnace side walls is less than with conventional AC furnaces but, instead of this positive effect, DC furnace has also negative effects. For instance, the consumption of the bottom refractory is much higher than with AC furnaces due to the configuration of the bottom anode. That is, due to the anode cathode effect in electrical circuit, the hot spot is being located in the bottom anode where a hot spot already exists.

In DC furnaces, the bottom anode construction requires relatively more maintenance since, as earlier mentioned, the current shall heat up the anode so much that this gets consumed much faster than cathode electrode. This also affects to the consumption rate of refractory at the bottom of the furnace.

Even though the electrical network does not have to be as stable as in AC furnaces, DC furnace applications requires a reactor and thyristor rectifier; these raise the equipment cost dramatically compared to conventional furnaces that only require transformers. Rectifiers and reactors are still currently expensive equipments. However, in general, costs are coming down due to technology development and decreasing of the component prices.

Size is a limiting factor for the DC-furnaces because the graphite electrode has only a limited current carrying capacity. It is possible to change from one electrode applications to double or triple electrode applications; nevertheless, this would imply the loss of some of the advantages that can be achieved with the use of one single electrode such as doubling the electrical component for the electrodes since both are working independently from each others. However, when using two electrode combinations in DC application more power and productivity can be produced with even lower electrode consumption. [12],

Rectifier and transformer costs are a key factor when selecting DC-process for the smelting plants. Large scale thyristor controlled rectifiers are highly expensive equipments. The more automation and the more pulses rectifier has, the higher the costs naturally are. [1]

As a summary following aspects should be considered when evaluating the AC-and DC applications.

Positive aspects on DC furnace:

- Smaller electrode consumption
- Reduced flicker effect and the capability to operate DC furnaces in weak main networks
- Reduced electricity consumption
- Strong stirring effect which improves metallurgical properties of molten metal and slag
- Accurate and easy control of the process
- Reducing Noise Hazards
- Direct feed of the ore and dust. No agglomeration required
- More expensive electrical components required

Negative aspects on DC furnace:

- Limited furnace size due to electrode current carrying capacity compared to AC applications
- More expensive refractory material needs to be used, due to conductive bottom
- Wear of the bottom lining is faster due to anode electrode design.
- Bottom has to be liquid metal in order to provide good path for the current to flow

3 DC-FURNACE

3.1 Electrical circuit and components

3.1.1 Transformer

Transformer is the main power supply for DC-furnaces. It is the key item in order to provide the necessary amount of power as per the production and process requirements. Therefore, it is essentially important to specify and design transformers with enough capacity as per the process requirements so that the power factor of chosen transformer is on the correct area.

During the design phase is important to understand the importance of the capacity requirements of transformer. Transformer has an operating window that is represented in the following diagram as current in Y –axis and voltage on X-axis. For example, Figure 8 represents the transformer's operating curve of Pori DC-pilot furnace. This transformer can produce 3kA of constant current and 200 volts giving total power output of 600kW. Even this transformer can produce informed 600kW, the working window for the transformer would be only one small dot at the cross section of X and Y axis which is demonstrated with green arrow in figure 8.

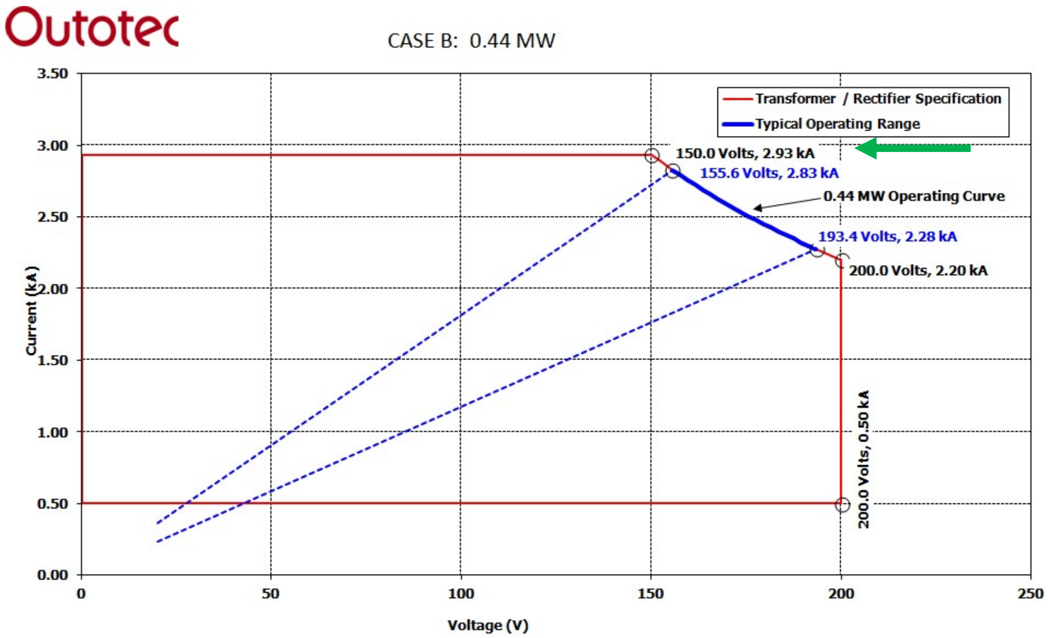


Figure 8. Transformer operating window in Pori ORC pilot plant [5]

DC-furnaces are normally operated with constant power and resistance set point values which mean that, in theory, with this transformer 600kW furnace power output could be achieved when resistant set point would be 66 mohm. This mentioned set point is based on ideal conditions in the process and electrical circuits; otherwise the stated maximum power could not be achieved due to continuously changing circumstances.

$$R = V/I = 200V/3000A = 66 \text{ mohm} \qquad (1)$$

$$P = I*R^{(2)} = 3000A*(66 \text{ mohm})^2 = 600 \text{ kW} \qquad (2)$$

In practice, achieving this power output is not possible because the resistance inside the furnace is never constant. Several reasons contribute to having a resistance that is not constant inside the furnace such as gas composition, slag depth and its resistivity, foaming effect, thrust of the arc.

Because of the reasons mentioned in the previous paragraphs, the blue dotted window in the operating window diagram (Figure 8) represents the actual transformer operating window, where it can provide the maximum power to the furnace within specific resistance set point limits. When the resistance is varying also the arc length is varying and this variation is directly proportional; that is, the higher the resistance set point, the higher the voltage is and the longer the arc length is. However, these relations are not logarithmic as it is possible to be seen from the operating window's blue curve in Figure 8 that represents these relations.

In this Pori ORC DC-pilot case the transformer can provide its maximum power from continuous operating point of view, when the resistance set points are set or the furnace is operated between following resistance set point range:

$$R = V/I = 155{,}6V / 2{,}83kA = 54{,}98 \text{ mohm} \qquad (3)$$

And

$$R = V/I = 193{,}4V / 2{,}28kA = 84{,}82 \text{ mohm} \qquad (4)$$

As a result, the actual maximum power is of 0,44MW as stated in Figure 5 which is approximately 27% less than transformer's stated capacity and hence, the arc length is not going to become too long or too short. The dotted blue line gives the actual operating window for the furnace between >55-85< mohms when ferrochrome is produced. By following the dotted window a safe operation range for the electrode is achieved in conjunction with the furnace power. In case resistance set point would have been chosen out of this window it does not affect to the transformers operation as it would affect to the electrode control and the arc length. In this case, a great risk of submerged operation would exist which can lead to breakdown of electrode as an example.

Regarding other materials like ilmenite, the slag is very conductive, only 5-16 mohm would be required in order to have valid resistance set point values. Therefore, transformer's operating window would be much wider than the one shown in Figure 8 for ferroalloy.

Transformers capacity is not under dimensioned for ferrochrome smelting but it actually gives less power than planned and for this reason, the feed rate of the raw material cannot be maximized which affects to the output /production rate of molten metal and slag.

3.1.2 Rectifier

The rectifier is the main component in the DC electrical network and as previously mentioned, rectifiers were the biggest constrain for why DC-technology was expensive to be launched to the market in 1990's and earlier. Earlier rectifiers were diode controlled because of the very high price of thyristor control systems, since thyristos were considered as new technology and the costs for them are therefore higher. Diode controlled rectifiers were not even an accurate control method. All this changed when in the late 1980's thyristor controlled rectifiers prices went down. Since then, the technology has been improving dramatically making it possible that thyristor controlled rectifiers are commonly used in DC-furnaces. [1], [2]

Rectifiers are controlling the current and the voltage what is fed into DC electrical circuits. Based on the set point values given by the operator, a separated logic control system is calculating the electrical values required by the rectifier and, once those values are received, the rectifier control system reacts accordingly.

Rectifiers are used as the main control system for adjusting current and voltage according to process requirements.

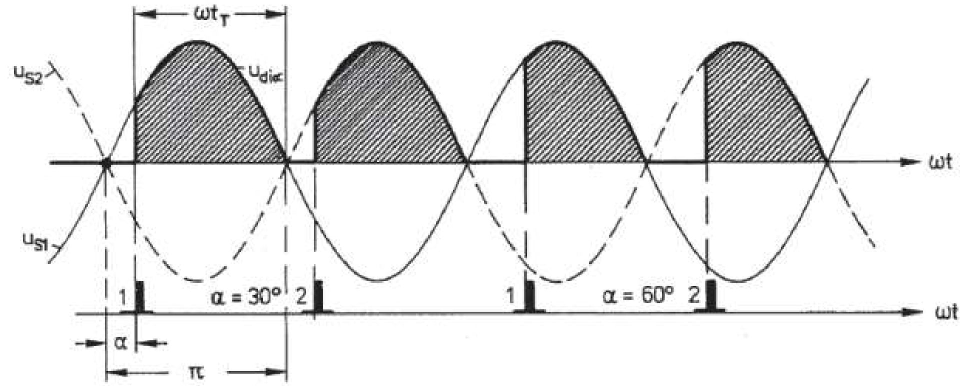


Figure 9. Thyristor control [13]

Thyristors are semiconductors that are working as switches with very high response time. Figure 9 represents the control logic of thyristor control logic.

Depending on how much the firing angle α is, the voltage and the current are varying as per the same. For example, when the firing angle α is 60° as in Figure 9, point 2, the thyristors are starting to conduct later which results in a lower current and lover voltage output. If firing angle α would be 30° as in point 1, thyristors are able to conduct current earlier which results higher current and voltage values as output. [14]

Rectifiers are used as a fast and primary control for the current and voltage in DC electrical circuit due to its fast response time (15-20 milliseconds). The electrode movement controls system functions as secondary control for the current and voltage. [14]

Depending on the rectifiers and the solutions that have been chosen, rectifiers have different amount pulse systems; being pulse systems the term is used when referring to the amount of thyristors that are in series in the rectifier. Basically, the more thyristors, the more stable current pulse achieved in the output is demonstrate in Figure 10 three examples are show, 6-pulse, 12-pulse and 24-pulse rectifier systems. [15]

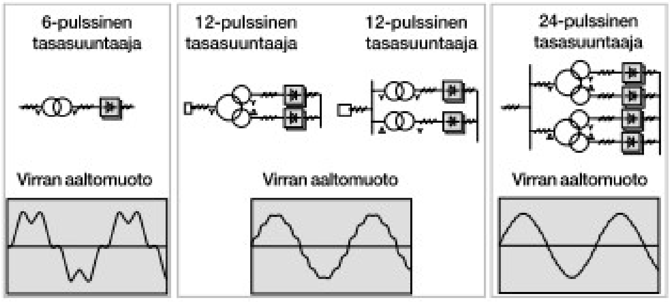


Figure 10. Different rectifier pulse systems and output signal [15]

Normally, 12 or 24 pulse system rectifiers are used in high current applications. However, even 48 pulse system rectifiers are available in the market for lover current applications; unfortunately, they are also highly expensive. Therefore, the more economical practice is to connect two rectifiers in series in order to achieve 24 pulse rectifying output. [13], [15]

3.1.3 Reactor

The reactor is a large size inductance coil which is used in DC electric circuit to compensate the flicker effect that results from the main electrical network. It is installed always at the negative side of the electrical circuit between electrode and rectifier. Reactors are a cheaper solution to use in the plants which are located at remote locations where stable main power network is not available. In such cases, installation of static VAR compensation would be one possibility to ensure stable power is fed to the DC electrical circuit but unfortunately, this would be a very expensive investment compared to the cost of a reactor that does not require any controllable logic or any other auxiliary connections.

The plasma arc is never stable and it changes its locations continuously around the electrode tip depending on where the lowest resistance route in the slag bath is. Since the arc has also a thrust force towards the slag bath and sometimes splashes will be formed, causing occasionally short circuits between the electrode tip (negative side) and slag bath (positive side). These short circuits may be lasting a few milliseconds. In this type of situations, the reactor is operating as a filter in the closed electrical network and protecting rectifier from these short circuits. Thyristor controlled rectifiers are sensitive to this type of short circuits and as a result thyristors could get damaged.

The fact that the reactor is an inductance coil means that it has also an internal resistance. This internal resistance is highly important for the arc from a stability point of view. Without any internal resistance in the circuit, the arc would be highly unstable and impossible to be controlled.

3.1.4 Electrode control

Hydraulic units are used to control the graphite electrode movement through the roof. Controlling is required to feed the necessary amount of new electrode due to consumption of the graphite. During the start-up and tapping the electrode is lowered and raised as required. Movements of the electrode are controlled with two hydraulic cylinders that are acting as required by the operator or by the automation system.

Continuous electrode control is required in order to achieve the required resistance set point (arc length). In chapter 3.1.2 it was mentioned that rectifier is main controller for the current and voltage adjustment. Hydraulic electrode control is functioning as secondary control system together with main control system that is changing the position of electrode as per the resistance set point.

The electrodes used in this application are prebaked graphite electrodes which can be attached together with thread joints or a similar method. During the design of the DC-arc furnace, one of the most important issues is to consider the following two aspects regarding electrode: The diameter of the electrode and its current carrying capacity. For the graphite electrode, the current carrying capacity is around $28A/cm^2$. These two factors have to be in line with the designed furnace power output and of course with the actual costs.

Since electrodes are having limitations on the current carrying capacity, most commonly used electrodes are 600mm diameter. However, 700mm diameter electrodes are also available upon request. Larger diameter electrodes can be used also but it would affect directly to the construction and economics due to fact that stronger materials would be required to be used in order to provide a strong structure for electrode arms. When the current carrying capacity is the limiting factor of the furnace power in single electrode applications, the problem can be solved by using a double electrode solution which will have a positive effect on the furnace power output but a negative effect on the electrode consumption compared to single electrode applications.

3.1.5 Bus tubes

Bus tubes are designed according to the current carrying capacity, having enough resources to stand possible short-circuit circumstance without any physical breakdown. Regarding the DC furnace routing, bus tubes are one of the important factors that have to be considered in design phase. Depending on the applications and the different type of anode designs the bus tube routes are varying a lot.

Magnetic fields are formed around the bus tubes due to the high current that is fed into the furnace. Plasma arcs are very sensitive to the magnetic fields and for that reason, the routing of the bus tubes should be designed in a way that their magnetic field is disturbing the arc as less as possible. Using higher currents causes higher magnetic fields around the furnace, which at the same time is causing an arc bending effect.

The best practice is to design the bus tube routes that go to the bottom anode as vertically aligned to the bottom of the furnace. This way, bus tubes are making a minimum disturbance to the arc because the magnetic fields are formed as vertical and therefore, they are not bending the arc as much as if the bus tubes would come as horizontally into to the anode plate. This is based on the right hand thumb rule, Figure 11, in which the thumb is pointing in the current's direction and rest of the fingers are pointing in the magnetic field's direction.

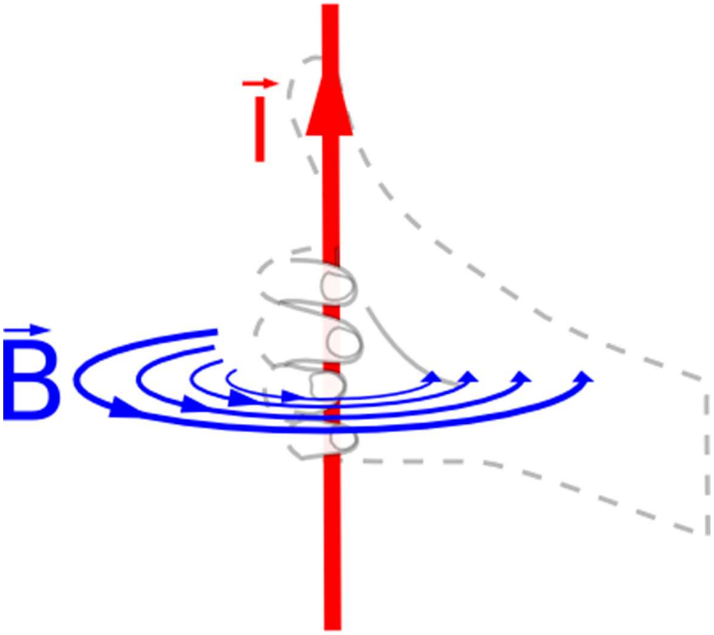


Figure 11. Right hand rule

3.2 Arc and magnetic fields

3.2.1 Arc

Arcs and magnetic fields are very complex phenomenon. In fact, a lot of research has been conducted related to magnetic fields related in DC EAF applications. In this chapter, only the main points are going to be considered in order to give basic understanding of the arcs and so, to have a better understanding from the control point of view.

The arc is formed from ionized particles in high temperatures. These particles open the electrical conductive path between the two different polarities in the furnace: The cathode, negative side (graphite electrode) and the anode, positive side (slag bath). At very high temperatures such as 5000 Kelvins, molecules of the gas are ionized and become positively charged ions and also negatively charged electrons. As a result, neutral but very strong conductive plasma can be formed. Plasma is working as a conducting material which allows current to travel from negative to positive polarity and hence, an electrical circuit is then formed. [7], [11] Plasma arc is formed from a very small area on the electrode tip (Figure 12). The arc has a high velocity and as a result a high thrust force which and is therefore effective for heating and melting the metal. Due to this thrust force the arc is also effectively stirring the molten bath. Stirring is a very important feature from the metallurgical point of view as it gives to the bath a homogeneous chemical composition. This zone where the arc penetrates slag layer has been observed to have very rapid melting, fast chemical reactions and good mixing characteristics. [7], [11]

Arc is never constant and it is wandering on the surface of the electrode tip depending on where shortest path to close electrical circuit is located. The arc is changing its position several times in only few milliseconds periods as has been observed by the high speed camera by Mintek research team in their research campaigns. The reason for the arc changing its position is that the thrust force of the arc is causing splashing on the molten bath and consequently, it is making movement on the surface of the bath. The closer the arc is to the surface the more stable is the arc and the more thrust force exists towards the molten bath. If the arc is getting longer, it becomes more unstable and starts moving more around the electrode tip. [7], [11], [14]

Double arcs are not rare either because of this moving path phenomenon. Occasionally, all circumstances are ideal inside the furnace (gas composition, electrode tip, splashing and shape of molten bath) for this type of phenomena to occur. This double arc phenomenon can be seen in Figure 13 and was captured by Mintek research team. The total current is divided in this case between these two arcs. Normally, the electrode tip has always a conical shape for the reason that arc is formed more easily from this type of end than from a totally flat type of electrode. [7], [11]

Figure 12. Stable arc in DC furnace [14]

Figure 13. Double arc, single electrode [14]

A strong magnetic field has a considerable effect regarding bending behaviour of the arc. High current bus bars are used to supply the current to the electrodes and high current shall naturally result in high magnetic fields on the surroundings. The magnetic fields are affecting to the arc in a way that the arc shall start bending towards a higher self-driven magnetic force. This phenomenon can be compensated by using straps or similar equipment that shall drive the current and therefore also magnetic force equally around the cylindrical shell in order to stabilize the arc bending. Without compensating the electrical magnetic forces, the arc would be in a wrong angle towards the molten bath resulting in an incomplete stirring, a wrong heat balance in the furnace, a faster consumption of graphite electrode and possibly also a breakdown of the furnace side wall refractory layers. [7], [11], [14]

3.2.2 Arc characteristics

Ben Bowman made a long term work in studying the plasma arc characteristics and as a result he has summarized the data from DC electrical arcs between 1 to 10 kA ranges. In these studies, Bowman investigated and discovered how the arc voltage varies as a function of the arc length as well as the current when conditions are stable in the furnace. He also modelled the high intensity plasma arc which schematic principle can be seen from Figure 14 and the relation of voltage, current and dark length in Graph 1. Bowman discovered that plasma arc forms from a relatively small spot on top of the electrode tip and expands towards the anode side. [7], [11]

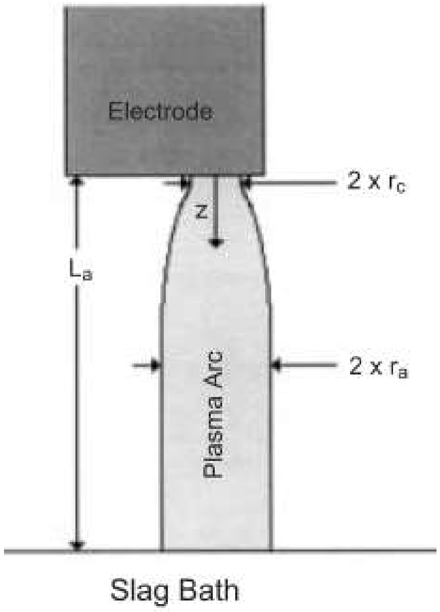


Figure 14. Plasma spot forming [11]

Equation 5 describes the shape of the conducting volume of the arc as a function of the distance from the cathode attachment spot (DC arc photography and modelling).

$$\frac{r_a}{r_k} = 3.2 - 2.2\exp\left(\frac{z}{5r_k}\right) \qquad (5)$$

According to Bowman's research, the arc radius r_a is varying with distance z, from the cathode surface. In this case b

Arc shape and the arc voltage can be

$$V = \rho_a \times \sqrt{\frac{I \times j_k}{\pi}}\, x \int \left(\frac{r_k}{r_a}\right)^2 dZ \qquad (6)$$

$$Z = \frac{z}{r_k} \qquad (6\text{-}1)$$

$$V_a = \frac{I\rho_a}{m\pi}\left[-\frac{1}{a^2+ab} + \frac{1}{a^2+ab.\exp(\mathrm{mL})} + \frac{\ln(a+b)}{a^2} + \frac{mL}{a^2} - \frac{\ln[a+b.\exp(mL)]}{a^2}\right] \qquad (6\text{-}2)$$

$$A=3.2r_k \qquad (6\text{-}3)$$

$$b= -2.2r_k \qquad (6\text{-}4)$$

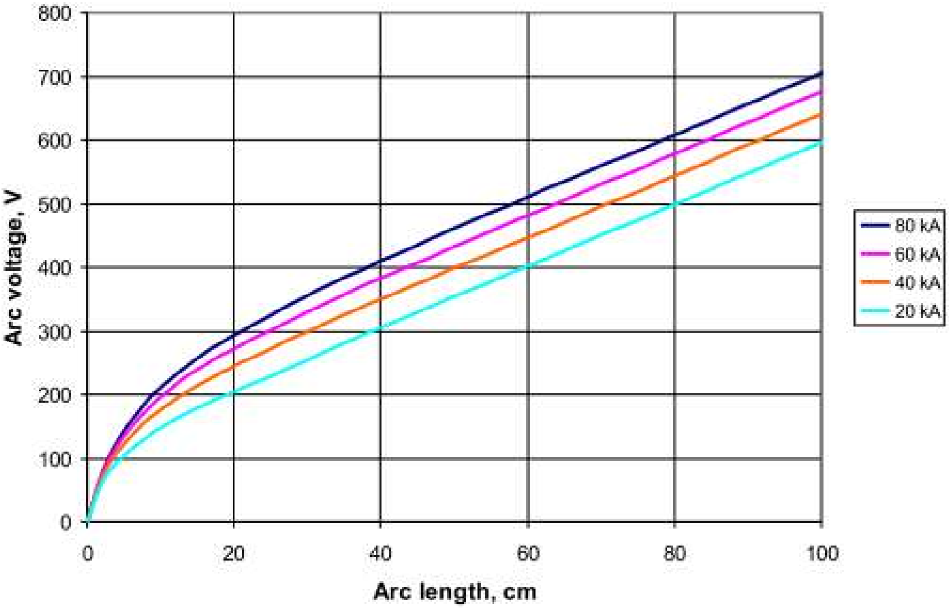
$$m = \frac{-1}{5r_k} \qquad (6\text{-}5)$$

$$r_k = \sqrt{\frac{I}{\pi(\frac{350}{cm^2})}} \qquad (6\text{-}6)$$

As the final result the equation gives the nonlinear expression relating the arc's voltage to its length and current. These examples can be seen from graph1. [11]

It can be noticed that in the beginning arc length and voltage are almost the same with all the different currents. When the arc length starts to raise also voltage is rising and the relation of voltage, current and the arc length is almost linear. Equation six can be used as reference point when determining the actual length of the arc in the test trial.

Graph1. Arc voltage as function of arc length at different currents [14]



4 CONTROL PHILOSOPHY

4.1 General philosophy

The basic control principle of DC arc smelting furnaces can be compared to TIG-welding or plasma cutting processes where the arc is ignited on top of the base material and the electrode is not in physical contact with the material being welded and which is working as an anode. During welding, the length of the arc is not constant all the time and this affects to operating parameters such as voltage and current. In welding processes, the operator sets basically, the current set point as the main operating parameter and the welding machine control system shall adjust automatically the voltage and current according to the required set point demand, in order to provide a stable arc during the welding or plasma cutting process. This type of control system is described as a constant current control method and the same can be applied to DC arc operation with several other factors to be considered from process point of view.

DC arc furnace can also be operated with a constant power control method. In this control method, the current and the voltage are controlled indirectly by power set point and resistance set point values which operator shall set. The constant power method shall give more stable control of the plasma arc than the constant current control. The constant current method is a very sensitive control philosophy for the arc furnace where the feed rate of material is not always exact due to various reasons such blockages in the charging tubes among others. The constant power control can give more flexibility for the control system to react in varying situations in process which is important in order to avoid any equipment or electrode breakages.

No matter which control philosophy shall be chosen, the constant current or the constant power, the most important factor in the process is the correct heat to power ratio according the conditions of process. The same can be also observed during the welding process. When too much filler material has been fed during the welding, the current set point is not anymore enough for that particular feed rate and then the welding will be insufficient and cold weld seams without proper penetration shall exist. The opposite happens when too little filler material has been fed for a specific current set point value demand. In this case, the seam and base material shall melt and proper welding seam will not be sufficient. This same basic principle can be transferred to a DC arc furnace. The feed rate of the raw material into the furnace has to be in line with furnace power requirements since the feed rate has a great influence on the voltage and current values and so, it has a direct effect on the balance of the power output.

4.2 Process control flow

Important factor in constant power control method and in all other control methods as well is that power and feed ratio has to be in line with power requirements. Total electrical power fed into furnace shall never be used as 100% inclusively for the material smelting purposes. Total electrical power will be lost in the electrical circuits, heat transfer to furnace cooling water, thermal radiation in off-gases, in raw material heating and therefore only part of the total electrical power shall be used directly for smelting raw material. Therefore, in order achieve good balance in control the main control parameters with DC furnace control are:

- Chrome input/power input (kg chromite/MWh)
- Antracite / chorimite ratio (kg anthracite/ kg chromite)
- Power set point of furnace (MW)
- Resistance set point(mohm)
- Thickness of allay and slag (regular tapping schedules)

These set points are affecting to material feeders that feed the material into furnace as per required flow rate and to current and voltage running values via rectifier and electrode hydraulics.

In Figure 15 is shown general control diagram for the DC- furnace operated by constant power control. Four different set points are inputted to the system and according to these values automation logic shall calculate and process the accurate set points according to requirements as resulting the outputs.

Mass balance calculations are critical for the fluent and accurate operating of the furnace. A preliminary mass balance calculation has to be performed by the metallurgist who has the deep knowledge of the raw material energy requirements and the heat losses of the furnace.

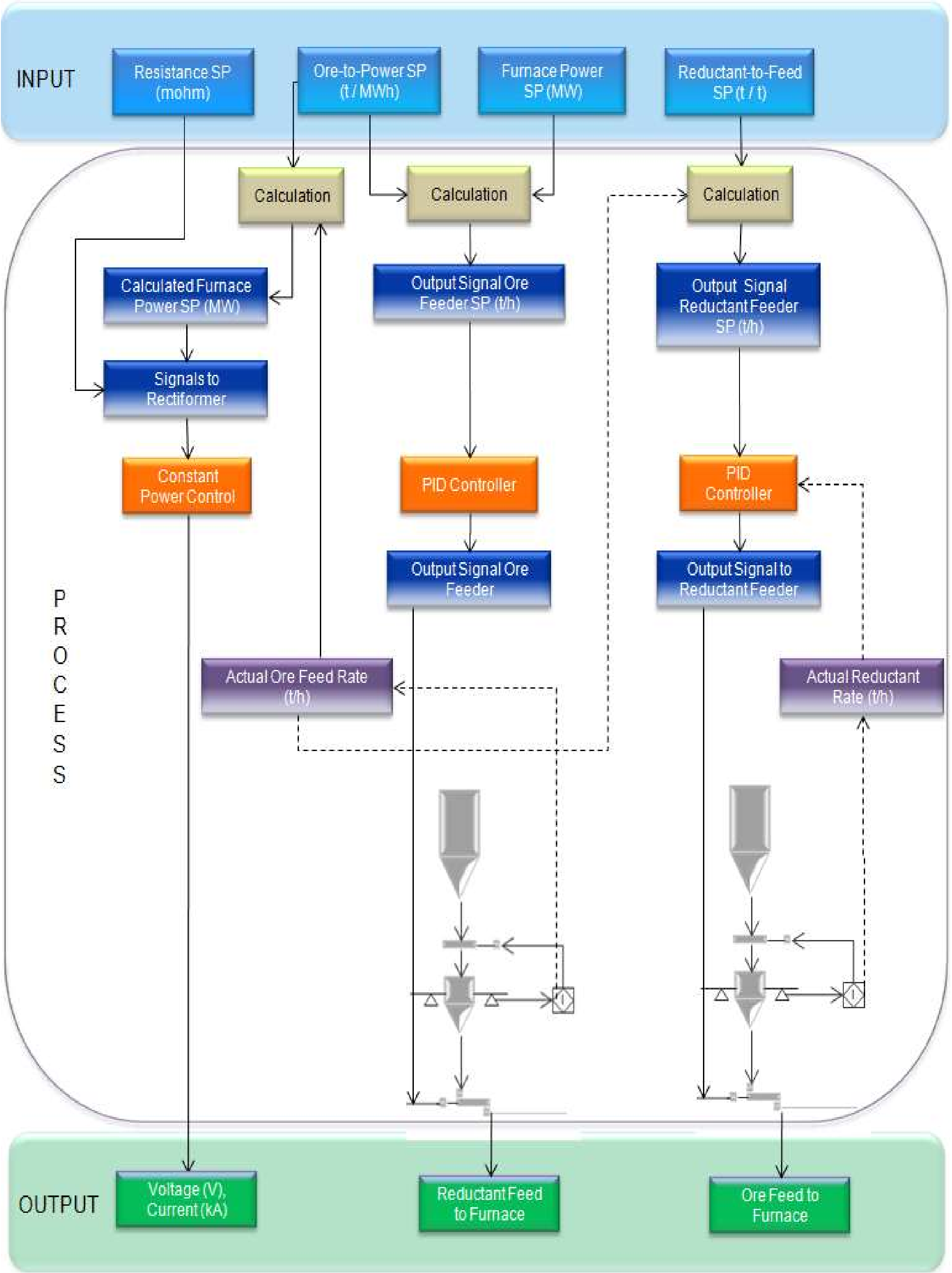


Figure 15. General flow diagram of DC control system [5]

4.3 Set point relations

4.3.1 Furnace power set point

Power set point determines the output and production capacity of the furnace. This set point is working together with the resistance set point and ore to power set point values. The furnace power and ore feed rate are the primary set points and the resistance is working as secondary set point. After setting up the furnace power set point and ore to power set point, automation system calculates continuously the best optimal current, voltage values that can be achieved with the required resistance set point value and requests rectifier to perform these values.

4.3.2 Resistance Set point

The resistance set point is used for controlling the arc length during the smelting process. Basically, this set point value indicates the distance between the graphite electrode tip and the slag surface. The resistance set point is also required for calculating the output power of the furnace which, at the same time, it's a parameter that determines the production rate. The different slag's have different type of resistivity, below two examples stated:

- Ilmenite 6-18 mohm
- Ferroalloys 50-85 mohm,

Several factors are affecting to the resistance and consequently, also to the arc length. Most significant ones are the slag bath height (resistivity), the material characteristics of feed material, the viscosity of the molten bath, and the temperature of the gas in the furnace.

The resistance set point is set by the operator from the control room and sent to logic in this case PCS7, which calculates correct voltage and current values for the specific resistance that is required in order to keep the desired power output as close as possible to set point. After this, PCS 7 sends these values to the rectifier control system that calculates the accurate firing angle of the thyristors based on the required values that are required for that specific moment in the process. Since the firing angle affects also to the voltage level of the process, PCS7 controls the voltage level in the process by adjusting electrode position with a hydraulic proportional valve at the same time. By companying these two adjusting method rectifier control (fast) and hydraulic electrode movement (slow) it is possible to achieve the balance in control of smelting process. The PCS7 is acting as master device and calculating all process parameters according process requirements. It controls all the main aspects, transformer, rectifier, electrode movement and material feeding systems.

4.3.3 Ore to Power set point

It is highly important that the correct amount of feed material is fed into the furnace and it is based on the furnace power requirements. The energy balance has to be correct so that the molten metal and slag is having correct temperature. After setting up the furnace power set point and ore to power set point, automation system calculates the required patch amount and sends it further to material feeder. Bin scales are sending feedback of actual weight of fed material back to automation system which can control the feeder to stop/reduce/increase the feeding rate compared to the power set point value.

4.3.4 Reductant to ore setpoint

Reductant is fed with certain predefined percentage into furnace as per the actual weight of ore fed in to the furnace. Automation system receives the information from the scales how much ore has been fed in to the furnace and then simultaneously calculates the required amount of reductant to be fed in to the furnace. Feedback to the automation system is coming from bin scales how much material has been fed. When required amount has been fed then feed is stopped.

4.4 Control description

The Pori DC-furnace control philosophy was designed on the basis of constant power control method. In constant power control, the idea is to keep the power variations as small as possible by controlling the parameters that affect to the final power.

The power of the system is kept constant by changing the current output and voltage from the rectifier. The DC-furnace is controlled with two main functions which are the resistance set point and the power set point. The power determines the production capacity through the output of the furnace and the resistance determines the distance from the electrode to the slag (The higher the voltage, the higher the distance from the slag is and the higher the resistance is.)

$$P= I*R^2 \qquad (8)$$

Where:

P = Power
I = Current
R = Resistance

$$R=V/I \qquad (9)$$

Where:

R = Resistance
V = Voltage
I = Current

From the equations above it can be determined that when Power and Resistance are set as constant set points, the only parameters that are changing are the current and the voltage. Rectifier control is the faster control method that and resistance the slower method. The control system is then reduced to controlling the current and the voltage.

4.5 Functional description

A 600kW DC furnace is being controlled by a separate PCS7 Control system which is working independently from the Proscon control system which is handling auxiliary equipment controls. The PCS7 control system is controlling a 6,3kV vacuum circuit breaker, a tap changer, a rectifier and a hydraulic system; being the hydraulic systems' function to control the electrode slipping device.

4.6 Transformer control

After selecting the DC furnace from control cabinet as control point for the transformer, the 6,3kV vacuum circuit breaker and the tap changer are fully in DC furnace scope of control. The voltage level in the transformers secondary wiring can be changed by the help of a 21 step tap load changer.

4.7 Rectifier

By pressing the ON button, the operator sets the rectifier to the operating mode. The rectifier is started with the RUN command and stopped by pressing the STOP button. The operator defines the set values for the circuit resistance (the extent of the arc) and the furnace power. Based on the values, the Siemens logic calculates the required current using the formula $P=R*I^2$ (P and R are defined by the operator) and sends it to the rectifier as request or set value.

As the power and the resistance have been defined as the set values, the voltage V is left from the formula $R=V/I$. The voltage varies through the power, current and resistance indirectly. The task of the rectifier is to adjust the firing angle of the tree-terminal p-n-p-n transistors based on the prevailing current demand and adjust the current so that the calculated current demand in relation to the power is met, and so that the power set by the operator can be achieved.

The adjustment of the current by changing the firing angle of the tree-terminal p-n-p-n transistors, however, also has an ascending or descending effect on the current. Momentary resistance is calculated by the computer based on the current and voltage of the rectifier. This is visible in the control room graphics. It is also set as the measured value to the level controller of the electrode. In other words, the level of the electrode is adjusted indirectly using the voltage even though in this case, the resistance is used as the measured variable. This is because the resistance alters when the voltage rises or drops. When the resistance goes below the set value, the logic sends a command to lift the electrode until the achieved resistance set value has been attained, in other words, until the voltage has been raised.

The control room graphics have their own input fields for resistance and power.

The rectifier gives the following signals:

- Electrode voltage
- Electrode current
- Firing angle

The rectifier gives the following status or alarm signals:

- Rectifier “ready on”
- Rectifier “run”
- Rectifier ”trip”
- Rectifier ”alarm”
- Rectifier ”is on setpoint”
- Rectifier is ”remote/local”

The rectifier contains a local control panel for detailed information and diagnostics.

4.8 Electrode control logic

The electrodes can be slipped, raised or lowered either manually or automatically by the control system. In manual mode it is possible to control the electrode lifting device from a local control panel that is located near the furnace) when the local/remote button has been set as “local” or when local /remote switch has been selected as “remote” from operator desk.

When manual mode for regulating cylinders has been selected, operator can raise and lower the electrode manually from local switches or from operator interface.

In automatic mode logic system is controlling regulating cylinders as per the process parameters thorough resistance control.

Following signals are available from hydraulic system:

- Hydraulic feed pressure
- Slipping cylinders pressure
- Pressing cylinders pressure

- Contact shoe pressure at furnace
- Contact shoe pressure at proportional valve
- Regulating cylinder A, position
- Regulating cylinder B, position
- Electrode position (via profibus)

Following status and alarm signals are available from hydraulic system:

- Oilfilter DP 1, alarm
- Oilfilter DP 2, alarm
- Oil level extreamely low, alarm
- Oil level low, alarm

4.8.1 Controlling regulating cylinders

The operator sets the regulating cylinder in the automatic mode from the control room PC. The electrode resistance set value then controls lifting and lowering of the electrode. In the set value, the variable according to the formula R=V/I is the voltage V and current I. In other words, the voltage and current variables control the motion of the electrode (the current control is high-speed and the voltage control is slow).

In the manual mode, the operator sets the regulating cylinder control in the manual mode in the control room PC. The operator can then move the electrode by modifying the regulator 104ZIC04 output value. One keystroke moves the electrode as defined in the set value (the default is 10 mm). The operator can change the default value.

The regulating cylinder movements are measured in millimeters using the transmitters104EL01-ZI01 (A) and 104EL01-ZI02 (B). In the manual control, the average of measurements ZI01 and ZI02 is used.

4.8.2 Slipping the electrode down automatically

The operator can slip the electrode 20 mm by pressing the slipping button. For a longer slipping range, press the slipping button several times.
The operator presses the activation button for slipping on the control room PC. The button flashes during slipping and remains flashing 10 seconds after finishing the task.
The electrode is slipped 20 mm is according to the following sequence:

1. Prerequisites for start-up
   - The slipping down button has been pressed
   - The hydraulic pump 104PU01 is in operation
   - The clamping cylinder is closed

- The fastening pressure PT05 > 95

2. Stop the regulating cylinders and lock the power regulation system
3. Delay after stopping
4. Slipping pressure (6 bars) set as the compression pressure of contact shoes
5. Move the slipping cylinders up by activating 104HP01-HXV03A, which causes the electrode to slide downwards in the contact shoe
6. The cylinders are at the upper limit when pressure in the slipping line transmitter 104HP01-PT04 grows. Turn off 104HP01-HXV03A. The power switch devices become compressed on top of the electrode. The compression pressure is set to the run mode (11 bars). The slipping cylinders have been completely pressed.
7. Delay after stopping
8. The clamping cylinders are open, control is set on 104 HP-HXV02A
9. When the clamping cylinder pressure indication in the pressure transmitter 104HP01-PT05 is < 22 bars (the user has to define the set limit in Siemens), the cylinder is open and does not hold the electrode.
10. Lower the electrode 20 mm by activating the solenoid 104HP-HXV03B. This movement is read from the position transmitter 104EL01-ZI01 which is attached to the electrode. When the electrode has moved by 20 mm or more than 10 seconds have passed, turn off 104HP01-HXV03B.
11. Steer the slipping cylinders 20 mm.
12. The electrode has now been lowered by 20 mm.
13. Delay after the electrode has stopped.
14. Close the clamping cylinder by turning off the solenoid 104HP-HXV02A.
15. If the pressure indication of the clamping cylinder in the pressure transmitter 104HP01-PT05 is low (the user must define the set limit in Siemens), assume that the clamp has been attached and holds the electrode.
16. Delay after the turning off.
17. If the regulating cylinders were on automatic control, set them back to manual control.

4.8.3 Slipping the electrode up automatically

To slip the electrode up, press the slipping up button.
The electrode is slipped up according to the following sequence:

1. Prerequisites for start-up
   - The slipping up button has been pressed
   - The hydraulic pump 104PU01 is in operation
   - The clamping cylinder is closed
   - The fastening pressure PT05 > 95
2. Stop the regulating cylinders and lock the power regulation system
3. Delay after stopping

4. Compression pressure of contact shoes is the running pressure (11 bars). The power switch devices become compressed on top of the electrode.
5. The clamping cylinders are open, the control is set on 104 HP-HXV02A
6. When the clamping cylinder pressure indication in the pressure transmitter 104HP01-PT05 is < 22 bars (the user has to define the set limit in Siemens), the cylinder is open and does not hold the electrode.
7. Move the slipping cylinders up by activating 104HP01-HXV03A
8. The electrode moves up by 20 mm. This movement is read from the position transmitter 104EL01-ZI01 which is attached to the electrode. When the electrode has moved 20 mm or more than 10 seconds have passed, turn off 104HP01-HXV03A.
9. The cylinders are at the upper limit when pressure in the slipping line transmitter 104HP01-PT04 grows. Turn off 104HP01-HXV03A. The compression pressure of the contact shoes is set to the slipping mode (6 bars). The slipping cylinders have been completely pressed.
10. Close the clamping cylinder by turning off the solenoid 104HP-HXV02A.
11. If the pressure indication of the clamping cylinder in the pressure transmitter 104HP01-PT05 is low (the user must define the set limit in Siemens), assume that the clamp has been attached and holds the electrode.
12. Steer the slipping cylinders down by 20 mm.
13. Delay after the electrode has stopped.
14. Running pressure is set as the compression pressure of contact shoes.
15. If the regulating cylinders were on automatic control, set them back to manual control.

4.8.4 Slipping the electrode manually

If the slipping control is in manual mode, the operator can perform slipping operations one by one from the control room PC while the local switch 104HP001-HS01 is in the “remote” mode.

If the local switch is in the “local” mode, you can perform the slipping operations locally from the furnace.

When it is possible to move the electrode, the operator can lift and lower the electrode.

4.8.5 Starting the DC furnace

For instructions on starting the furnace, refer to the furnace instructions.

4.8.6 Stopping the DC furnace

The smelting furnace is stopped according to the following procedure:

- The rectifier is turned off
- The transformer vacuum switch is open
- The level control of the electrode is forced to manual mode when the rectifier is turned off
- The electrode is locked to its position. Ensure that the electrode is above the molten material.
- The lock valve 104HP001-HXV05A control is not turned off because it must be possible to lift the regulating cylinder.
- In addition, if needed, install band clamps
- Stop the hydraulics
- The cooling system, stops operating on automatic mode

4.8.7 Emergency stop of DC furnace

Press the emergency stop button to initiate the emergency stop:

  - from one location place in the conrol room
  - from four locations in the field
  - from one location in the rectifier
- When you press the emergency stop button, the following takes place:
  - opens the 6.3 kV switch
  - stops the feed conveyors
  - rectifier is turned off
- The cooling system continues working on automatic mode when the emergency stop button has been pressed.

4.8.8 Material feed of DC furnace

The material to be fed has to be in correct ratio considering the furnace electric power. From the control logic, the operator defines the set value for the material to be fed in relation to the furnace power (t/kWh). The operator also defines the furnace power set value (kW). Based on these values, the logic must calculate the exact amount of the material to be fed. This gives the calculated raw material feed rate (t/h) for that exact amount of power.

The request is sent to the vibrating feeder which starts to feed the material (t/h). This value (t/h) is derived from the set values based on calculations. The material bin scale observes the weight of the material to be fed and sends information on the realized feed rate back to the logic for recalculation and feed rate adjustment. The logic must compare this realized raw material feed to the actual furnace power (which is also visible in the control room graphics view) and to the calculated relation of set values. By doing this, the logic can regulate the correct mixture for the electric power of the furnace provided by the rectifier at that particular moment. If the actual power and the amount of material to be fed are within allowed limits, in other words, if the ratio of power and material feed is correct, the feed rate is not adjusted. (The process must provide the limit values within which the material feed must remain.) If the material to be fed greatly differs from the actual power of the furnace, the material feed must be added or reduced from the calculated set value.

In the calculation of the material feed, you need to take into account the furnace power filtering during a specific period of time (for example, five seconds). Based on this, the power value is calculated for the vibrating feeder material correction. This is important for the correct operation of the vibrating feeder as the actual power of the furnace varies considerably during five seconds, in which case the vibrating feeder operation and material feed would be very uneven. Through the filtering, this imbalance can be balanced.

The set values and actual material feed values must be visible in the operator PCS view. When feeding the reducer, the set value t/t in relation to the realized material feed is defined in the operator PCS view. The logic again calculates the required amount of the reducer in relation to the realized raw material feed and sends a request to the vibrating feeder. The vibrating feeder starts the material feed, and the bin scale sends data to the logic about the realized amount of material, and the calculation corrects the material feed by adding or reducing the amount of raw material.

It is recommended to implement a programming to the material distributor, which can be used to run material to that part of the furnace to which more raw materials must be fed in case some part of the furnace starts to heat too much.

The charging tubes area is divided into sectors regarding the thermo elements. When the temperature differences exceed the limit values, the logic automatically changes from the sequence distributor so that it drives itself to the correct sector for material feed until the temperature difference between sectors is in balance. After this, the logic changes the sequence back to the automatic mode in which the material to be fed is equally divided between all charging tubes

5 ELECTRICAL SYSTEM DESCRIPTION OF PORI DC-FURNACE

5.1 System components

Main electrical system of the Pori DC-furnace in holds following components:

- Transformer
- Tap Changer
- Breaker
- Rectifier
- Reactor
- Bus bars
- Cathode (electrode)
- Anode (bottom bins).

Figure 16. Prebaked graphite electrodes

5.1.1 Rectifier

There are different types of rectifiers as explained in earlier chapter 3.1.2. In Pori ORC case, rectifier of 3kA and 200 V with six pulse bridged thyristors was originally chosen. In theory this rectifier would give power of 600kW for this application. Rectifier has own logic system which controls the current and voltage set points as requested from main control system by adjusting the firing angle.

Figure 17. Rectifier connected to bus bars

5.1.2 Reactor

Reactor was connected in series with the bus bar system between rectifier and anode pole of the furnace. The purpose of the reactor is to stabilize the current flows from the rectifier to the system by predefined impedance which helps stabilizing the arc. In case of short circuits shall occur between electrode and the slag due to splashing. Reactor is also working as power resource and providing enough capacity.

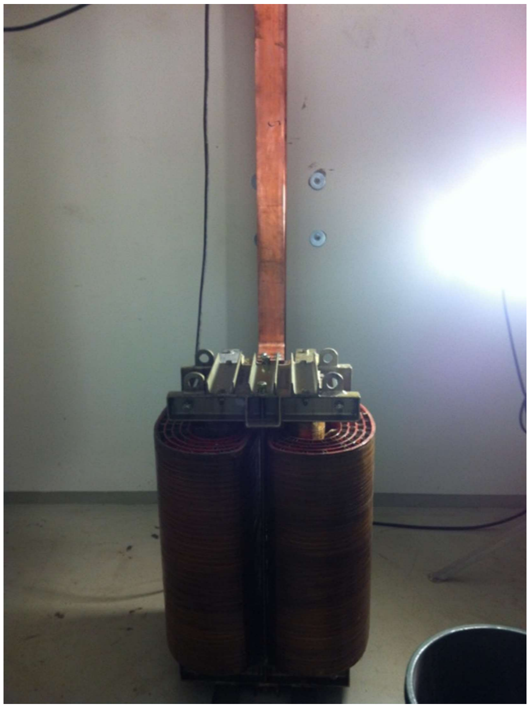


Figure 18. Reactor in Pori ORC

5.2 Bus bars

Bus bars are made from four different copper bars, and are divided in three different sections as described in Figure 20. Bus bars A and B, which are seen closer to floor level on the picture, are coming together from reactor room and then separating to both side of the furnace bottom to anode pole of the electric furnace. Bus bar routings were precisely dimensioned on the same way to avoid deviations in the magnetic field. Bus bar from electrode to rectifier, seen on top of the picture is coming as high as possible from bus bars A and B to minimize magnetic field disturbance for the system.

Bus bars are designed to stand eight times higher short circuit capacity than what is the rectifier output and are supplied with shunts for current measurement purposes form both lines, A and B, just before they are connecting to anode pole. In Figure 19 the connection to anode pole is visible and there can be seen also round strips which are used to guide the current and magnetic field in case needed. Also the bottom anode is clearly visible.

Figure 19. Connection of bus bars to anode and the anode pin

Figure 20. Bus bars coming from rectifier room to furnace

5.3 Automation

Automation is divided in different sections which are connected to main automation system supplied by Siemens. Rectifier has own control system that in this case is DCS 800 control system by ABB. Process automation is controlled by Proscon and connected to main logic Siemens PCS7. Main diagram of the automation control is seen in figure 21(Attachment 1).

Proscon automation system is responsible of all material feeding devices for the furnace including the auxiliary systems such as cooling water and off gas handling and it will handle all controls and logics related to these systems independently. Proscon is connected to Siemens PCS 7 that is the main logic system of the DC-furnace control processes. Siemens PCS 7 is controlling furnace set points, transformer, rectifier and electrode hydraulics.

DCS 800 is controlling only rectifier's current and voltage output by set points received from Siemens PCS7. Current is controlled by regulating firing angle of the thyristors and voltage is controlled indirectly with hydraulic proportional valve that controls electrode height from the slag level that influence on the voltage level required.

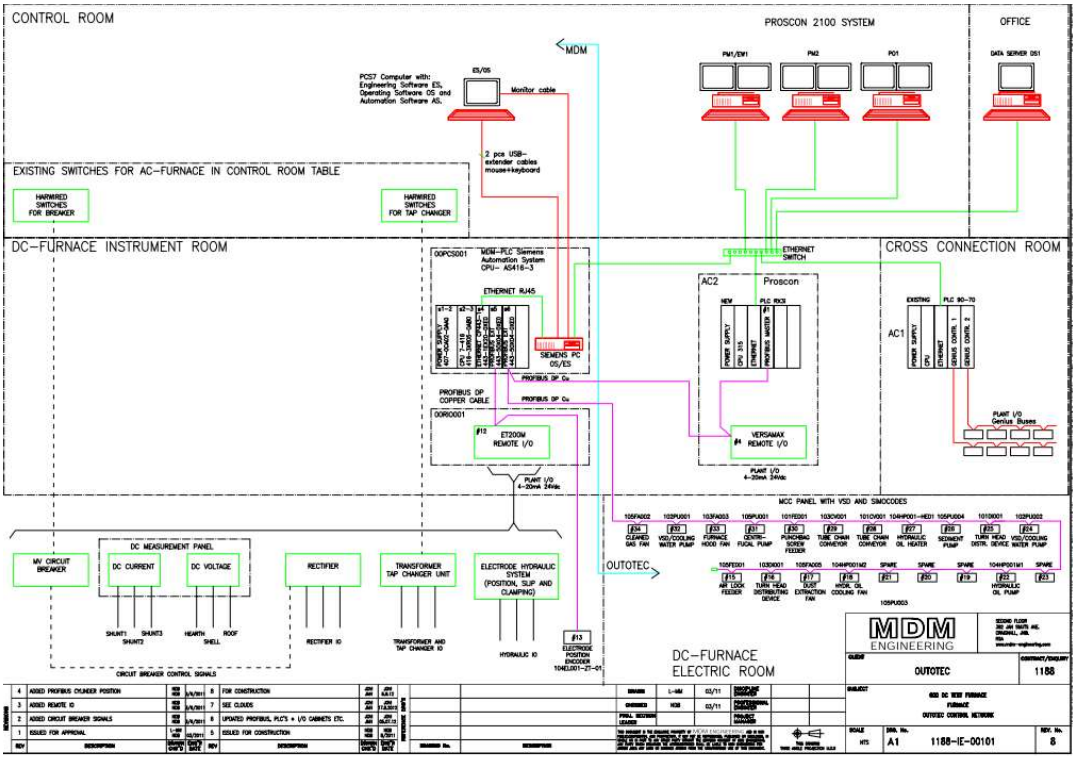


Figure 21. Description of automation control system [Appendix 1]

6 TEST TRIAL

6.1 General

Test trial was taken place in December 2012 in Outotec Pori Research Center and was targeted to be two weeks long. Several small problems were occurred before the actual trial but eventually they were solved on time and test trial started on 8th of December and finished on 20th of December.

6.2 Analysing the results

In attachment 2, also presented in Figure 22, is considered only the four variables to be checked, they are, Resistance set point (mOhm), Current (A), Power (kW) and Voltage (V). In the X-axis is informed the time and in this case it has been informed as days. From the chart can be noticed shutdowns between 9 th and 10th of December and another one between 17th and 18th of December. The reason for those ramps going down were on 9th installation of conductive strips on the bottom anode in order to balance the current flow in order to guide the arc more straight due to magnetic fields. On the 17th small accident on the tap holes which caused small fires at the test plant. However, in both of the cases problems were corrected and the test trials were able to continue in smooth manner. Even the full time line chart is not very clear it is still noticeable that when the resistance goes higher, also the voltage goes higher and the current goes down in order to meet the required power set point value. As the ore feed rate set point was not connected to furnace power set point values, evaluation of the data is not available on this regard. Therefore, in the following examples only shall be evaluated only the relation between the actual values and set point values.

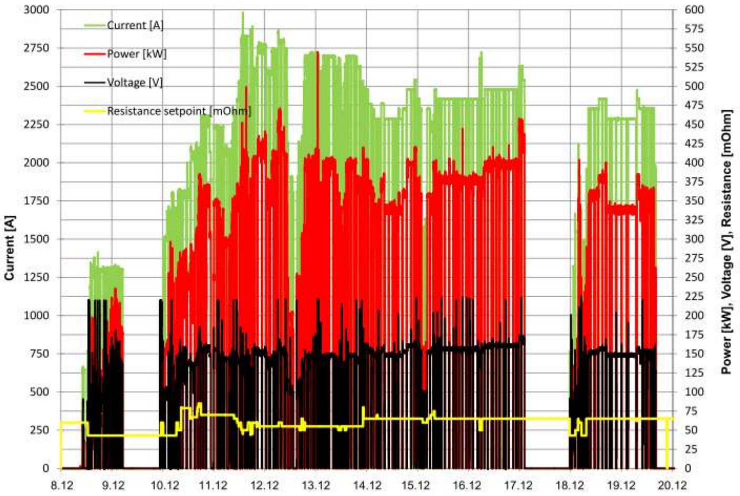
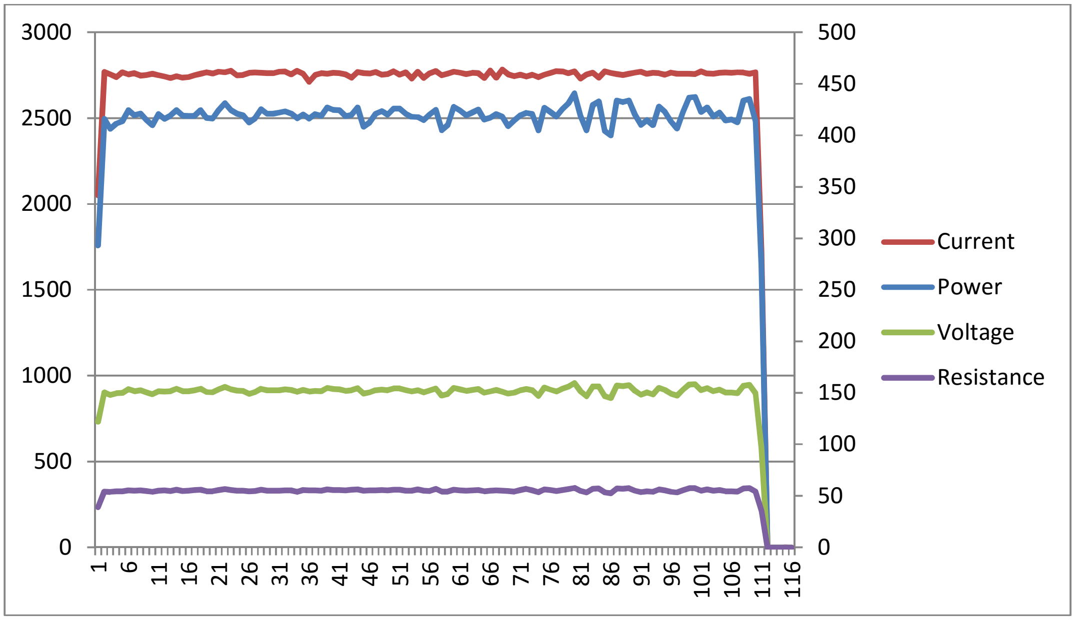


Figure 22. Full log of test trial

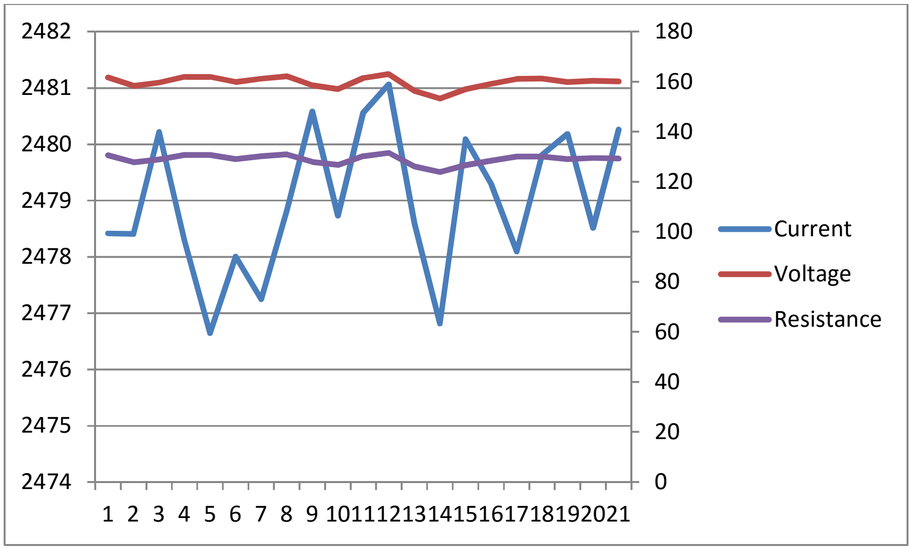
More visible trend is available in chart 2. In this chart same variables has been considered than in figure 19. Trend is 116 minute long and taken on 11.12.2012 between 22:40 and 00:35. Resistance trend can be noticed to be rather smooth which also affects to voltage and keeps it rather steady. Noticeable is that when resistance trend changes the voltage trend reacts the similar manner. In addition to previous, current trend reacts opposite manner than voltage because automation is trying to keep the requested power level in appropriate level.

Chart2. 116 minute trend of main variables



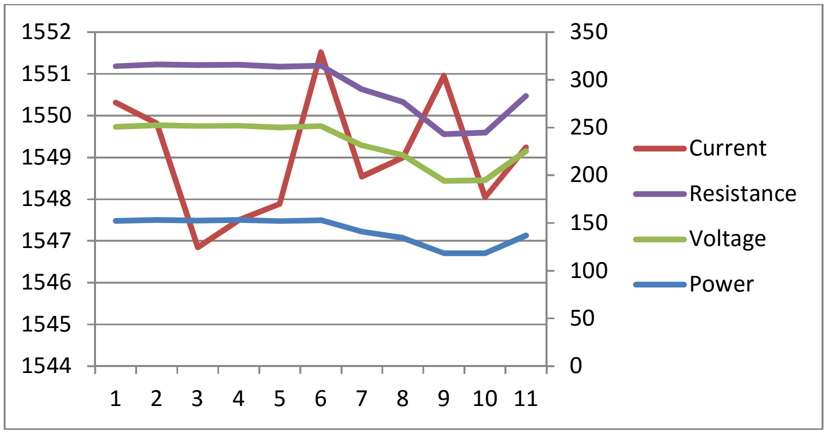
In Chart 3 only following parameters has been considered, voltage, current and resistance in time interval of 21 minutes. Power trend was intentionally left out from the chart due to demonstration the relation of voltage and resistance. Resistance and voltage have identical trend where as the current works opposite and very rapidly. Reason for this type of behaviour is that when the automation demands lifting or lowering the electrode in order to keep the desired resistance set point the current has to change in fast manner in order allow the automation run the furnace at desired power level. This fast reaction is controlled then from the rectifier which controls the firing angle and therefore also the current.

Chart 3. 21 minute trend, relation of voltage, current and resistance



In Chart 4 four parameters are considered again but in shorter trend time, in this case 11 minutes. The same effect can be identified that resistance and voltage are following each other and the current is making the most significant changes in order to keep the power in constant value.

Chart 4. 11 minute trend, Power, Current, Resistance, Voltage



Because the two main automation systems were working independently the relation of power control and material feed rate were not possible to evaluate. Based on the trend and data gathered from the test trial it is noticeable that the automation PCS7, rectifier DCS800 and electrode hydraulic control systems are working well and as desired.

Material feeding system and furnace operation system should be implemented together on the next trial run, in order to further gather information and feedback how the logic can handle smoothly additional information. This would require more detailed programming and parameters to be considered than current two independent systems.

At the beginning of the test trial parameters were fluctuating too rapidly and also the electrode movement was almost constant. This was due to of non filtered data of control parameters which then affected the system to react too fast into changing situations. The problem was solved by adding internal timers and calculators to the program which resulted as a filtered data to automation system to proceed in regulating procedures.

7 CONCLUSIONS

7.1 Summary

Test campaign was considered successful from automation point of view whereas the system functioned as requested and designed. During the pilot project it was decided in the beginning that DC furnace shall be operated separately with two operating systems. Power control was handled via PCS7 and the material feed and all other cooling and auxiliary equipments were controlled with Proscon system. This was rather wise choice since this pilot project was one of a kind in history of Outotec and there were several new points to consider in operation point of view that it was surer to keep the two main operation system separated during the first test run.

Automation system functioned properly and with thyristor control system and response time was good in continuously changing situations as it can be noticed from trial results. Secondary control system (electrode lifting) functioned smoothly and fast as per the resistance set point values. Both furnace control systems worked at the beginning even too fast which caused too rapid fluctuations in the parameters. System was reacting in too fast response in order to allow the process itself to correct the situation. Electrode movement was occasionally too rapid in relation to set point values and this was solved by modifying the control protocol by increasing minimum and maximum limits in certain time interval. These actions resolved the problems and furnace power control system was operating more fluently than earlier.

During the test trial it was noticed that electrode consumption was minimal compared to AC applications, also the sound hazard was eliminated since the furnace was almost quiet and it was hard to say was it even on. Operators were positively surprised on the easiness of the control.

Operator control interface was easy to use but since two independent systems were in use simultaneously it caused little bit additional care on having correct set points. Interface screen layout was an acceptable level but further development can be done in order to get it more simplified.

One interesting point was noticed from the bus bars current measurement. In Figure 20 bus bars are dividing to two separate sides and for some reason on the higher bus bar route the current was considerably higher than in the lower bus bar route. This resulted also on higher magnetic field on this side of the bus bar and furnace shell. The reason remind unknown for this phenomenon.

7.2 Future improvements

Related to further developing the operating system, implementing the furnace power control system and material control system together with the auxiliary systems should be done in order to simplify the operators work. This would reduce the automation system been reduced only to one main system which can be handle these entire tasks simultaneously together. Now the operators were separately setting set point values via two main system which worked well but the operators had to know the required feed rate matching to power requirements.

Lifting and lowering the electrode was done from the operators interface with mouse by clicking several times the lowering or lifting icon. This might be slow in case there is critical to adjust the electrode in fast response. Therefore, a joystick control would good addition for the operators to quickly lift or lower the electrode in manual mode if needed.

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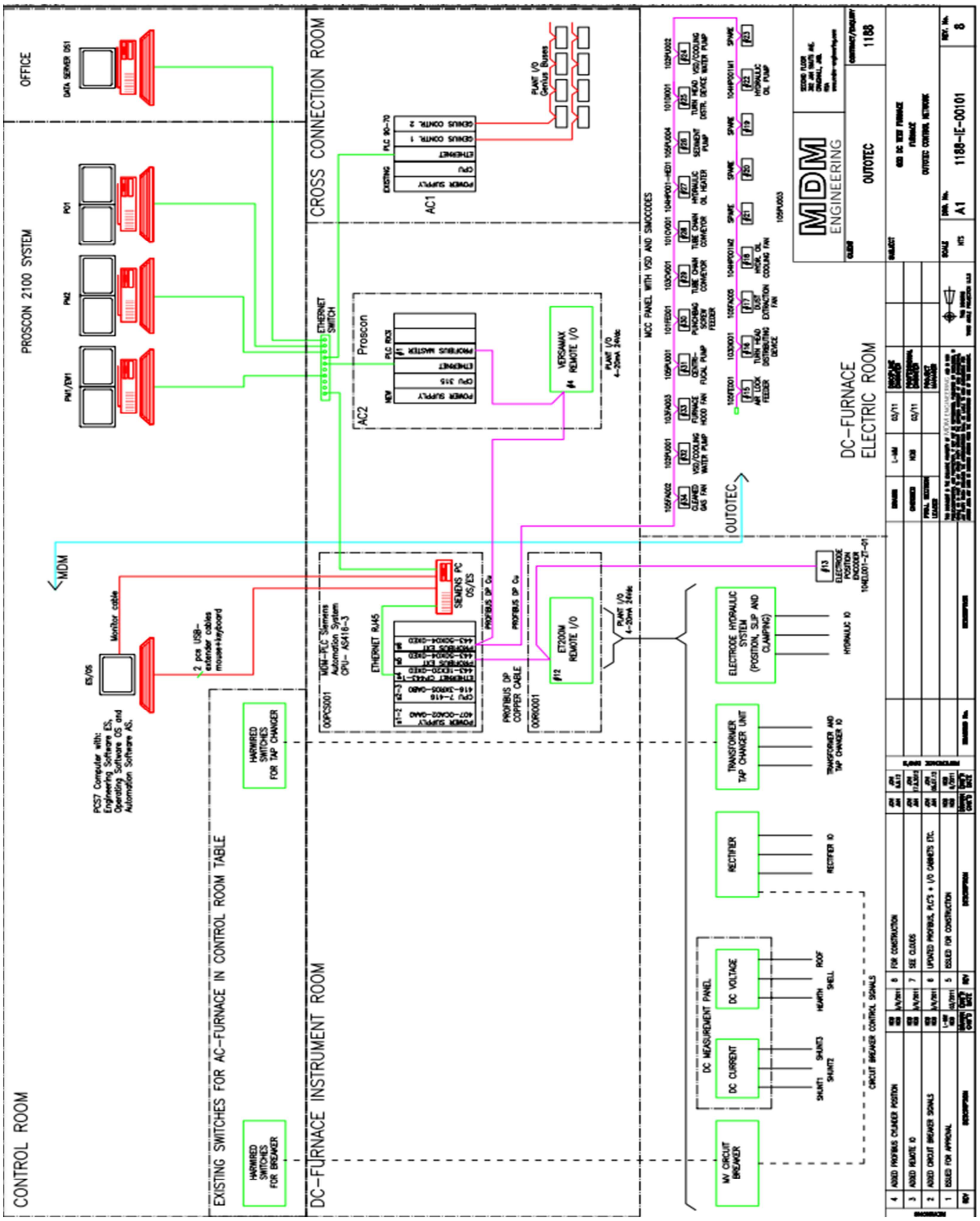
APPENDIX 1 DESCRIPTION OF AUTOMATION CONTROL SYSTEM



APPENDIX 2 FULL LOG OF TEST TRIAL