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Power Supply and Control in an Electrified Calcination Process

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Summary: Concrete as a building material is crucial in today's construction process. However, cement production, which acts as a glue in the concrete, leads to 5 o 7 % of the world's Co_2-emissions yearly [1]. In the Paris agreement, which has189 signatories, governments decided to take global action in a determined way to reduce greenhouse gas emissions to limit the global temperature below 2 °C to avoid environmental, economic and social costs and harms [2]. Nearly 65% ofCo_2 is produced in the calcination process, and 35% of the Co_2 results from fossil fuel consumption for the required thermal energy for calcination. In the existing production system, the exit heat from the kiln is used for preheating the raw material. Norcem as a pioneer company, is planning to electrify the calcination system to capture pure Co_2. The electrification of the process needs 77MW electrical energy. In this study, a phase control SCR power supply is designed. Silcon Carbide heating elements is used for heating production. increase in the resistance of the heating element during operation by time, temperature limit of the heating elements, current harmonics are the main objectives that needs reserve voltage, power control and harmonic filtering systems respectively. A three windings furnace transformer is applied to provide the reserve voltage, and SCR/thyristors (Triac) is used for power control and single LC filter is used for harmonics issues.

Dymola is a simulation tool which is used for this study. Effect of Delta/Star connection of the heating elements, Vector group of transformers on the harmonics, Cable sizing are studied. A 100 MVA power substation is being considered in the factory to feed the company. The results of the study show that there are some concerns about Silicon Carbide heating elements that are an economic issue. These types of heating elements must be replaced with new ones when they reach the maximum limit of its resistivity. Also, for high power consumption of the project, the local electric authority must provide a high voltage line to the company. The cost of the project is high, and the efficiency of the method needs to be studied more.

Preface

This master thesis is written as a final assignment of the master's science program at the Department of Electrical Power Engineering at the University of south-East Norway. The study aims to design a power supply for calcination furnaces in the cement industry using Silicon Carbide heating resistors as a heat source requiring 77MW electric power. The main characteristics of the power supply include the capability of 100% reserve voltage and a power control system applying SCR/Thyristors. Electrification of the calcination process in the cement industry is a new method that allows capturing pure Co2 as a greenhouse gas. Norcem company is going to establish the system for the first time in the world if the project meets their criteria.

I want to thank my supervisor, Kjetil Svendsen, who helped me clarify the aspect of the assignment. I also want to thank PhD candidate Ron Mangalam Jacob who was available during my assignment. Furthermore, the project could haven't been done without the Furnace transformer's design values, which were provided by my ex-colleague Mehrdad. K in Iran Transfo company.

Porsgrunn, 10-05-2022

Alireza Bazargan

Contents

Nomenclature

R_t	**-**	**Total resistance**	**[Ω]**
r	-	Per Element resistance	[Ω]
P_t	-	Lost power on total resistance	[W]
p	-	Lost power on one resistance	[W]

P	-	Active power	[W]
U	-	The line-to-line voltage	[V]
I	-	Line current	[A]
θ	-	Phase angle	[°]
U_n	-	Phase voltage	[V]
r	-	Resistance(load)	[Ω]
I_n	-	Phase current	[A]

p	-	Nominal power of each heating element	[W]
D	-	Diameter of a heating element	[m]
r	-	Resistivity	[Ω-m^2/m]
L	-	Length of each heating element	[m]
A	-	The cross-section area of the heating element	[m^2]
R	-	Resistance of each heating element	[Ω]

N_{el}	-	Total number of heating elements	[-]
P	-	Total power	[W]
P	-	Power of each heating element	[W]

P_T	-	Total power losses of transformer	[W]
P_{NL}	-	No-load losses of transformer	[W]
P_{LL}	-	Load losses of transformer	[W]
P_{EC}	-	Winding Eddy current losses	[W]
P_{OSL}	-	Other stray losses in the structure of the transformer	[W]
I	-	Current	[A]
R	-	Winding resistance	[Ω]
h	-	Harmonic order	[-]
h_{max}	-	Maximum harmonic order	[-]
I_h	-	r.m.s value of harmonic current per unit	[A]
e	-	denotes the ratio of fundamental frequency eddy current losses to DC losses, both at the reference temperature	[-]
q	-	The exponential constant is dependent on the type of winding and frequency. Typical values are 1.7 for transformers with round or rectangular cross-section conductors in both LV and HV windings and 1.5 for those with foil LV winding	[-]
I_h	-	r.m.s value of harmonic current per unit	[A]
I_1	-	the magnitude of the fundamental current	[A]
$I_{\in}$	-	the magnitude of the total r.m.s load current, including all harmonic components	[A]
S_H	-	New loading capacity of the transformer	[KVA]
S_n	-	Rated capacity of the transformer	[KVA]

X_f - Filter reactance at the fundamental frequency [Ω]
X_L - Inductor reactance at the fundamental frequency [Ω]
X_C - Capacitor reactance at the fundamental frequency [Ω]
I_h - the amplitude of the maximum harmonic current in a particular order [A]
V_h - the magnitude of load voltage at the certain harmonic [V]
Q_f - Filter rated power [Var]
C - Filter capacitance [F]
L - Filter inductance [H]
f - Fundamental frequency [Hz]
V - Maximum load voltage [V]

μ - Permeability of the conductor [H/m]
ω - Angular frequency [rad/s]
r - Resistivity of conductor [Ω-m^2/m]

ΔV - Voltage drops [%]
I_{fL} - Nominal full load current [A]
X - The reactance of the cable [Ω/km]
φ - Load power factor [pu]
V_n - Nominal voltage [V]
R - Resistance of the cable [Ω]

I_c - Installed Current carrying capacity of cable at site condition [A]
k_0 - Cable derating factor for variation of the surrounding temperature [-]

k_1	-	Cable derating factor for variation of thermal resistivity of soil in the ground	[-]
k_2	-	Cable derating factor for dept of laying	[-]
k_3	-	Cable derating factor for cable arrangement	[-]
I_0	-	Cable current capability at the typical standard condition	[A]

I_{sc}	-	Allowable short-circuit current of given cable size	[KA]
k	-	Insulation material type coefficient of the cable	[-]
S	-	Cross section area of cable	$[mm^2]$
t	-	Short-circuit duration	[s]

I_{sc}	-	short-circuit current	[A]
FLA	-	Full load current	[A]
Z_t	-	Transformer impedance UK%	[%]

1 Introduction

Concrete as a building material is crucial in today's construction process. However, cement production, which acts as a glue in the concrete, leads to 5 to 7 % of the world's Co_2-emissions yearly [1]. In the Paris agreement, which has189 signatories, governments decided to take global action in a determined way to reduce greenhouse gas emissions to limit the global temperature below 2 °C to avoid environmental, economic and social costs and harms [2]. After this agreement, governments, companies, and citizens worldwide began to take action. Norcem, as a pioneer company in the cement industry, decided to capture the Co_2 emission up to 400000 tons per year which is almost close to 200000 light cars emissions annually. Calcination is one crucial step of the cement production process, leading to Co_2 production as a byproduct. Nearly 65% of Co_2 is produced in the calcination process, and 35% of the Co_2 results from fossil fuel consumption for the required thermal energy for calcination. In the existing production system, the exit heat from the kiln is used for preheating the raw material. This heated gas is mixed with Co_2 produced in the calcination process. to capture Co_2And there is a need for another downstream process to separate Co_2 from other mixed gas [3]

Electrification of the calciner as an alternative solution will cause pure Co_2 production, and there is no need for additional downstream processes, and carbon capturing will be done directly.

The University of South-Eastern Norway is working on electrifying the calciner on the ELSE 2 project. In the benchmark production of 1 $Mton/year$ of clinker, the cement calciner needs around 77MW thermal energy. A resistance heating concept may provide this heat in the calciner. This study aims to design an electrical circuit to produce 77MW of thermal energy using resistance heating concepts.

1.1 Cement production process

Limestone as raw material for cement production is extracted from quarries or mines. Next, it is crashed and stored, and in the next step, it is grounded to a powder called a raw meal. To obtain proper warm meals, some additives such as Aluminum (Al), Silicium(Si) and Iron(Fe) are added. The warm meal must be dried in this step, and heat from the kiln exit is used. The raw meal passes and is stored in the large silos, and next, the raw meals are put through a burning process. First, raw material is heated in a series linked cyclone tower (preheater tower) whose height could be 80 meters. The cyclone tower acts as an efficient heat exchanger. By heating raw meals, some chemical actions occur. Heating converts the Calcium carbonate into Calcium oxide and Carbon dioxide ($CaCo_3 \rightarrow CaO + Co_2$). This process is called 'Calcination'. Nearly 65% of Co_2 is produced in the calcination process, and the rest, 35%, is made because of fossil fuel consumption for heating cement kiln.

The raw meal then goes inside the rotary kiln for further heating up to a temperature of 1450°C.

The kiln is a steel pipe with 60 to 80 meters and a 4.5 to 5 meters diameter. The kiln is considered the most critical part of any cement factory. When the particles in the meals react with the additives, small clinker pellets are formed. This process is called Sintering.

The clinker enters the cooling system, which is cooled rapidly to almost 100 °C before being transported to the storage silo. In the final stage, the clinker is grounded in cement mills, and 3 to 5 % of gypsum is added to prevent the concrete from hardening too quickly. Next, cement can be transported to storage silos for packing bags or loading and delivery [4].

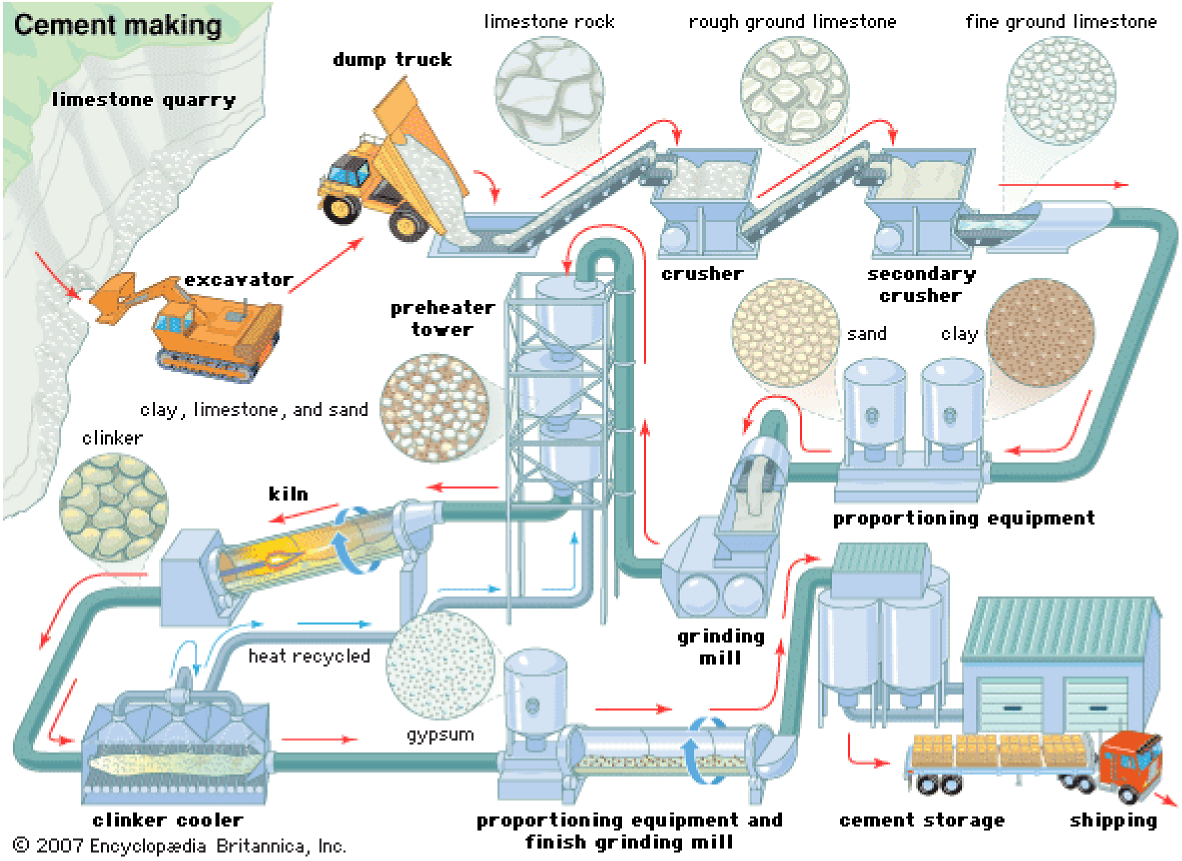

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Figure 1-1Cement manufacturing process-Simplified flow char [4]

1.2 Carbon capturing and storage (CCS)

Carbon capturing will contribute to a cleaner local environment, benefiting everyone and nature. One of the solutions for reducing Co_2 emission and more efficient CCS is the electrification of the calcination process. By electrification of the calcination process, two advantages are achieved:

- The Co_2 emission from fossil fuel combustion in the calcination process is eliminated.
- The exhaust gas from the calcination process is pure Co_2 that can be captured directly without any downstream process for Co_2 separation.

Pulverized coal as fuel is applied to calcination and kiln heating systems in the existing system. Kiln exhaust heat is used for calcination, which results in the mixing of Co_2 by other byproduct gases from the kiln process. For CCS in this condition, there is a need for another approach for

Co_2 separation. Electrification of the calcination eases this problem. Figure1-2 shows the regular cement kiln system with two preheaters.

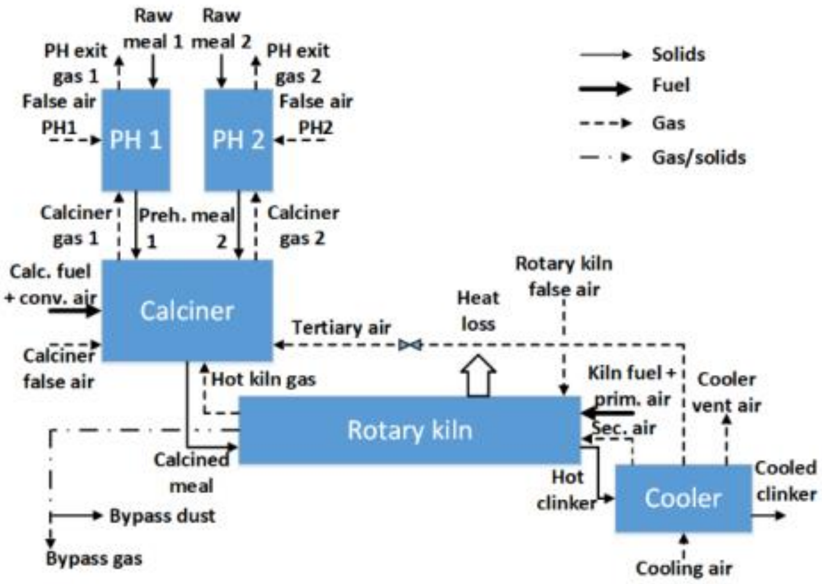


Figure 1-2 Regular cement kiln system [3]

By applying electrification and adding a carbon-capturing system, all required calciner fuel for heating is replaced by electrical energy. There is no need for kiln exhaust gas in the calcination process. So, it means the gases that are produced by decarbonization in the calcination process are pure Co_2 which can be captured. Figure 1-3 shows the new cement kiln system with an electrified calciner.

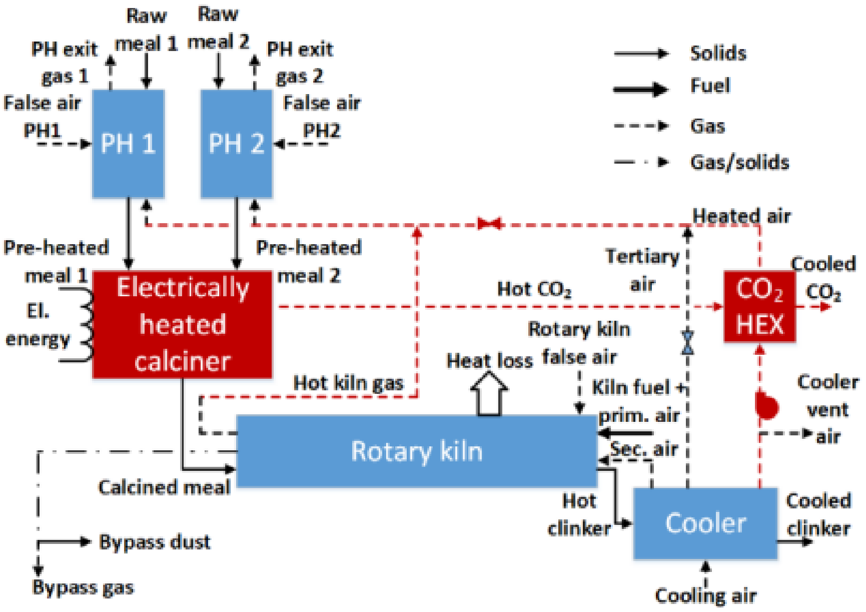


Figure 1-3: The cement kiln system equipped with electrified calciner-red parts is new [3]

Various electrical heat production systems can be applied for the calcination process. Two types can categorize these heating systems.

- Direct thermal energy transfer: for transferring the heat energy to the raw meal, different radiation/waves might be used, and no heat transfer medium is needed, which is a good advantage. However, microwave technology consumes more energy and has some safety concerns for personnel and the system. Local hot spots could decompose or melt the raw material [3].
- Indirect thermal energy transfer: resistance-based heating or plasma generation can heat a medium (solid or gas medium). This medium can transfer its heat energy by radiation or convection

The solid medium can be utilized as an energy transfer medium. When the solid medium is heated by electricity, the raw meal contacts it. Ohmic resistance or induction method can be applied for heating solid medium. Heat transfer is done by combining direct contact (conduction) and radiation. The surface contact between the solid medium and the raw meal might be increased by utilizing a rotatory furnace for the calcination process.

In the benchmark production of 1 $Mton/year$ of clinker, the cement calciner needs around 77MW of thermal energy. A resistance heating concept may be used to supply this heat in the calciner [3]. This study aims to design an electrical circuit to provide $77MW$ of thermal energy using resistance heating concepts.

2 Power supply

There are various electrical heating systems used in industrial and domestic applicants. A short classification of the electric heating systems is presented in the table.

Table 21: Classification of electric heating systems [5]

Electric Heating Methods	Power frequency Heating systems	Resistance heating	Direct Resistance heating
			Indirect Resistance heating
			Infrared or radiant heating.
		Arc Heating	Direct arc heating
			Indirect arc heating
	High-frequency heating systems	Induction heating	Direct induction heating
			indirect induction heating
		Dielectric heating	

In this project, the Indirect Resistance heating method will be studied. The electric current is forced through a resistance conductor to produce heat. Then this heat transfers to the body of the heating subject by radiation or convection through a solid medium.

An electric furnace can be designed by both AC and DC supply. The resistances also can be utilized in different arrangements such as Delta or star connection. Each method has its pros and cons. This chapter gives a brief overview of AC and DC furnaces and resistance arrangements.

2.1 AC vs DC power for heating element

A short history of DC and AC power and differences between AC and DC power are discussed in this section. Also, the RMS value of the voltage and current is explained mathematically. One resistive heating load was also modelled and simulated to compare DC and AC power supply heating.

2.1.1 AC and DC power

The power generated by an alternating current is an alternating power (AC), and power supplied by a direct current is known as DC power.AC is an acronym for Alternating current, and DC is an acronym for Direct Current.

In the late 1800s, Thomas Edison insisted on using DC current to transmit electricity, while Nikola Tesla and George Westinghouse proved the advantages of AC current for long transmission. After a long debate over safety and reliability, we see that most power transmission is done by AC current. However, high voltage DC currents are rarely used to transmit power since it is not difficult to invert the DC to AC [6]. The main difference between AC and DC is the moving direction of electrons. In DC, electrons move forward and are constant by time, while in AC, electrons move forward and backwards, which varies by time. The power delivered by DC is stable over time, but AC power is not constant and varies by time, a significant difference between AC and DC.

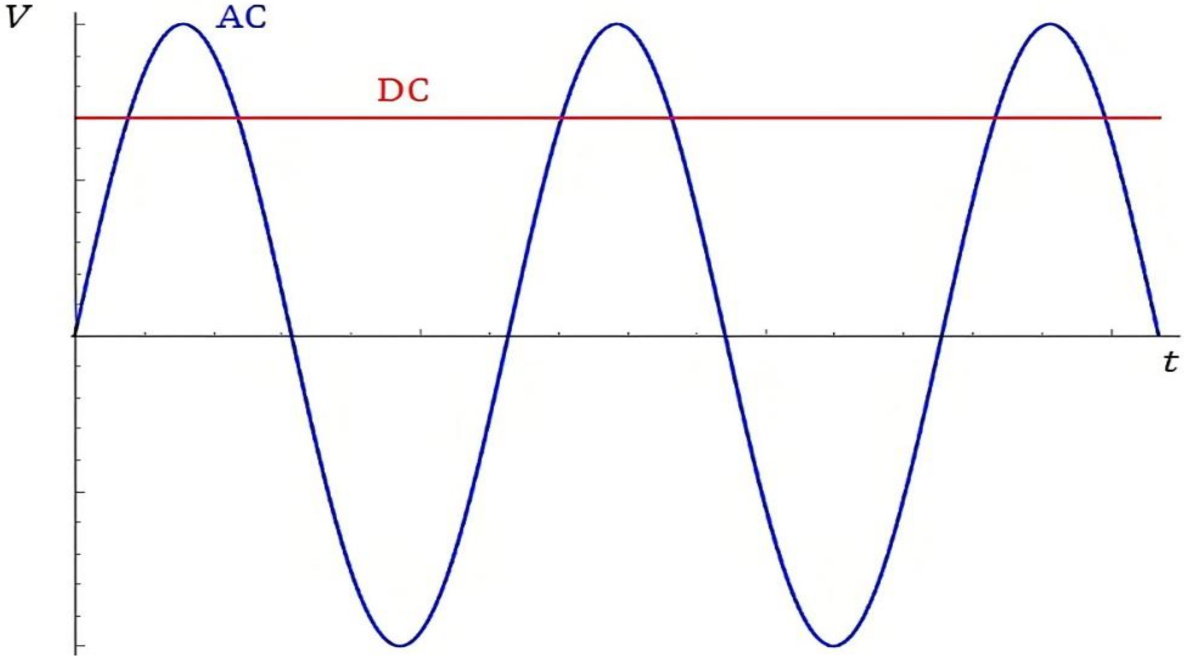


Figure 2-1:AC and DC current [7]

It is shown from figure2-1AC that power has a sinusoidal waveform; therefore, power or energy delivered per unit of time is not constant. Both current and Voltage have a peak and minimum value. None of these values represents current or Voltage reasonably. Also, the average value of the wave over a sinusoidal cycle will be zero. Hence, the root means the square value (RMS) represents the alternating current and Voltage (I_{RMS} and V_{RMS}).

The RMS value of AC current is equal to the amount of DC current, which flows through a known resistor, having the same resistance and temperature, to produce the same heat for the given time. This current is called RMS current or effective current (I_{eff}). For example, I is the alternating current flowing in resistor R for time t second, which generates the same amount of heat produced by DC current (I_{eff}).

The area below the current curve is divided by an equal length, as shown in figure (2-2).

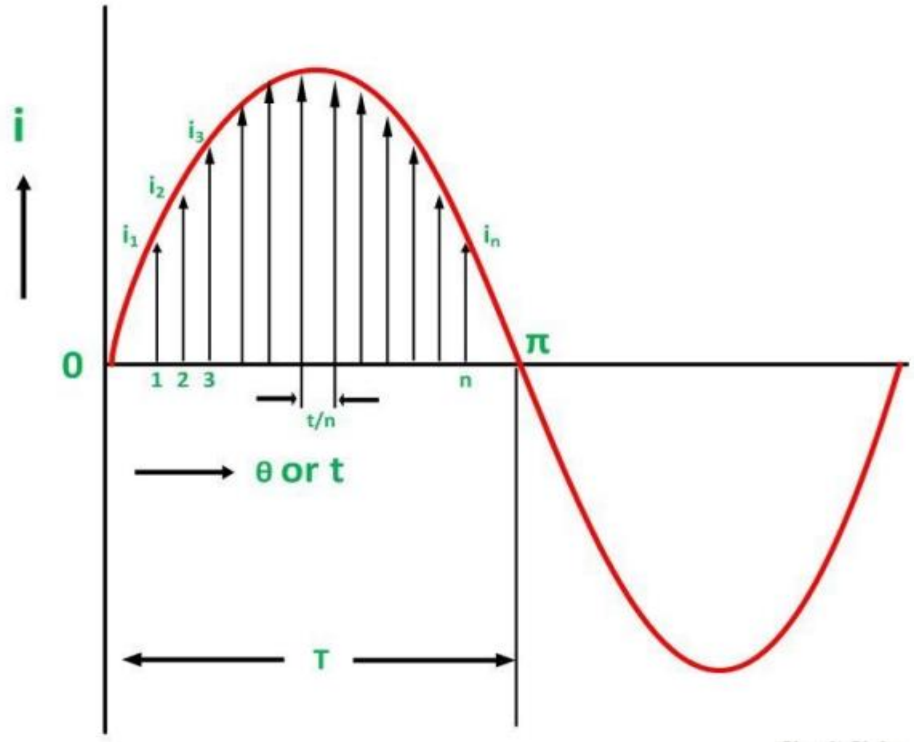


Figure 2-2:AC current [7]

Heat production:

First interval $=\frac{i_1^2.R.t}{n}$ Joule

Second interval$=\frac{i_2^2.R.t}{n}$ Joule

Third interval$=\frac{i_3^2.R.t}{n}$ Joule

n interval$=\frac{i_n^2.R.t}{n}$ Joule

then:

$$Total\ heat = R.t\left(\frac{i_1^2+i_2^2+i_3^2+\cdots i_n^2}{n}\right) \text{ Joule} \tag{2-1}$$

Since the effective value of this current is on the left side of the equation, the total heat will be:

$$Totall\ heat = R.t.I_{eff}^2 \tag{2-2}$$

Equating the equations (2-1) and (2-2), we get:

$$R.t.I_{eff}^2 = \mathrm{R.t}(\frac{i_1^2 + i_2^2 + i_3^2 + \cdots i_n^2}{n}) \quad (2\text{-}3)$$

Or

$$I_{eff} = \sqrt{\frac{i_1^2+i_2^2+i_3^2+\cdots i_n^2}{n}} \quad (2\text{-}4)$$

Which are root means square of instantaneous values [2]. The relation between RMS and peak value is:

$$V_{peak}=\sqrt{2}\,.V_{RMS} \quad (25)$$

$$I_{peak}=\sqrt{2}\,.I_{RMS} \quad (26)$$

Some of the key differences between AC and DC power systems are listed below:

- The direction of electrons: DC is unidirectional current, but AC is bidirectional current
- Generation: AC is generated by a dynamic magnetic field (Generators), and DC is generated by a static magnetic field (Chemical cell). It is also possible to convert AC to DC and vice versa by convertors and invertors.
- Frequency: The frequency of AC power is 50 to 60 Hz depending on the country, while the frequency of DC power is zero.
- Type of loads: For an AC power system, the load can be capacitive, inductive or resistive. For a DC power system, the load is always resistive.
- Power factor: In an AC system, power factor varies between 0 to 1. In the DC system the power factor is always 1.
- Transmission: AC power transmission is easy, especially for long distances. DC power transmission is more challenging because losses are proportional to distance, and long-distance DC cannot be a solution.
- Storage: DC power can be stored (Battery), but AC power cannot be stored [7].
- Instantons power is different comparing DC and AC power

Considering all the points above, we notice that only the difference in instantaneous power may affect the temperature in this project, and the rest of the issues are not related to this study. To better understand the impact of instantaneous power on the temperature, a straightforward model simulated both DC and AC Power. The resistance of the heating element is 1.363ohm, and the power of the element is 91.2KW. This heating element was supplied once by 352 V in AC and DC mode, and power losses and temperature were measured. Figure 2-3 shows the result. There is no difference between total power and temperature; however, the instantaneous power is different as we expected. A short simulation was performed to determine the effect of this instantaneous power on temperature.

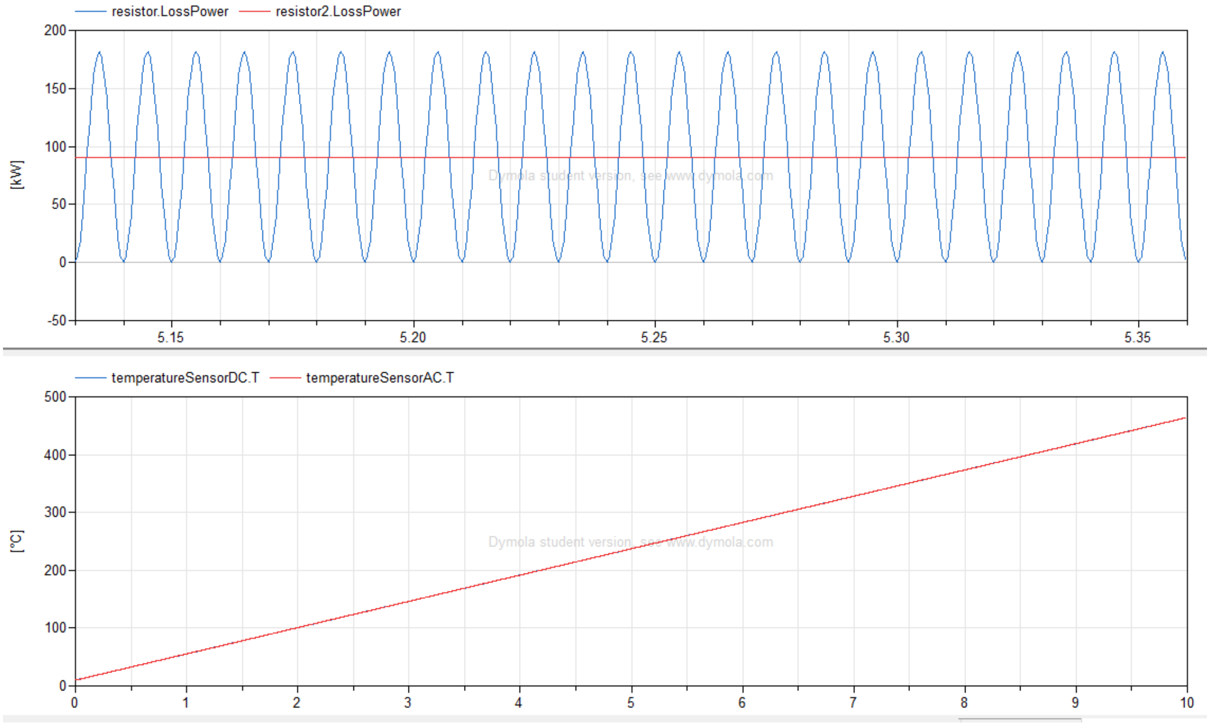


Figure 2-3: comparison between AC and DC power supply of the heating element

Simulation time was set to 0.1 s, and the result is shown in the figure2-4.

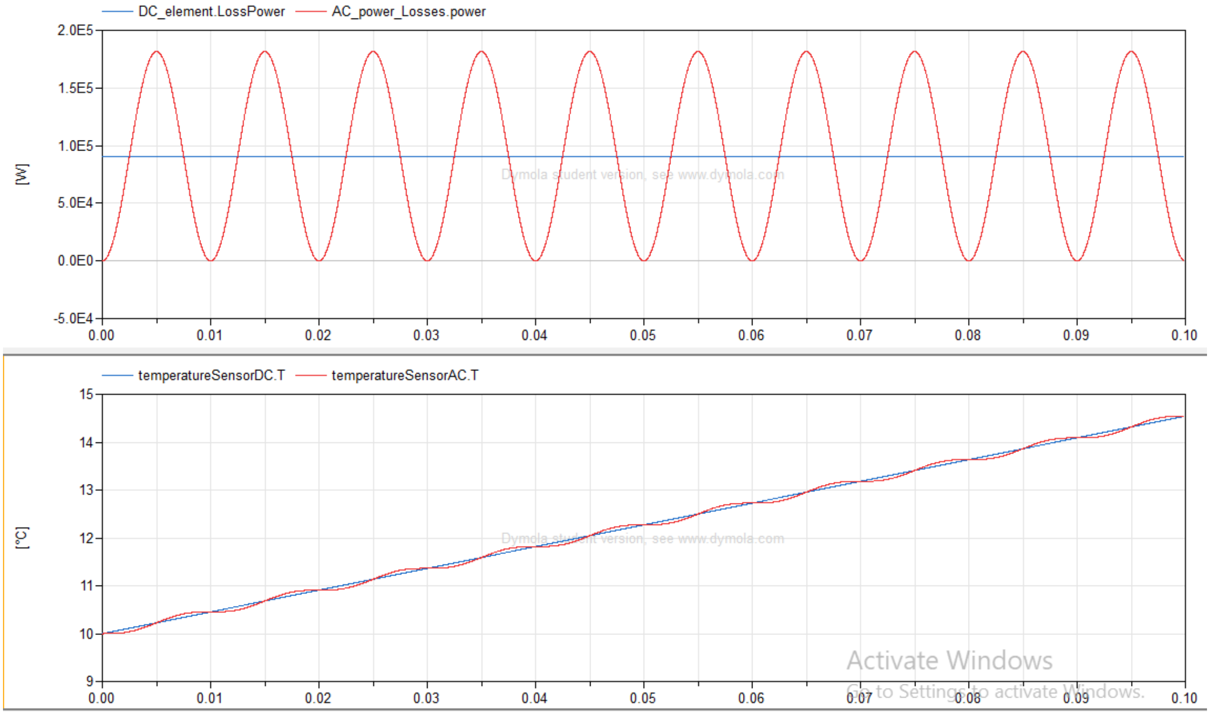


Figure 2-4: temperature variation AC vs DC power

The variation is too small compared to the heating element's time constant, and it doesn't have any effect on the furnace temperature. Considering the cost of converting AC to DC, the solution for the heating furnace is AC power.

2.2 AC Load and Element Arrangement

In this chapter, Parallel and series connection models of heating elements and the effect of delta and star connection configurations in a three-phase AC system are discussed.

2.2.1 Series and Parallel connection of resistances

There are two common ways of connecting heating elements: Series and parallel. According to the connection method, heat production will change using similar heating elements. This connections method is used for achieving the desired thermal energy.

Figure2-5 shows three resistances in series connection mode.

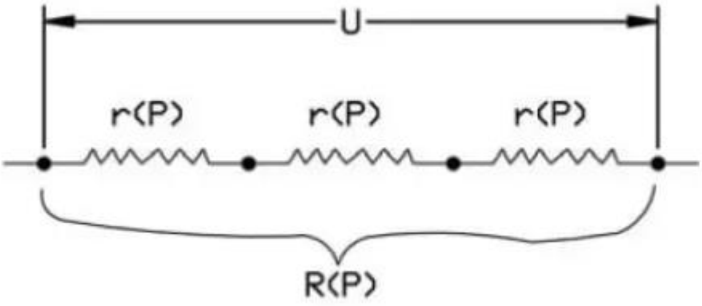


Figure 2-5: series connection [8]

Figure2-6 shows three resistances in parallel connection mode.

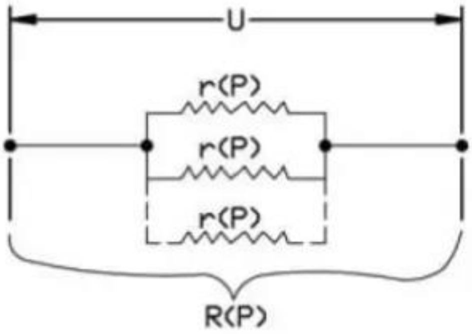


Figure 2-6: Parallel connection [8]

The calculation for both parallel and series model connections is presented in table 2-2.

Table 2-2: Power changes with different connections. [8]

Quantity Of elements (n)	Total Resistance		Total Power		Element wat density (w/cm^2)	
	Parallel R_t	Series R_t	Parallel P_t	Series P_t	Parallel	Series
2	R_t=r/2	R_t=2.r	P_t=2.p	P_t=p/2	Unchanged	Divided by 4
3	R_t =r/3	R_t=3.r	P_t=3.p	P_t=p/3	Unchanged	Divided by 9
x	R_t=r/x	R_t=x.r	P_t=x.p	P_t=p/x	Unchanged	Divided by x^2

2.2.2 Star and delta load connection comparison

In an AC power system, there are three voltage terminals. Any load connected to these terminals can be set by Delta or star arrangement.

- Delta arrangement: Three resistances are connected end to end and form a triangle or delta shape.

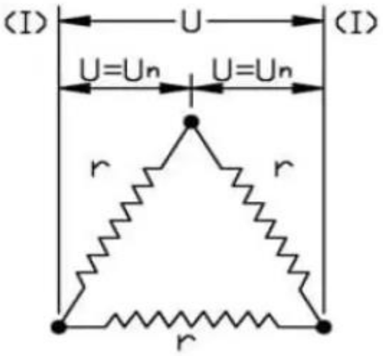


Figure 2-7: Delta connection [8]

Power delivered to the delta connection load in a three-phase AC system is calculated using equation (2-9).

$$P = \sqrt{3}.U.I.\text{Cos}(\theta) \tag{2-9}$$

Where:

P - Active power [W]

U - The line-to-line voltage [V]

I - Line current [A]

Θ - Phase angle [°]

U_n - Phase voltage [V]

R - Resistance(load) [Ω]

I_n - Phase current [A]

In the delta connection:

$$U = U_n \tag{2-10}$$

$$I = \sqrt{3}.I_n \tag{2-11}$$

- Star arrangement: one end of all three resistances is connected to the star point

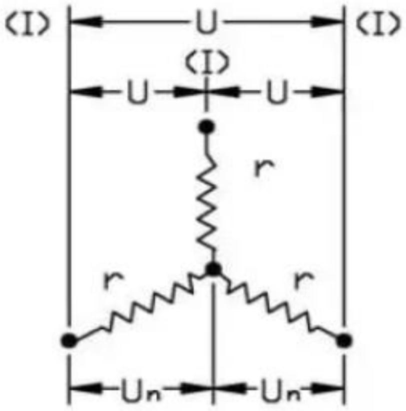


Figure 2-8: Star connection [8]

Power delivered to star connection is also calculated by equation (2-9). However, there is a significant difference in voltage and current. In star connection:

$$U = \sqrt{3}.U_n \tag{2-12}$$

$$I = I_n \tag{2-13}$$

To compare the effect of delta and star connection on power losses (Heat), two heating elements with different voltage levels are discussed in the table2-3. Total powerP_t is presented as a function of per element's power(p) to better understanding.

Table 2-3: Delta/Star element connection comparison [8]

Supply L-L Voltage (v)	230		230		400		400	
Heating element nominal voltage(v)	230		400		230		400	
Connection Mode	Δ	Y	Δ	Y	Δ	Y	Δ	Y
Wat density (w/cm^2)	No change	Divided by 3	Divided by 3	Divided by 9	Multiplied by 6	No change	No change	Divided by 3
Total power(P_t)	P_t=3p	P_t =p	P_t=p/3	P_t=p/3	P_t=9p	P_t=3p	P_t=3p	P_t=p
Comments*	1	2	3	2	4	5	6	2

*Comments:

1. No problem
2. Not recommended because of low power
3. It can be used as a reduced power step by using Star/delta connection system
4. Fire Hazard! Never use this arrangement
5. It is the most standard connection that allows the identical heaters to be used with a 400V star connection or 230V delta connection without power change
6. It is the most common configuration

It was comparing the Star and Delta connection results from the table and having in mind that the rating voltage of heating elements and wat density are constant. There is no significant difference between applying Delta or Star arrangement from the heating efficiency viewpoint. However, it is essential to decide which method to design power supply voltage levels.

R_t - Total resistance [Ω]
r - Per Element resistance [Ω]

P_t	-	Lost power on total resistance	[W]
p	-	Lost power on one resistance	[W]

The power losses in the heating elements in the unit power factor cause heat production. Power loss in the heating element is calculated by:

$$P_t = R_t . I^2 \tag{2-7}$$

The equation (2-7) shows that power losses (Heat) on the element directly relate to the resistance and current. In a constant supply voltage, increasing resistance will cause a reduction in current according to Ohm's law:

$$V = R . I \tag{2-8}$$

Considering the relation between R and I, and also equation (2-7), proves that the reduction in R_t will provide more power losses in constant Voltage since current is in the power of two in the equation (2-7).

The parallel arrangement of heating elements for heating is the best choice because, in this system, the wat density of each element is kept unchanged, which is vital. Reducing the resistance to increasing power losses in constant voltage supply is possible.

2.2.3 Impact of star/delta connection of load on power supply

Resistance of each element is determined R=1.363 ohm, and considering wat density, the element rating voltage is calculated U= 353 V. In the Case of star connection for 77MW load line voltage of power supply according to equation (2-12) is :

$$V_{LL} = \sqrt{3}\text{*U=611 V}$$

Line current is calculated by equation(2-9):

$$I_L = \frac{P}{\sqrt{3} * V_{LL}} = \frac{77000}{\sqrt{3} * 0.611} \text{=72.759KA}$$

If delta connection is selected, the nominal values of voltage and current are calculated:

line voltage of power supply referring to equation(2-10) is:

$$V_{LL} \text{ =U=353 V}$$

Line current is calculated by equation(2-9):

$$I_L = \frac{P}{\sqrt{3} * V_{LL}} = \frac{77000}{\sqrt{3} * 0.353} \text{=125.9 KA}$$

This high current will be carried from the furnace transformer's low voltage terminals to the heating element terminals. Busbars, circuit breakers and other power components will be provided according to these numbers, and it is vital to select the proper arrangement.

2.2.4 Impact of different arrangements of the heating elements on nominal Voltage and current of power supply

The arrangement of the elements is shown in figure2-9, which are in parallel connection. The resistance and material of each element are the same.

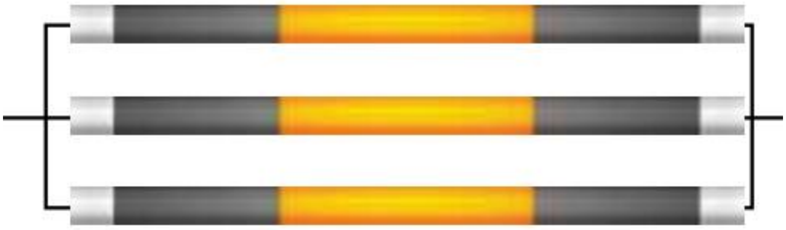


Figure 2-9: Case1, Heating elements in parallel connection [9]

The advantage of this arrangement is if one of the elements fails during service time, other elements won't be overloaded. The elements' arrangement is vital, and it is one of the base design parameters for power supply. For instance, an alternative arrangement is shown in figure2-10. In this arrangement, the line current and Voltage are affected dramatically.

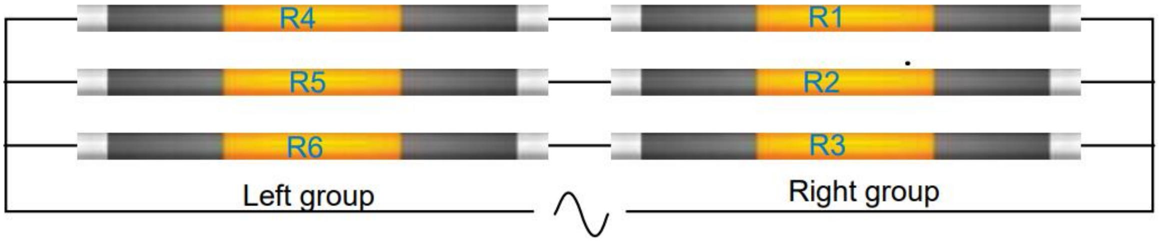


Figure 2-10: Case2, Heating elements in series and parallel connection [9]

Since two elements are in series connection to keep the power of the element constant, The line voltage must be two times than before (V_{LL}=1222 v). Then the line current decreases:

$$I_L = \frac{P}{\sqrt{3} * V_{LL}} = \frac{77000}{\sqrt{3} * 1.222} = 36.379\text{KA}$$

These values of Voltage and current are very proper to the previous arrangement. However, there might be some physical limits to installation and insulation. Table2-4 shows the nominal power supply values for star and delta connection in this arrangement.

Table 2-4: Nominal values of power supply

Connection method	Star	Delta
Power (MW)	77	77
Voltage (v)	1222	706
Current (KA)	36.38	62.9

Table2-5 shows the power losses from each element in detail applying this arrangement.

Table 2-5: Power losses of the elements

	Resistance Ohm	Voltage (v)	Current (A)	Power (KW)
R1	1.363	353	259.17	91.5
R2	1.363	353	259.17	91.5
R3	1.363	353	259.17	91.5
R4	1.363	353	259.17	91.5
R5	1.363	353	259.17	91.5
R6	1.363	353	259.17	91.5
Left group	0.454	353	776.96	274.26
Right group	0.454	353	776.96	274.26
R total	0.9086	706	777	548.5

One drawback of this arrangement is that when one element is disconnected, the second element, which is in series with failed elements, will be out of service. In fact, two elements are removed from the load. Table2-6 shows the details in number in case of failing one element. It is seen from the result that there is no overloaded element after a fault.

Table 2-6: Power change after fault

	Resistance Ohm	Voltage (v)	Current (A)	Power (KW)
R1	1.363	353	259	91.5
R2	disconnected			
R3	1.363	353	259	91.5
R4	1.363	353	259	91.5
R5	1.363	0	0	0
R6	1.363	353	259	91.5
Left group	0.454	353	518	183
Right group	0.6815	353	518	183
R total	1.363	706	518	366

Suppose the arrangement in case 2 is applied to the star connection. In that case, the line voltage of the power supply, which was calculated in section 2.2.3, will increase by two times, and the current will be divided by 2. The new nominal values of power supply are shown in table2-4 for both star and delta connection of elements in parallel and series arrangement same as case2.

Figure 2-11 shows another arrangement of the elements.

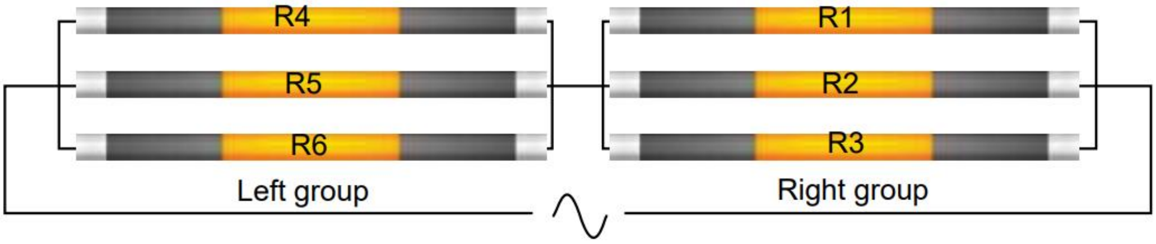


Figure 2-11: Case3, Heating elements in series and parallel connection, not recommended [9]

This arrangement has some weaknesses, and that is not recommended. Consider R2 disconnected. This will cause overloading of R1 and R3, and those elements will fail soon after R2. In normal service conditions, the power of each element is P=92KW.

The supply voltage V=706 v and resistance R=1.363ohm. Table2-7 and table2-8 show differences between two conditions before fault and after a fault.

Table 2-7: Normal loading before a fault

	Resistance Ohm	Voltage (v)	Current (A)	Power (KW)
R1	1.363	353	259.17	91.5
R2	1.363	353	259.17	91.5
R3	1.363	353	259.17	91.5
R4	1.363	353	259.17	91.5
R5	1.363	353	259.17	91.5
R6	1.363	353	259.17	91.5
Left group	0.454	353	776.96	274.26
Right group	0.454	353	776.96	274.26
R total	0.9086	706	777	548.5

Table 2-8 shows results after fault and disconnection of one element(R2).

Table 2-8: after Fault

	Resistance Ohm	Voltage (v)	Current (A)	Power (KW)
R1	1.363	423.6	310.78	131.64
R2	disconnected			
R3	1.363	423.6	310.78	131.64
R4	1.363	282.4	207.19	58.51
R5	1.363	282.4	207.19	58.51
R6	1.363	282.4	207.19	58.51
Left group	0.454	207.2	621.57	128.78
Right group	0.6815	423.6	621.57	263.297
R total	1.1355	706	621.75	438.957

It is seen from the tables that elements R1 and R3 are overloaded up to 143%. In comparison, other elements in the left group experience a decrease in load up to 64% of nominal power of each element. Total power of the group also drops to 80% of nominal rating of 6 elements. The overloaded elements will fail soon if the full load condition is kept.

2.3 Heating element calculation

Two heating elements including Silicon Carbide and Kanthal APM are studied in the following. Both elements are manufactured with Kanthal company.

2.3.1 Silicon carbide elements

The Silicon Carbide (SiC) heating elements can be used in applications ranging from 600°C to 1600°C. The heating elements are made from high purity alpha silicon carbide grains, which are extruded in the form of rods or tubes. They have more capability of higher loading than metallic heating elements. Standard elements are available in the market, and for this study, one standard size with a diameter of 55 mm and a length of 2400 mm was selected. The resistivity of SiC heating elements is 1.35e-3 Ω-m.

Figure 2-12: Sic heating element [9]

There is a recommendation wat density for these types of heating elements in the manufacturer's catalogue according to the temperature of the furnace and heating element.

The furnace temperature is 900°C, and the maximum heating element temperature is decided on 1300°C. The recommended wat density for this operation temperature is 22 wat/cm^2 [9].

The power of each heating element is calculated by:

$$\text{Power[wat]=Area of each element } [cm^2] * \text{ wat density } [\text{wat}/cm^2] \qquad (2\text{-}14)$$

The area of each element is calculated by:

$$A = \pi . D . L \qquad (2\text{-}15)$$

$$A=\pi*5.5*240=4147 cm^2$$

Using the equation(2-14) power of each element is:

$$p=4147*22=91234 \text{ wat} \rightarrow 91.23 \text{ kw}$$

The resistance of each heating element is calculated:

$$R=r.L/A \qquad \textbf{(2-16)}$$

The area is calculated by:

$$A= \pi.\ (D^2/4) \qquad (2\text{-}17)$$

$$A= \pi.\ (0.0055^2/4) = 0.00237\ m^2$$

Resistance is calculated using equation**(2-16)**.

$$R=1.35e\text{-}3 * 2.4/0.00237 \rightarrow R=1.363\Omega$$

p	-	Nominal power of each heating element	[W]
D	-	Diameter of a heating element	[m]
r	-	Resistivity	[Ω-m^2/m]
L	-	Length of each heating element	[m]
A	-	The cross-section area of the heating element	[m^2]
R	-	Resistance of each heating element	[Ω]

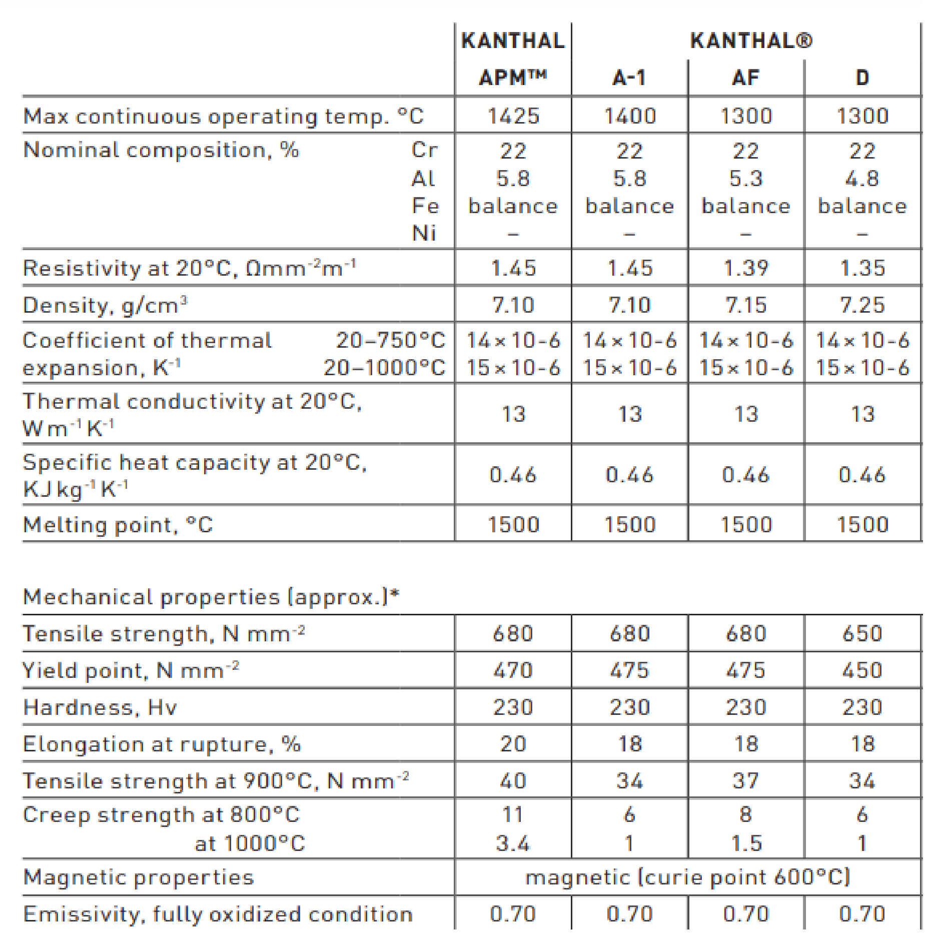
2.3.2 Kanthal APM heating elements

Kanthal APM™ is a resistance material that can improve the performance at high temperatures, where conventional metallic elements are getting problems like bunching, creeping, and oxide spallation, and to open new applications where metallic elements are not used today. Some advantages and disadvantages are listed here:

- IMPROVED HOT STRENGTH, GIVING: much better form stability of the heating element, less need for element support, low resistance change (ageing), longer element life
- EXCELLENT OXIDE, GIVING: good protection in most atmospheres, especially corrosive atmospheres, no scaling and impurities, a longer element life
- AVOID TEMPERATURE FLUCTUATIONS: The operating life of the heating elements will be reduced by rapid temperature fluctuations. It is therefore advisable to choose electric control equipment, which gives as even a temperature as possible, e.g. by using thyristors [9]

Kanthal alloys are generally available in wire, ribbon or strip form. The physical and mechanical properties of the alloys are listed in the table below:

Table 2-9: Physical and mechanical properties of kanthal alloy [9]



	KANTHAL APM™	KANTHAL® A-1	KANTHAL® AF	KANTHAL® D
Max continuous operating temp. °C	1425	1400	1300	1300
Nominal composition, % Cr Al Fe Ni	22 5.8 balance –	22 5.8 balance –	22 5.3 balance –	22 4.8 balance –
Resistivity at 20°C, $\Omega mm^{-2}m^{-1}$	1.45	1.45	1.39	1.35
Density, g/cm^3	7.10	7.10	7.15	7.25
Coefficient of thermal expansion, K^{-1} 20–750°C 20–1000°C	14 × 10-6 15 × 10-6	14 × 10-6 15 × 10-6	14 × 10-6 15 × 10-6	14 × 10-6 15 × 10-6
Thermal conductivity at 20°C, $W m^{-1} K^{-1}$	13	13	13	13
Specific heat capacity at 20°C, $KJ kg^{-1} K^{-1}$	0.46	0.46	0.46	0.46
Melting point, °C	1500	1500	1500	1500

Mechanical properties (approx.)*

Tensile strength, $N mm^{-2}$	680	680	680	650
Yield point, $N mm^{-2}$	470	475	475	450
Hardness, Hv	230	230	230	230
Elongation at rupture, %	20	18	18	18
Tensile strength at 900°C, $N mm^{-2}$	40	34	37	34
Creep strength at 800°C at 1000°C	11 3.4	6 1	8 1.5	6 1
Magnetic properties	magnetic (curie point 600°C)			
Emissivity, fully oxidized condition	0.70	0.70	0.70	0.70

* The values given apply for wire sizes of 4 mm diameter for the Kanthal alloys

Element design is also of great importance. The more freely radiating the element form, the higher the maximum surface load can be. Therefore, the ROB (rod over bend) type element (heavy corrugated wire, mounted on the surface) can be loaded the highest, followed by the corrugated strip element. Coil elements on ceramic tubes can be loaded higher than coil elements in grooves.

There is some limit from the manufacturer about the size of the elements, which has a substantial impact on the wat density of the elements. There are four categories for using this type of element. Figure2-13 shows four kinds of elements.

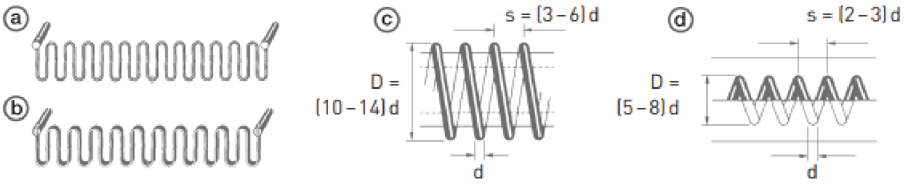


Figure 2-13: Kanthal APM element construction category [9]

1. ELEMENT TYPES A (HEAVY WIRE) the minimum diameter is 5 mm.

2. AND B (STRIP): Strip thickness minimum 2.5 mm. Pitch minimum 50 mm at maximum loop length and maximum surface load. Here is maximum loop length according to maximum temperature of element:
   - < 900°C 300 mm
   - 1000°C 250 mm
   - 1100°C 200 mm
   - 1200°C 150 mm
   - 1300°C 100 mm
3. ELEMENT TYPE C: Wire element on the ceramic tube. Wire diameter minimum 3 mm.
4. ELEMENT TYPE D: Wire and strip element in grooves. Wire diameter minimum 3 mm, strip thickness minimum 2m

According to the initial available study, the maximum temperature of this element that can stand out in a calcination environment is 1100°C. The furnace temperature also decided to 900°C. Figure2-14 shows recommended wat density for this type of element.

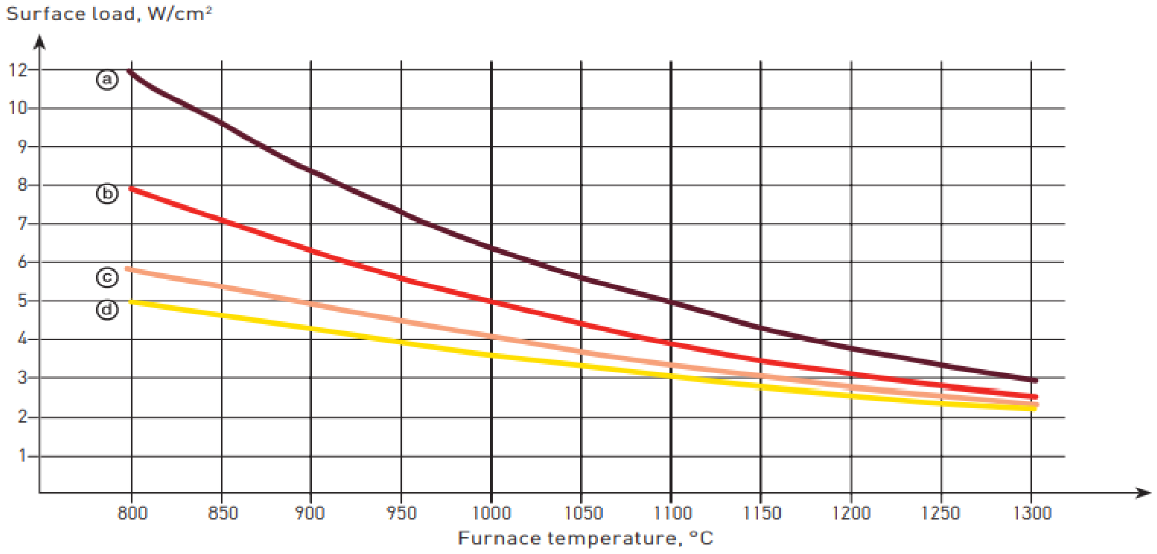


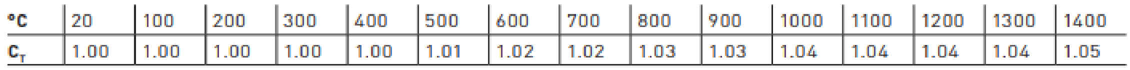
Figure 2-14: Maximum recommended surface loads for Kanthal APM Alloys [9]

If type(a) is used, the maximum wat density is 8.5 W/cm^2The material thickness directly relates to the element life; in that case, like the wire diameter increases, the more alloying element is available per surface unit to form a new oxide. Thus, thicker wires will give a longer life at a given temperature than thinner wires. Accordingly, for strip elements, increased thickness provides longer life. As a general rule, the recommendation is a minimum 3mm wire diameter and 2 mm strip thickness.

Impurities in the furnace atmosphere, for instance, oil, dust, volatiles or carbon deposits, can damage the heating elements. Sulphur is harmful to all nickel alloys. Chlorine in different forms will attack both Kanthal alloys. Splashes of molten metal or salt may also damage the heating elements [9].

Type a and b cannot be used in this project because of the length limit and type C is selected as an alternative to compare with SiC elements. Here is listed some information about Kanta

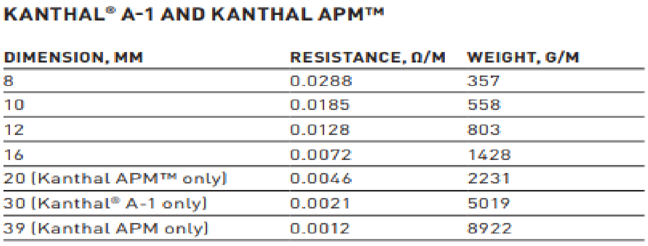
Hal APM wire. Resistivity 1.45 Ω mm2 m-1. Density 7.1 g cm-3. To obtain resistivity at working temperature, multiply by factor Ct in the following table



°C	20	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400
C_T	1.00	1.00	1.00	1.00	1.00	1.01	1.02	1.02	1.03	1.03	1.04	1.04	1.04	1.04	1.05

RESISTANCE AND WEIGHT DATA

Table 2-10: Resistance of kanthal APM [10]



KANTHAL® A-1 AND KANTHAL APM™

DIMENSION, MM	RESISTANCE, Ω/M	WEIGHT, G/M
8	0.0288	357
10	0.0185	558
12	0.0128	803
16	0.0072	1428
20 (Kanthal APM™ only)	0.0046	2231
30 (Kanthal® A-1 only)	0.0021	5019
39 (Kanthal APM only)	0.0012	8922

The calculation for Kanthal APM element is presented according to the information available in the product catalogue. Type C is selected for this calculation. The wire must be turned around the tubical ceramic. It is essential to keep distance between turns as suggested in the manufacturer's instruction manual to maintain a long operation time. Below are the dimensions of the ceramic and resistor wire in table2-11.

Table 2-11: Kanthal APM element calculation

Diameter of ceramic	42 mm
Diameter of wire	D=6.5mm
Length of ceramic	2400mm
Maximum wat density	4 W/cm^2
Resistivity at 1100 °C	1.04*1.45=1.508 Ω-mm^2/m
Distance between turns	S= 20mm
Number of turns	2400/26.5=90
Minimum Length of wire	90*3.14*4.2=1187.5cm
Area of wire	771.87cm^2
Power of element: A*wat density	772*4=3 kw
Resistance of each element: R= r.L/A	(1.45*1.04) * 11.875/3.14*3.25^2→ 0.54ohm
Number of elements for 77MW heating system	25666

Considering the number of elements, it is not suitable for this power supply. The main problem is the low wat density of the elements. And also, the lower operating temperature of the Kanthal APM corresponds to SiC elements**.**

3 Power supply and control

There are two main limitations in the heating system, which need a control system to be designed. First, the maximum Voltage of the heating element and second, the highest temperature of the heating element. In this chapter, different scenarios and control systems are discussed.

3.1 Power supply

To design a power supply for an electrical heating furnace, there is a need for some basic main parameters such as:

- Power of heating element
- The voltage of the heating element
- Resistance of heating element
- Star or Delta connection of load
- Total power of thermal energy required
- Furnace temperature
- Maximum heating element operation temperature

The Silicon Carbide Resistance element manufactured by Kanthal company is used to calculate nominal values. Some of the information above was calculated in section 2, and Voltage as the main power supply parameter is estimated in this section.

3.1.1 Nominal values of the heating element

The pure SiC resistance determined 1.363 ohms. There will be additional contact resistance and some tolerance for up to 15 % of the resistance. Considering these parameters, the value for the calculation is set to 1.5 ohms +_ 15%.

First, we calculate the minimum Voltage of the system by using the minimum resistance of the system, which is R_{min}=1.275ohm.

The minimum Voltage for the heating element is calculated by the equation (3.1)

$$U = \sqrt{p.R_{min}} \tag{3-1}$$

$U_{min} = \sqrt{91230 * 1.275}$=341 V converting to line voltage→ 590V

The nominal Voltage for the heating element is calculated by the equation (3-1)and the resistance value of 1.363 ohm.

$U_{nom} = \sqrt{91230 * 1.363}$=353 V converting to line voltage→ 611V

The maximum current is calculated by [9]:

$$I_{max} = \sqrt{\frac{p}{R_{min}}} \tag{3-2}$$

$$I_{max}= = 267.5\text{A}$$

The estimated number of heating elements is calculated:

$$N_{el}=\frac{P}{p} \tag{3-3}$$

$$N_{el}=\frac{77MW}{91.2Kw}=844$$

N_{el}	-	Total number of a heating element	[-]
P	-	Total power	[W]
P	-	Power of each heating element	[W]

3.1.2 Modelling and simulation of power supply

Dymola software is used for simulation in this study. A three-phase AC generator is considered an infinite bus from the grid that delivers 20 kv voltage to the furnace transformer.

The total load is divided into five units to obtain flexible load variation, each providing 15,4MW heat energy. Each unit consisted of 169 heating elements. In a three-phase system, each phase will supply 56 heating elements.

The nominal Voltage of each element was calculated at U= 353 V, which is phase voltage. Regarding the Delta or Star arrangement used, the line-to-line voltage of the power supply is estimated. If elements connect in Delta, the line voltage will be 353V. But if the elements are connected in a star, the line voltage will be 611V. Star connection is applied in this model, and the furnace transformer converts 20kv to 611 v and connects to heating elements. This is the simplest model as a first step. Figure 3-1 shows the schematic diagram of this simple model.

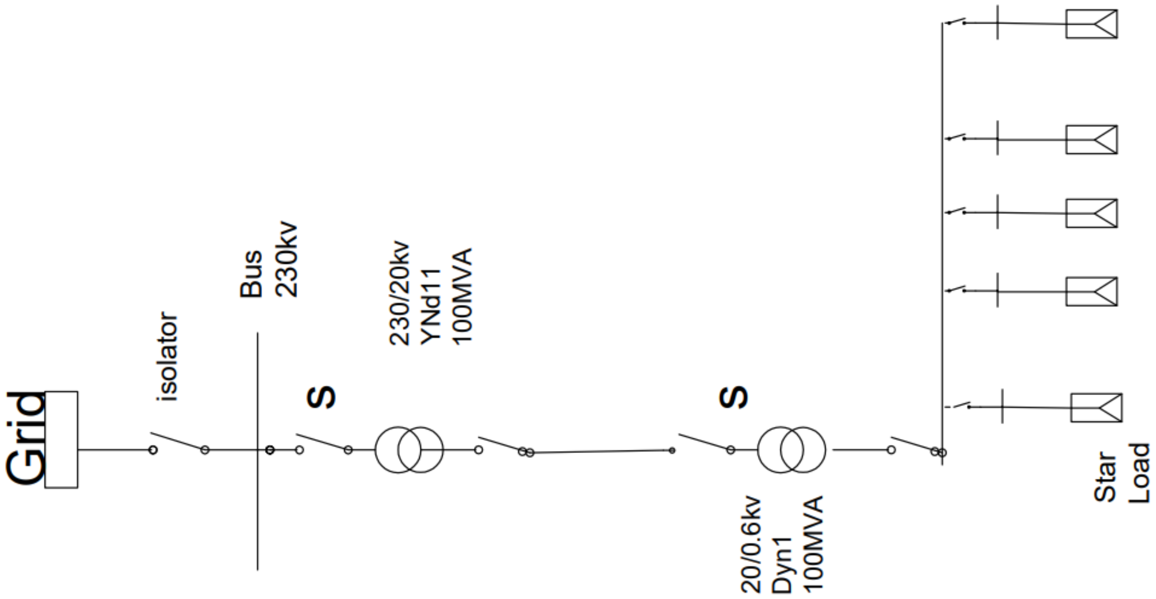


Figure 3-1:Power supply using Furnace transformer

Since the load is purely resistive, there is no disturbance on the Voltage and current as seen in the figur3-2 supplying 77MW load.

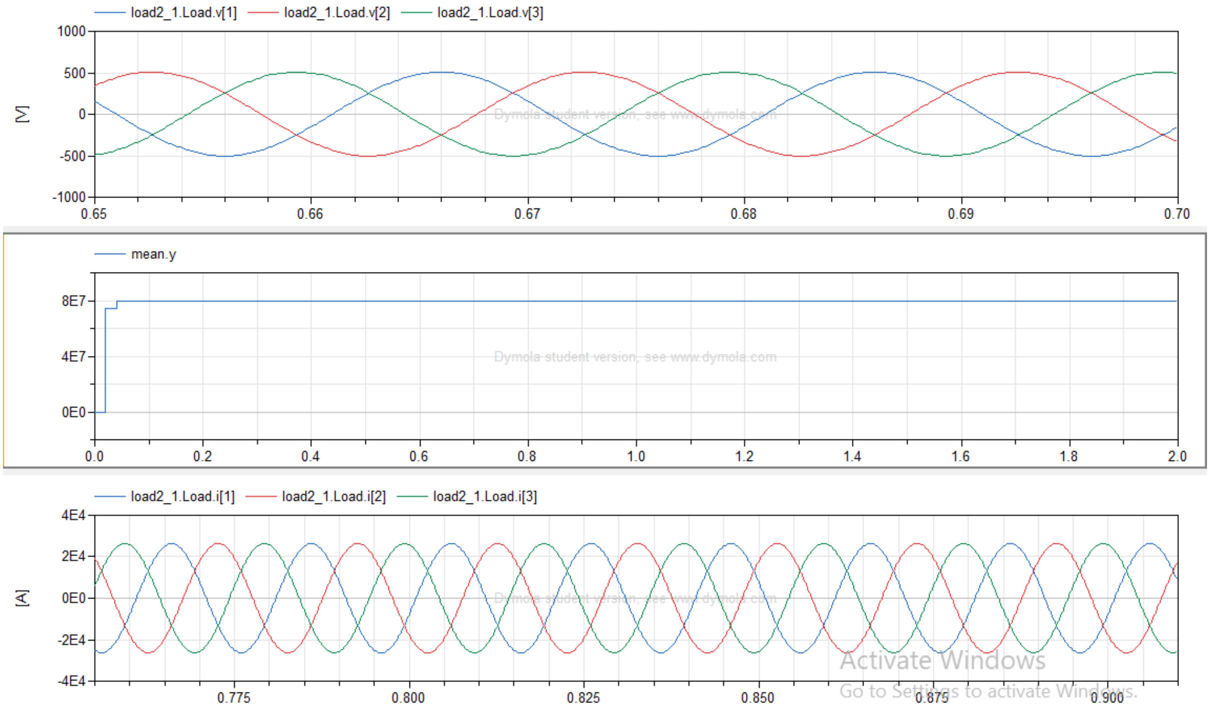


Figure 3-2: Simulation result of current, voltage at full load

77MW thermal energy is delivered to the furnace, and after a while, heating elements reach their maximum operating temperature and need to be kept at this level. Otherwise, heating elements will damage and finally fail. The line current is 72.7 KA in full power condition and switching this current on/off is not easy. Moreover, this switching should be done frequently, complicating the situation. It is impossible to switch the load off and on mechanically, often at high speed in this system, because of the high load current. One way to obtain this goal is utilizing SCR thyristor in series with transformer and loads.

3.1.3 Use of thyristor/SCR and transformer

The thyristor is derived from a Greek word meaning "Door". It is a semiconductor device consisting of three or more junctions, having two states, that can be switched on and off. Switching from off state to on state is triggered by a control signal. The term SCR is derived from Silicon Controlled Rectifier, a General Electric trade name for a thyristor type. SCR is a three terminal, four-layer semiconductor device consisting of P-type and N-type material doped in alternating layers. Figure3-3 shows the SCR with Layers PNPN, which has three terminals: Anod, cathode, and gate. The symbol of the SCR used in the circuit is shown.

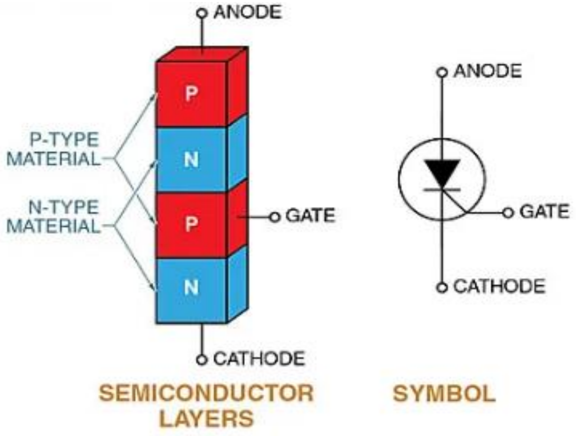


Figure 3-3:SCR thyristor symbol [11]

The SCR is a unidirectional thyristor and can be controlled only in one voltage polarity. Two thyristors must be used in anti-parallel to control both polarities in an AC supply. This thyristor arrangement is called Triac, which was introduced in 1960, a bidirectional thyristor that made it possible to control AC current over two halves of an AC current. By applying a signal to the gate terminal, which regulates the firing angle, the thyristor allows current flow when the phase angle meets the firing angle. This method is called a phase control system with SCR and has typical applications in the industry. Using Triac, AC current in both polarities can be controlled and conducted. Figure3-4 shows the symbol of a Triac.

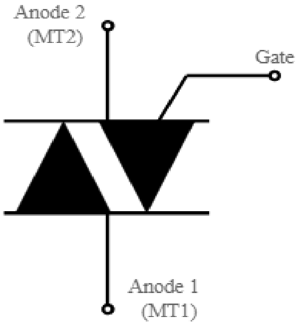


Figure 3-4:TRIAC symbol [11]

Some points must be considered while using Triacs. Because of the natural initial difference in the construction of these semiconductor devices, after triggering, firing is not done symmetrically in both thyristors, and it results in harmonics. The less symmetrical fires the Triac, the greater the harmonic. Also, switching frequency and large firing angle impacts the harmonics level. It is not usually desirable to have high harmonics in the power system.

Figure3-5 shows a simple diagram of the power supply using SCR and transformer.

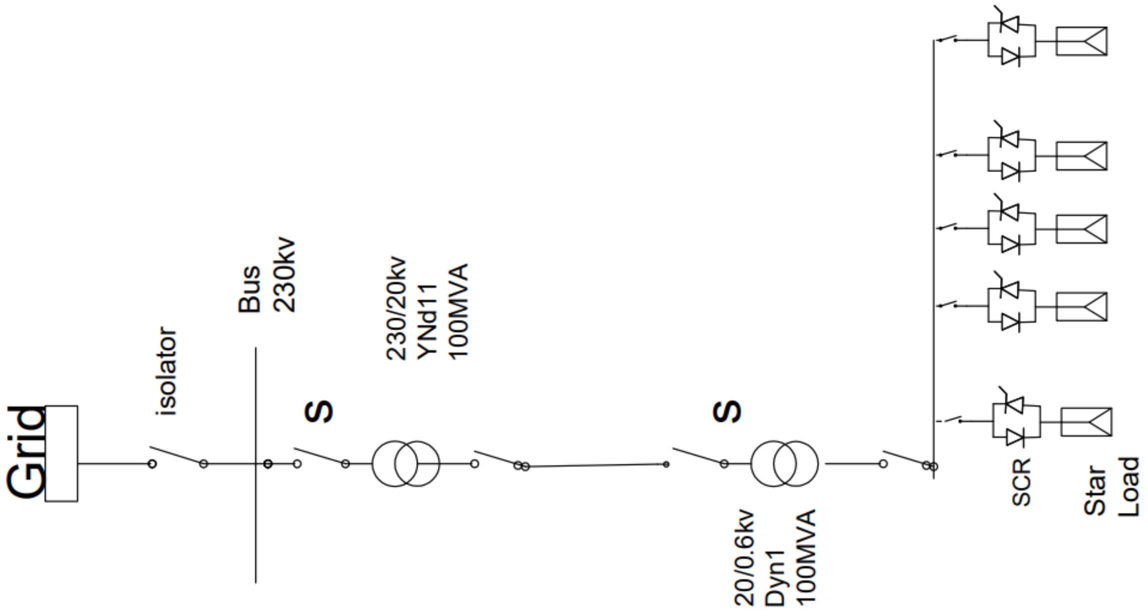


Figure 3-5: Simple diagram of Transformer and SCR controlled power supply

When the firing angle is zero, AC current flows in both polarities on the original sinusoidal shape, and power is maximum. By increasing the firing angle, the current loses its sinusoidal shape, which means the rms value of current decreases and, finally, power decreases. In this way, it is possible to regulate the power on the load side. Figure 3-6 shows how firing angle impacts the load and current.

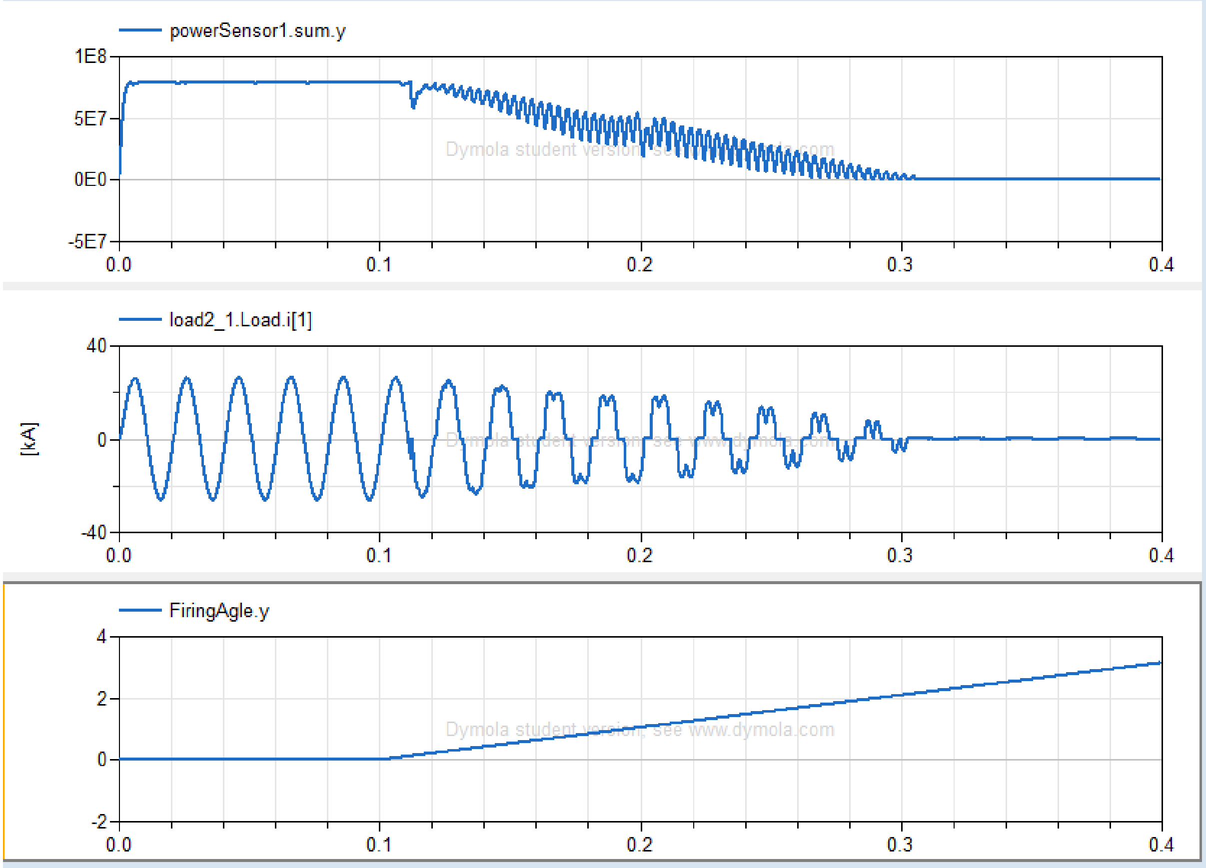


Figure 3-6: effect of firing angle on power and current

During 0 to 0.1 seconds, the firing angle is zero, the current is sinusoidal, and the power is constant. When the firing angle increases, the current loses its sinusoidal shape and harmonics, and power is not constant and fluctuates.

Since the number of elements in parallel connection is high and it is vital to keep the three phases' resistance in balance, it is more sufficient to use star connection and get feedback from a neutral point.

3.1.4 Reserve voltage and design requirement

Some other parameters are impacted by the voltage level of the power supply:

- Resistivity: the resistivity of the SiC heating element is not linear, and in environmental temperature, it is 240% higher than the operating condition at 1000°C.
- Resistance of the heating elements is increased by time in service. It generally increases 5-6% within 1000 hours of operation at a temperature of 1400°C in clean air.

So, reserve voltage is needed for the power supply's capability for long-time operation. For example, if 611 V is required to give full power with new elements, then a voltage range of 611-1222 V will be required to provide 100% voltage reserve, and a range of 611-917 V to give 50% reserve. To achieve 100 % reserve voltage, the use of Transformer and SCR thyristors is studied.

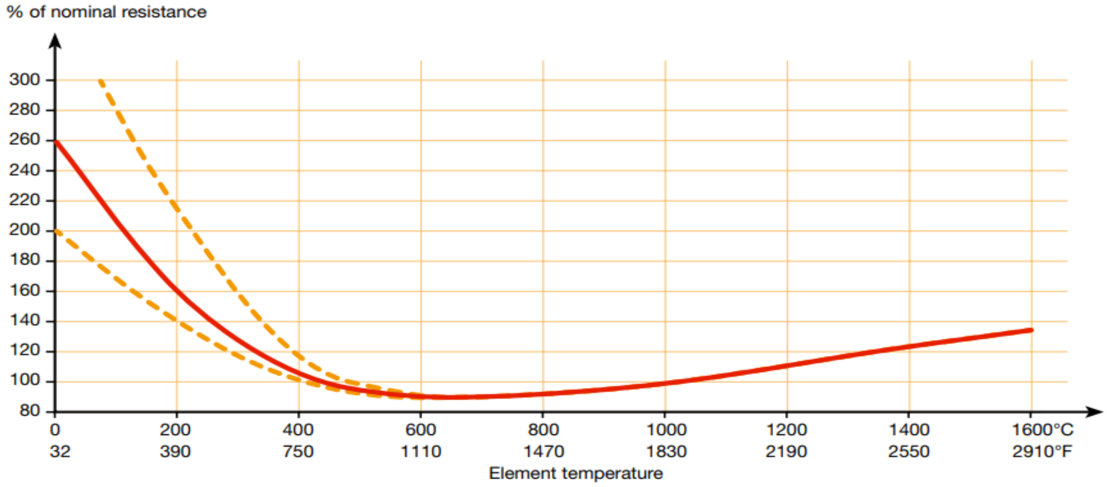


Figure 3-7: Resistivity/temperature characteristic curve [9]

We need a power supply with a voltage variation of 590 to 1222V in constant power. It is a vast range of voltage regulation. Making possible this level of variation, two approaches are studied.

- Case(I) :100% voltage regulation by SCR
- Case (II): Voltage regulation by both SCR and transformer

The first method (Case I) provides the maximum operating Voltage throughout a furnace transformer. According to element resistance and load condition, SCR controls the power by triggering the firing angle of SCR thyristors. The Voltage on the LV side of the transformer is 1222v, and power is controlled using SCR thyristors (Triac). In the second method(caseII), the furnace transformer is equipped with an on-load Tap-changer to compensate for a voltage drop of the elements in case of any increase in resistance during service. SCR only regulates the Voltage to keep reference temperature constant by a slight firing angle variation compared to the first method in which the firing angle is changed from 0 to 100%.

Each method has its pros and cons. The most critical parameter is cost and harmonics. A comparison between the two approaches will be presented in the following.

3.2 How to control Power supply

Two methods include Transformer/SCR thyristor introduced to provide 77MW power. In this chapter, some forms of power control are discussed.

3.2.1 Control system of the case (I)

One furnace transformer delivers the maximum Voltage of reserve voltage on its LV winding terminals at full load condition, which is 1222 V. SCR Thyristor (Triac) is used in series with the load. Applying a phase control system on load voltage, AC, is done by applying a wide range of firing angle for triggering SCR thyristors. If the firing angle is set to zero, the maximum rms voltage will apply to the load in both polarities. Figure3-8shows the simulated result for this configuration.

Furnace transformer:

- Power:100MVA
- Vector group: Dyn1/yn1
- Ratio:20/1.22 kv

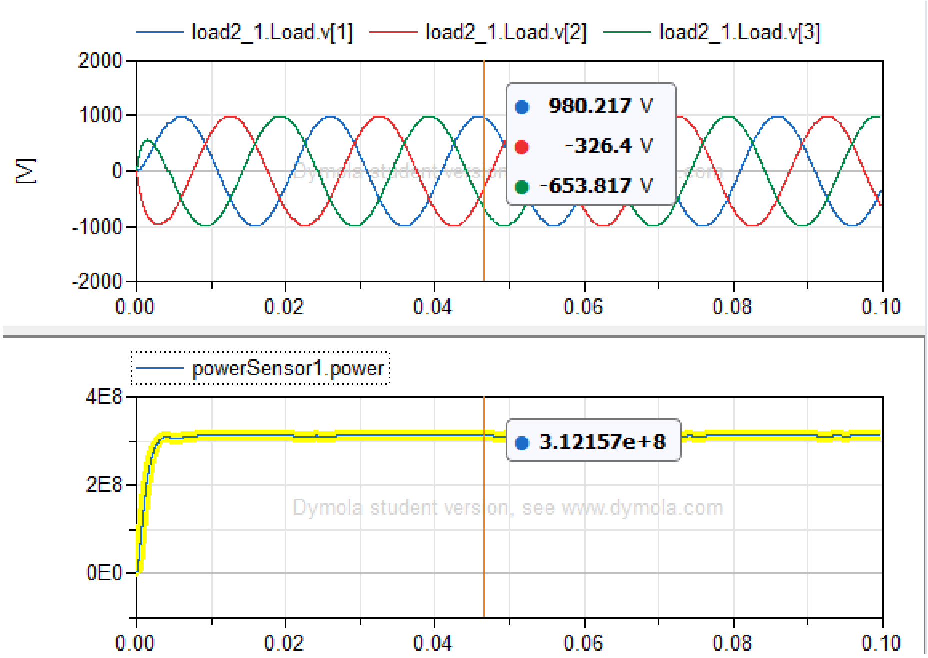


Figure 3-8: Maximum power delivery by fully open SCR

The most crucial drawback of this system is If the SCR fails to trigger correctly on time, 312MW power will be delivered to load if the source power capacity is high enough, and all the heating elements will be destroyed. So, it needs an additional protection system. Figure3-9 shows when the SCR begins properly to keep power at the desired level when the heating elements are new and have minimum resistance. In this condition, the Voltage must be 610v, and the maximum capacity must be 77MW. The firing angle was set to 1.6 radians.

However, the phase control system cannot meet this requirement instantaneously. Fluctuation in Voltage and power can damage the heating elements.

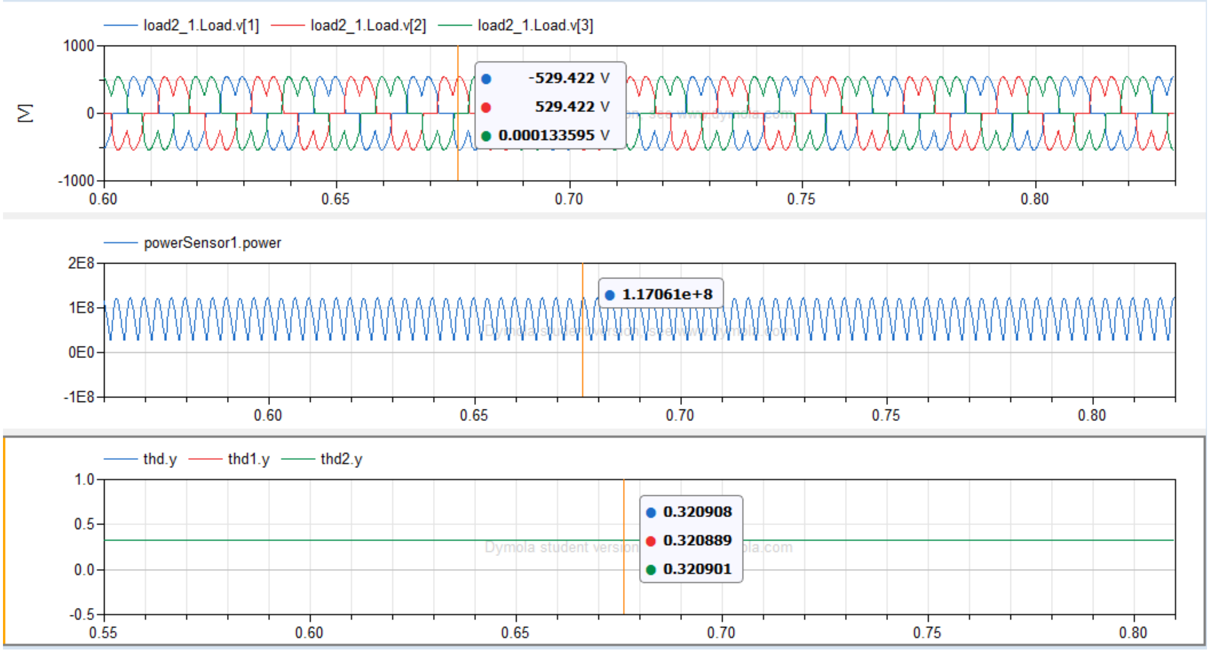


Figure 3-9: Harmonic content in regular operation

Also, the harmonics THD is considerably high in this control system.

3.2.2 Control system of Case (II)

Minimum and Maximum Voltage for heating elements during the lifetime is calculated between 590 to 1222 v in chapter3.1.1. We need a transformer that can provide this Voltage at constant power. It is not a typical transformer, and because of the high current, it is called a furnace transformer. When the system is new, the resistance of elements is 1.363 ohm, but after loading and service under 1300 °C, it increases 5 to 6 % every 1000 H.

If a power supply provides 100% reserved voltage, the maximum resistance of the heating elements, which can deliver 77 MW power, is calculated by:

$$R = \frac{U^2}{p} \tag{3-4}$$

$$R = \frac{(\frac{1222}{\sqrt{3}})^2}{91332} = = 5.45 \text{ ohm}$$

The maximum resistance for the heating elements is that the power supply can deliver 77MW energy—an almost 400% increase from the initial value estimated at 1.363ohm.

A three winding transformer can be designed to provide this wide range of voltage supply in constant power. The nominal values for the transformer are determined 20/1/0.7 kV at full load condition with equipped Voltage regulating winding on HV winding in 21 taps.

Furnace transformer:

- Power:100MVA three windings
- Vector group: Dyn1yn1

- Ratio:20/1/0.7 kv

The furnace transformer which is used in this system is the key asset. The Voltage and power are specified in section3.1.A three windings transformer is considered to supply the power at required voltages, making it possible to provide reserve voltage.

This transformer is supposed to be installed close to the calcination process to reduce the power losses due to high current. Therefore, power is transferred using high voltage cables from the power substation to the furnace transformer feeder. This power is supplied from the substation at a 20-kv voltage level. So, the high voltage side of the furnace transformer is kept at 20 kv. To achieve relatively smooth regulation in the LV side of the furnace transformer, an on-load tap changer is equipped on the HV winding of the furnace transformer. Table3-1 shows the Voltage and current delivered in each tap. The nominal tap of this transformer is 11.

Table 3-1: Voltage and current regulation on furnace transformer

	HV	LV1		LV2	
Tap	Voltage(v)	Voltage(v)	Current (KA)	Voltage(v)	Current (KA)
1	20000	589.74	78.36	842.11	54.85
2	20000	598.93	77.12	855.61	53.98
3	20000	608.7	75.88	869.57	53.12
4	20000	618.78	74.65	883.98	52.25
5	20000	629.21	73.41	898.88	51.39
6	20000	640	72.17	914.29	50.52
7	20000	651.16	70.93	930.23	49.65
8	20000	662.72	69.7	946.75	48.79
9	20000	674.7	68.46	963.86	47.92
10	20000	687.12	67.22	981.6	47.06
11	20000	700	65.98	1000	46.19
12	20000	713.18	64.75	1019.11	45.32
13	20000	727.27	63.51	1038.96	44.46
14	20000	741.72	62.27	1059.6	43.59
15	20000	756.76	61.04	1081.08	42.73
16	20000	772.41	59.8	1103.45	41.86
17	20000	788.73	58.56	1126.76	40.99
18	20000	805.76	57.32	1151.08	40.13
19	20000	823.53	56.09	1176.47	39.26
20	20000	842.11	54.85	1203.01	38.39
21	20000	861.54	53.61	1230.77	37.53

Step voltage for this transformer is 1.875% in 21 steps. When the system is new, and the resistances are at the minimum level, the load is connected to LV1.In this configuration, the power supply can be regulated between 589V to 861 V., which means the system can deliver full load power. At the same time, the resistance of the elements varied from 1.275 ohms to 2.713 ohms.

When the resistance of the elements becomes close to 2.7-ohm, the feeder bus from LV1 is switched to LV2, which can regulate Voltage between 842V to 1230 V. It means the system can deliver full load power. The resistance of the elements varies from 2.59 ohm up to 5.52 ohm.

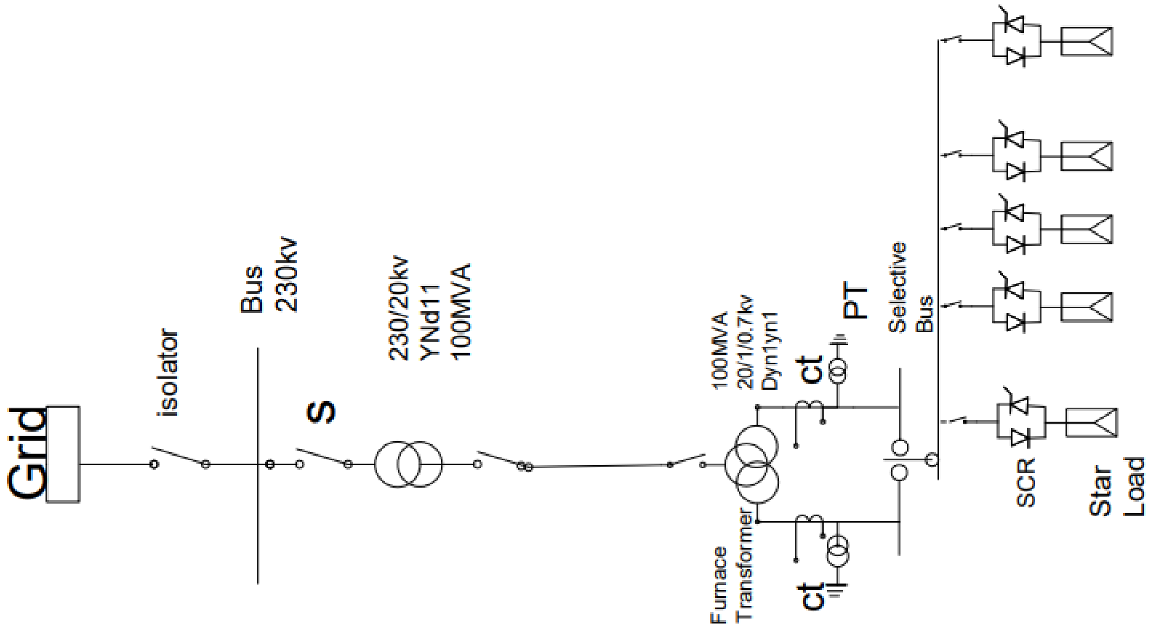


Figure 3-1: SLD of the power supply using three windings furnace transformer and SCR

This transformer is not a common type of transformer, and since the power in all taps is constant, a particular design is required to provide this specified power in all taps. The impedance of the transformers affects the phase control system, and it is vital to use almost actual values in the simulation program for sufficient analysis. Table3-2 shows the furnace transformer's impedance parameters used in this study at full load conditions.

Table 3-2: Impedance parameters of the transformers used for simulation

	Voltage(V)			Current (KA)	Impedance	R(ohm)		X(ohm)	
Tap	HV		LV	LV	UK% (100MVA)	HV (phase)	LV (phase)	HV (phase)	LV (phase)
1	20000	**LV2**	842.7	55	25.5	0.026	0.0001	1.53	0.00257
11	20000		998.4	46.7	17.2	0.0245	0.0001	1.032	0.00257
21	20000		1206.6	36.6	11.3	0.026	0.0001	0.678	0.00257
1	20000	**LV1**	589.8	78.5	25.5	0.026	0.00007	1.53	0.00126
11	20000		699.5	63.8	17.2	0.0245	0.00007	1.032	0.00126
21	20000		845	52.3	11.3	0.026	0.00007	0.678	0.00126

In everyday operation, the voltage level on the LV terminal of the transformer is set by a Tap-Changer depending on the resistance of the heating elements. Utilizing this transformer makes it easy to regulate the power when heating elements reach the maximum temperature. The firing angle will be slight during the lifetime of the elements, which impacts the harmonics level. In other words, during supplying 77MW, the firing angle is always zero, which is a significant achievement regarding harmonics and cooling issues. The only drawback is the cost of the transformer, which is more expensive than regular transformers.

When the reference temperature is reached, the controller must reduce the power. Two approaches can be considered. The first one is to increase the firing angle slightly and keep the temperature constant; the second approach sets the firing angle 0/3.14 (on/off) and keeps the temperature steady. Figure 3-10 shows the result of the firing angle tuning method.

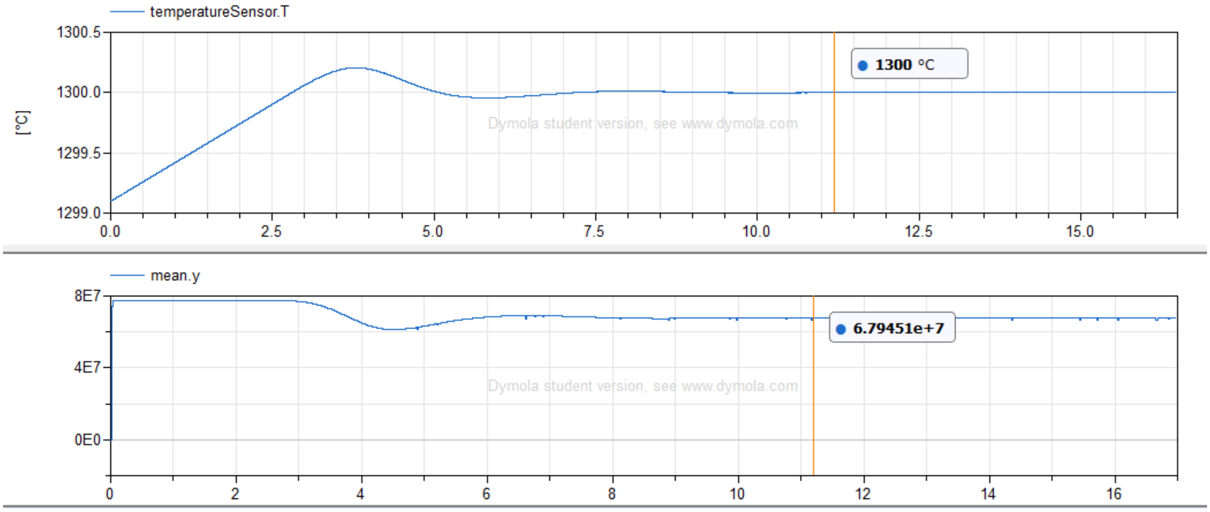


Figure 3-10: Temperature control by applying slight firing angle

4 Harmonics and power supply

This chapter introduces harmonics and discusses the effect of harmonics in the power system. Moreover, harmonics in the designed power supply are measured in simulation environments in different scenarios for loading and applying phase control systems.

4.1 What is harmonic?

Harmonics plays a negative role in the quality of power. Excessive harmonics can create serious power quality problems due to heat generation. These power quality problems can impact neutral cables, transformers, and motor overheating issues. But, what is the harmonic?

- IEC 61000-4-30 defines harmonic frequency, which is an integer multiple of the fundamental frequency
- IEEE519 defines the harmonic as a component of order bigger than one of the Fourier series of a periodic quality

A pure sinusoidal waveform only has the fundamental frequency component, but a distorted waveform is composed of various frequency components in addition to the fundamental frequency. Harmonics are components of a signal, having frequencies 2,3,4,…, N multiples of the signal frequency. Figure4-1 shows a pure sinusoidal signal with a frequency 60Hz and an amplitude of 1. Figure 4-2 shows one frequency component, which is in the order of the 3rd fundamental frequency. The amplitude of the harmonic component is 20% of the fundamental signal, and the frequency is 180Hz which means three times greater than the fundamental frequency. This 3rd is called the order of harmonic.

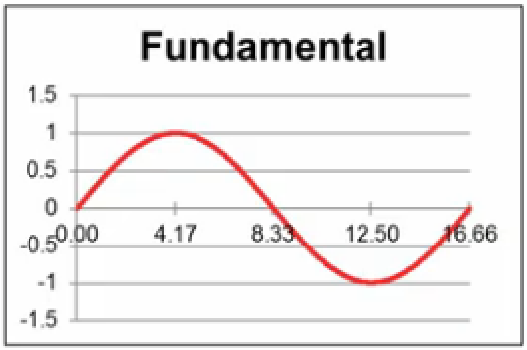


Figure 4-1: Pure sinusoidal signal f=60Hz [12]

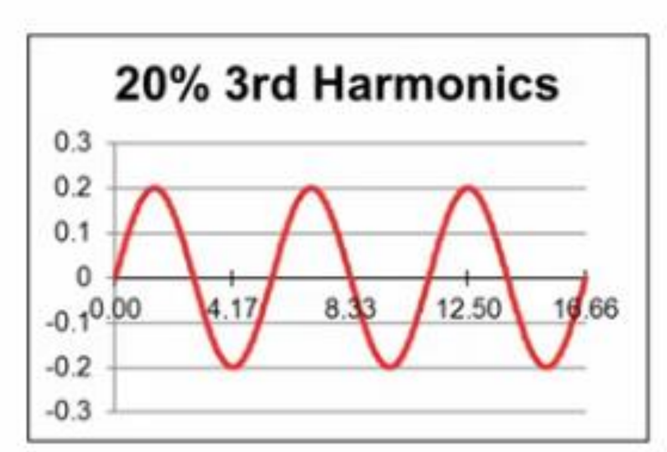


Figure 4-2:3rd harmonic f=180Hz [12]

The harmonic order is the ratio of harmonic frequency to the fundamental frequency. There might be different orders of harmonics in the power system. Figure 4-3 shows the 5th harmonic component of the signal.

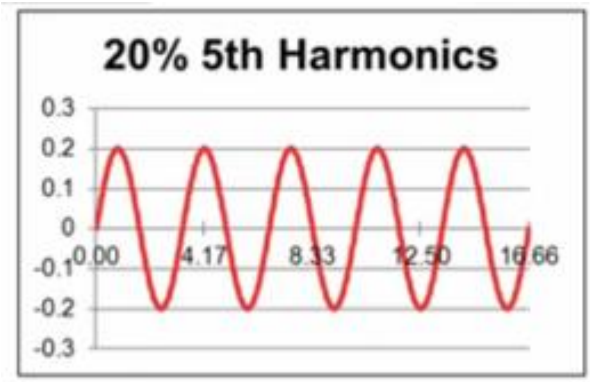


Figure 4-3:5th harmonic f=300Hz [12]

If we mix all the signals, the result will be a distorted signal like Figure 4-4.

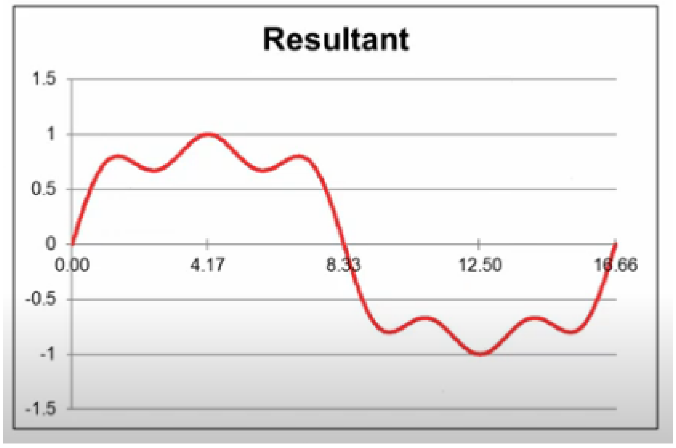
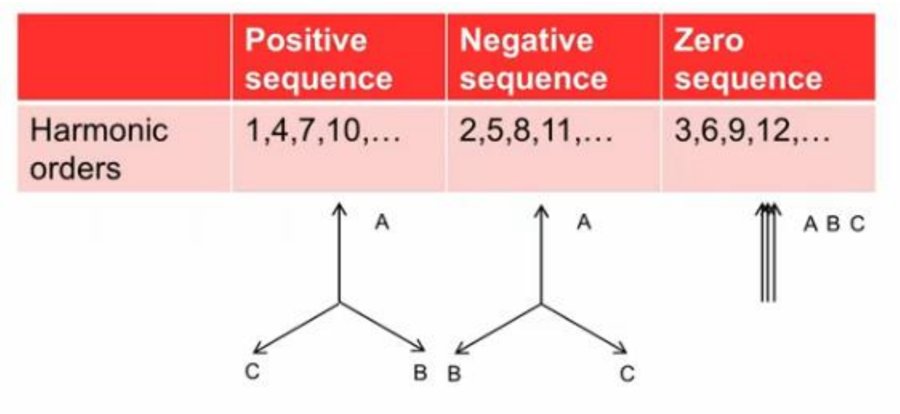


Figure 4-4: distorted signal by harmonics f=60Hz [12]

Harmonics also may be classified based on their phase sequence and rotational magnetic fields, as shown in the figure. Positive sequence currents make a magnetic field in the fundamental magnetic field direction and rotate in the same direction. Negative sequence harmonics create a magnetic field in the opposite direction of the fundamental magnetic field and cause the high current needed for the load. Zero sequence harmonics create a magnetic field that doesn't have phase rotation. These harmonics can increase current demand and cause heat [12].



	Positive sequence	Negative sequence	Zero sequence
Harmonic orders	1,4,7,10,...	2,5,8,11,...	3,6,9,12,...

Figure 4-5: Harmonics classification based on phase sequences [12]

Triple n-harmonics are odd multiples of third harmonics 3,6,9,.., N is called zero sequence harmonics which are added at the neutral of wye connected system. If the neutral wire in this system is not sized correctly, triple-n harmonics cause overheating at the neutral. These harmonics also can be trapped in the delta winding of transformers.

The positive, negative, and zero sequence harmonics run in sequential order (positive, negative, and zero). Since the fundamental frequency is positive, the second-order harmonic is a negative sequence harmonic. The third harmonic is a zero-sequence harmonic.

Harmonics arise out of non-linear loads. Non-linear loads are loads whose impedances are changed by Voltage. For example, transformer excitation current in the no-load condition is distorted by increasing Voltage when the core reaches saturation level. This is because of the non-linear characteristics of the core material. Switching power supplies draw current only on the wave's peak by utilizing thyristors that turn off and on and conduct current at a specific time. This means that load impedance is not constant and only draws current in conducting time.

So, the non-linear loads distort the fundamental signal. Large loads will cause a higher magnitude of distortion. Higher switching speed also leads to higher-order harmonics. In other words, voltage distortion is caused by the distorted current caused by non-linear loads.

We won't see the voltage curve distortion if the magnitude of the current harmonics is not high. But if the harmonics in the current are high, then the Voltage will load down figure4-6.

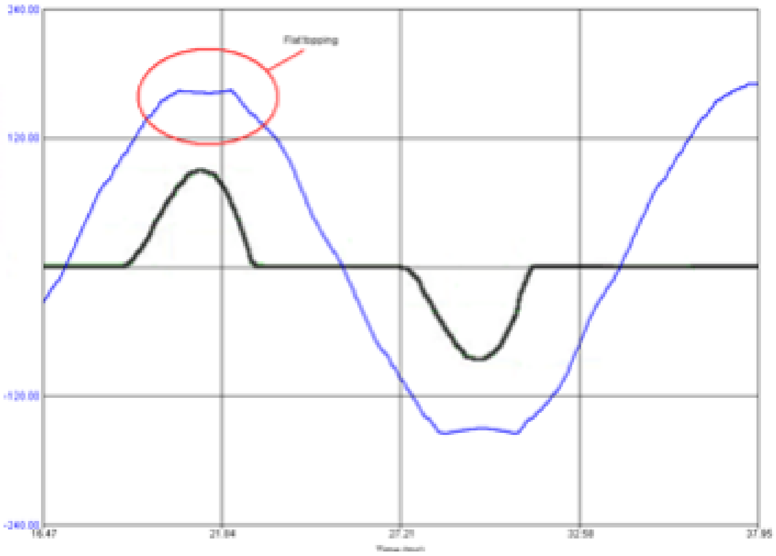


Figure 4-6: effect of harmonics on Voltage [12]

As seen in the figure4-6, the peak of the Voltage was affected. It is the most common type of harmonic, which is caused by a third-order harmonic that clips the height of Voltage.

Harmonics can heat cables and transformers. When an AC current flows through a conductor, it generates a magnetic field, and this alternating field induces a current inside that conductor when crossing it. These currents are called eddy currents which create a magnetic field that opposes the main magnetic field that created them. This repulsion of the fields will increase the resistance of the conductor and, in turn, provide heat and losses. Higher frequency harmonics increase the energy of eddy currents.

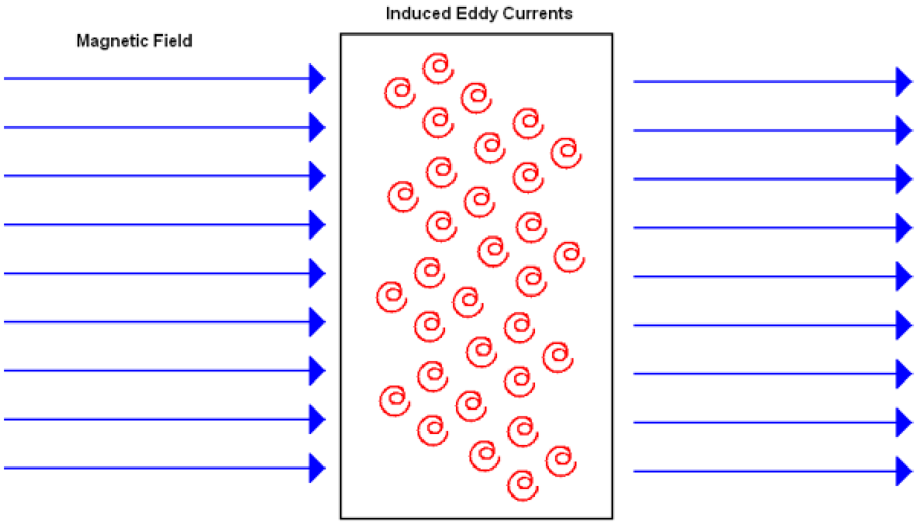


Figure 4-7: eddy currents in the conductor [12]

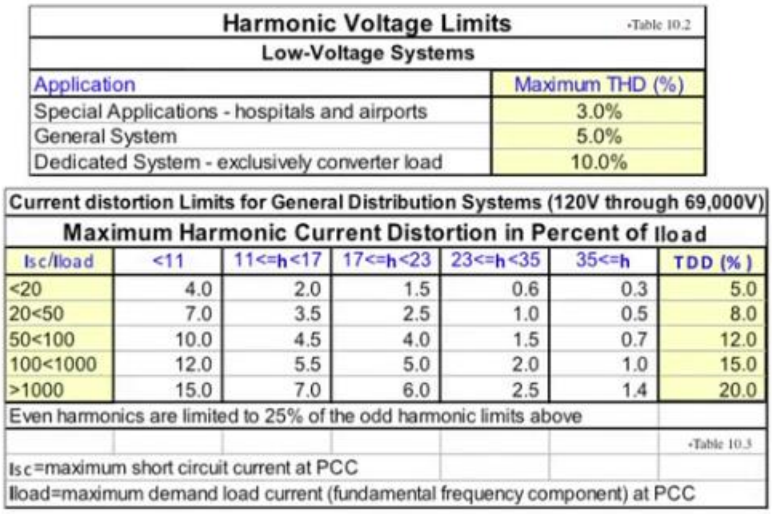
4.1.1 Harmonic measurement

IEC 61000-4-7 deals with harmonic measurement techniques. The measurement interval is 200ms, and at least up to 50th order harmonics are measured. Total harmonics distortion is a single parameter used to quantify the harmonic content in the system. It is obtained by using the equation:

$$THD = \sqrt{\sum_{i=2}^{50} \frac{Q_i^2}{Q_1^2}} \quad (4\text{-}1)$$

As per EN-50160, the acceptable THD limit for a low voltage power supply system is 8%.

Table 4-1: Acceptable limits for harmonics in IEEE519



Harmonic Voltage Limits •Table 10.2

Low-Voltage Systems

Application	Maximum THD (%)
Special Applications - hospitals and airports	3.0%
General System	5.0%
Dedicated System - exclusively converter load	10.0%

Current distortion Limits for General Distribution Systems (120V through 69,000V)

Maximum Harmonic Current Distortion in Percent of Iload

Isc/Iload	<11	11<=h<17	17<=h<23	23<=h<35	35<=h	TDD (%)
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above

•Table 10.3

Isc=maximum short circuit current at PCC

Iload=maximum demand load current (fundamental frequency component) at PCC

4.2 Harmonic analysis by simulation

This chapter applies different scenarios to the designed system, and THD is measured in the simulation environment. Load is entirely resistive, and when the SCR thyristor firing angle is Zero, it is estimated to see no harmonics in the system. Harmonics have arisen when the phase control system runs and triggers SCR with some firing angle.

Some assumption is considered for this system. SCR thyristor is regarded as an ideal thyristor. A constant voltage from the grid side is simulated using a three-phase generator that connects to the Furnace transformer at a 20kv level.

According to the IEC61000-4-7, the maximum harmonics in a low voltage system for a dedicated system that uses a thyristor is 10% and for current harmonic according to short-circuit current of the system, 4% is the maximum acceptable harmonic level. Also, harmonics exist in Voltage and current. Harmonics in current are essential, especially if they flow to the transformer and even in the grid.

4.2.1 Harmonic measurement Case(I)

In this model, SCR always triggers a more than zero firing angle. So, there will be harmonics depending on the firing angle and load condition. The worst situation happens when the heating elements are new, the resistance of the elements has its lowest value and the power supply designed to have 100% reserve voltage has to reduce the Voltage up to 100% by setting the firing angle to some immense value. Figure4-8 shows the result for this condition.

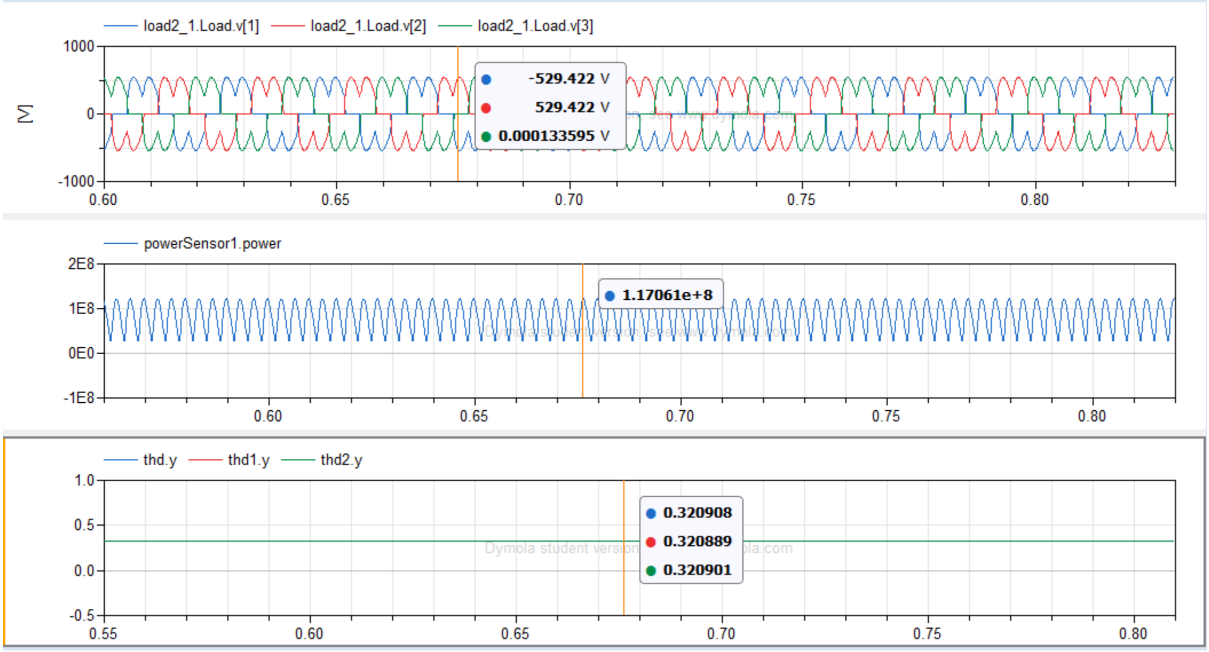


Figure 4-8: Simulation result of case I

As shown from the result, the phase control system is activated from the beginning in full load conditions, and THD is more than 30% in all three phases of the load. If the maximum temperature of the heating elements is met, the firing angle must be increased even more; therefore, THD will increase. Moreover, the high peak voltage and power damage the heating elements. Considering all the points, this cannot be a solution.

4.2.2 Harmonic measurement Case (II)

In this method, a furnace transformer can set the Voltage by its Tap-changer in everyday operation no matter resistance of heating elements has their lowest or highest value. This ability provides the possibility of full load supplying with zero most important firing angle. When heating elements reach their maximum operation temperature, SCR thyristors must reduce the power to keep the temperature constant inside the limited zone. Figure 4-9 shows the simulation result in full load condition.

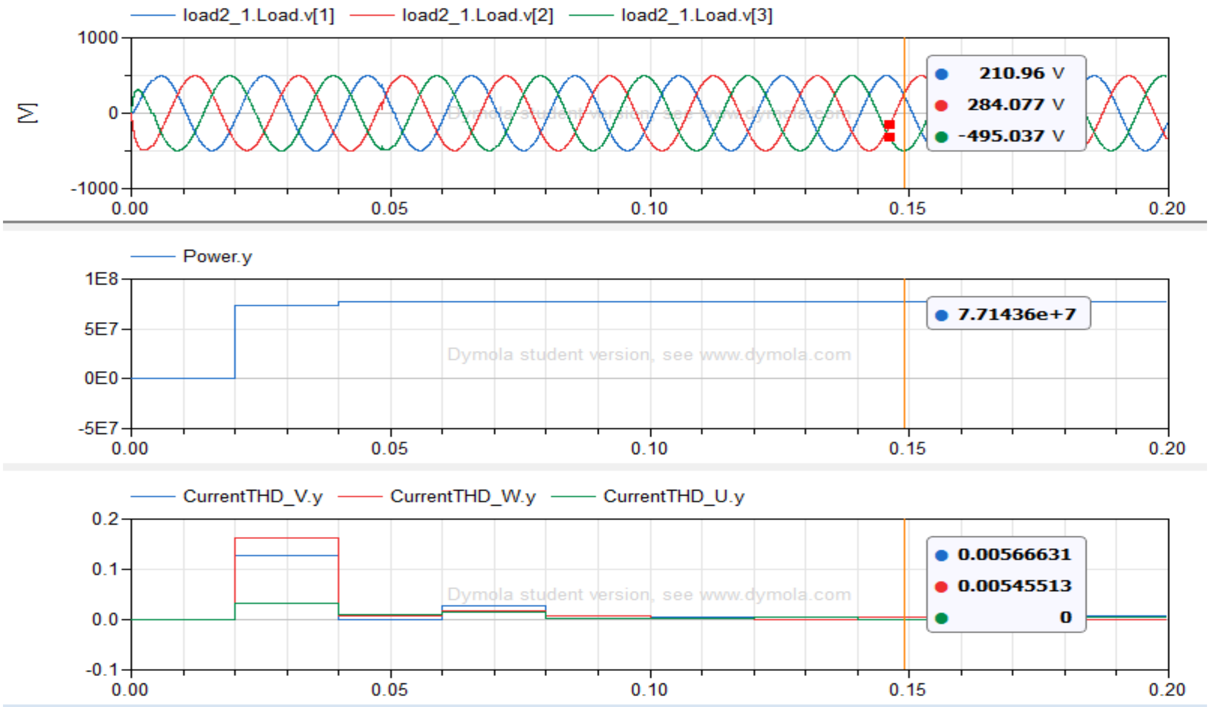


Figure 4-9: simulation result case II

In full load conditions where the firing angle is zero, THD in three phases measured almost zero. This is the best for the power supply. However, some other parameters affect the system, and power must be reduced frequently to keep the temperature in an acceptable zone. These parameters are most related to the calcination process, such as raw meal flow speed and volume and the initial temperature of the raw meal. If all these parameters are kept according to full load design conditions, the power supply continues in full load condition, which is the optimal point of operation. But in reality, that is impossible, the capacity of raw meal and flow rate and speed can be different, and the power supply control system must be able to make up for this variation.

Let's consider power supply has to decrease power in different scenarios and steps such as 5,10,15,20% by triggering SCR thyristors and measuring the THD both in current and Voltage. Table () shows THD levels for these scenarios on both sides of the furnace transformer. Also, harmonics content corresponding to the harmonic order is plotted in the four scenarios.

Table 4-2: THD level in different loading conditions

	THD %			
	Current	Voltage	Current	Voltage
Load	HV	HV	LV	LV
100%	0	0	0	0
95%	5	0	5	17
90%	8	0	8	22
85%	11	0	11	28
80%	13.3	0.3	13.3	31

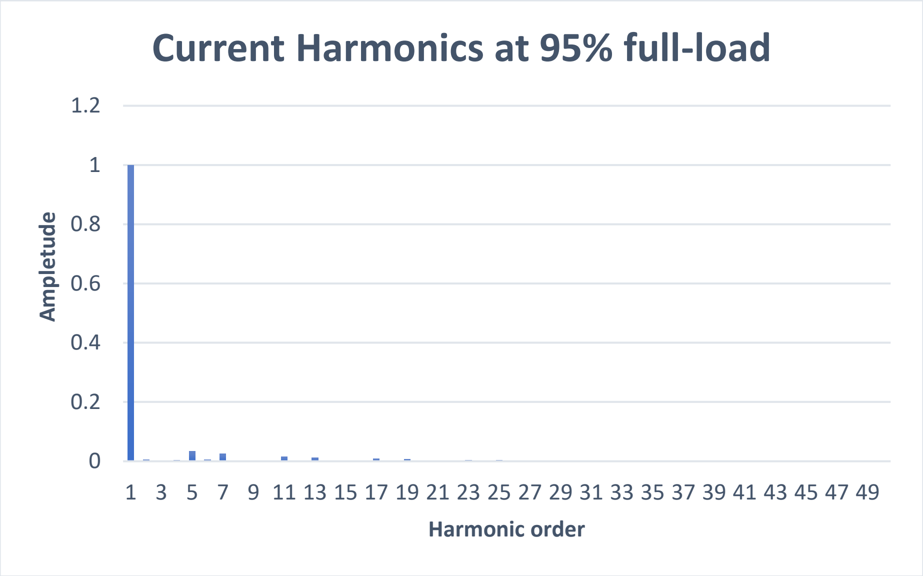


Figure 4-10: Harmonics at firing angle0.17 rad

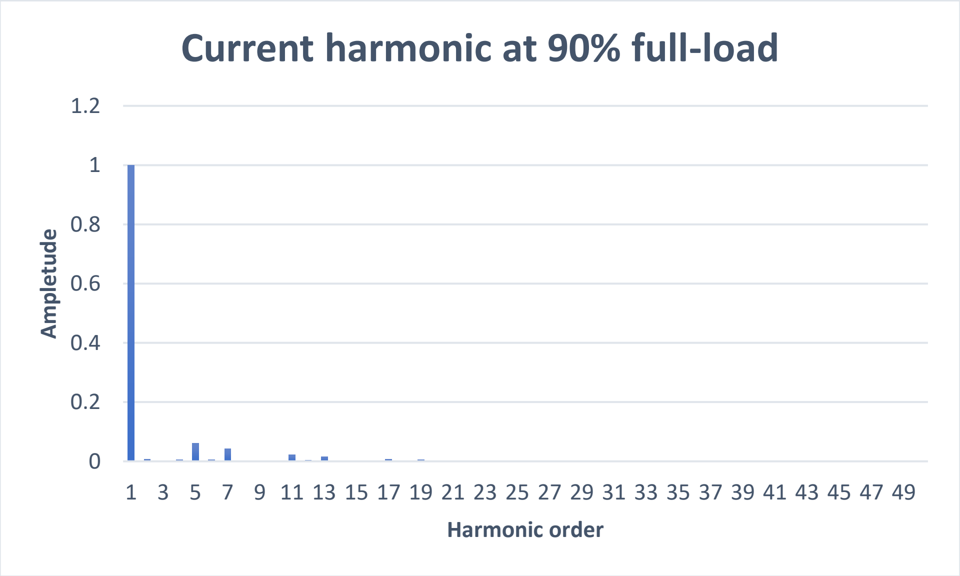


Figure 4-11: Harmonics at firing angle 0.27rad

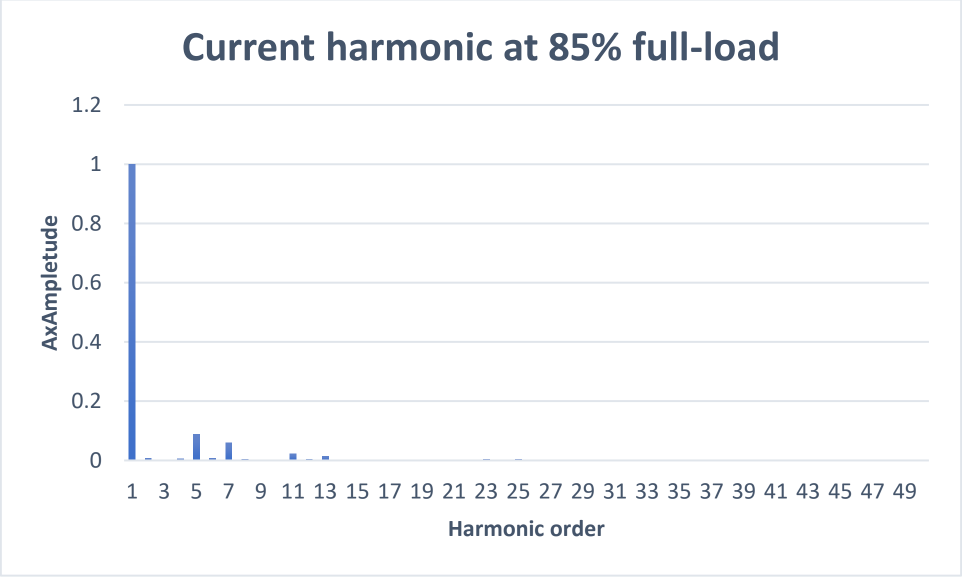


Figure 4-12: Harmonics at firing angle 0.37rad

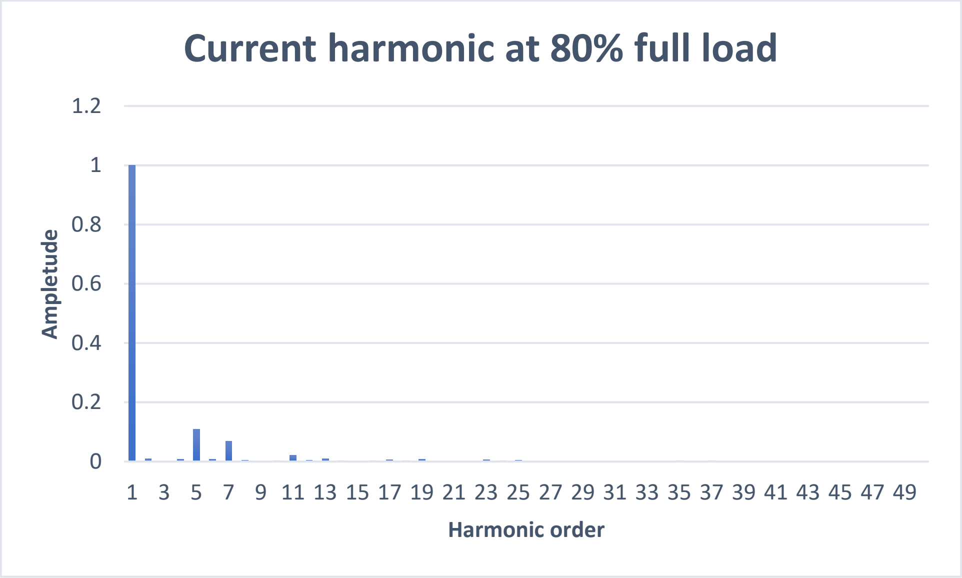


Figure 4-13: Harmonics at firing angle 0.44rad

The results show that Harmonics orders 5th and 7th are high and affect THD in large portions. They also pass the transformer and will impact the transformer and cables.

It is straightforward that there is a direct relationship between firing angle and harmonics.

If the system keeps a slight firing angle on SCR, the harmonics will be small. So, the flexibility of the power supply is essential and the production program. For instance, if the factory runs at 80% production capacity, one load unit can be removed from the system to keep the firing angle zero.

One other scenario is to switch SCR on/off instead of a slight firing angle. In this way, thyristors switch off when the maximum temperature is met. When the temperature reaches the minimum control level, thyristors get on, and current flows through the elements.

Figure4-14shows an example of this method.

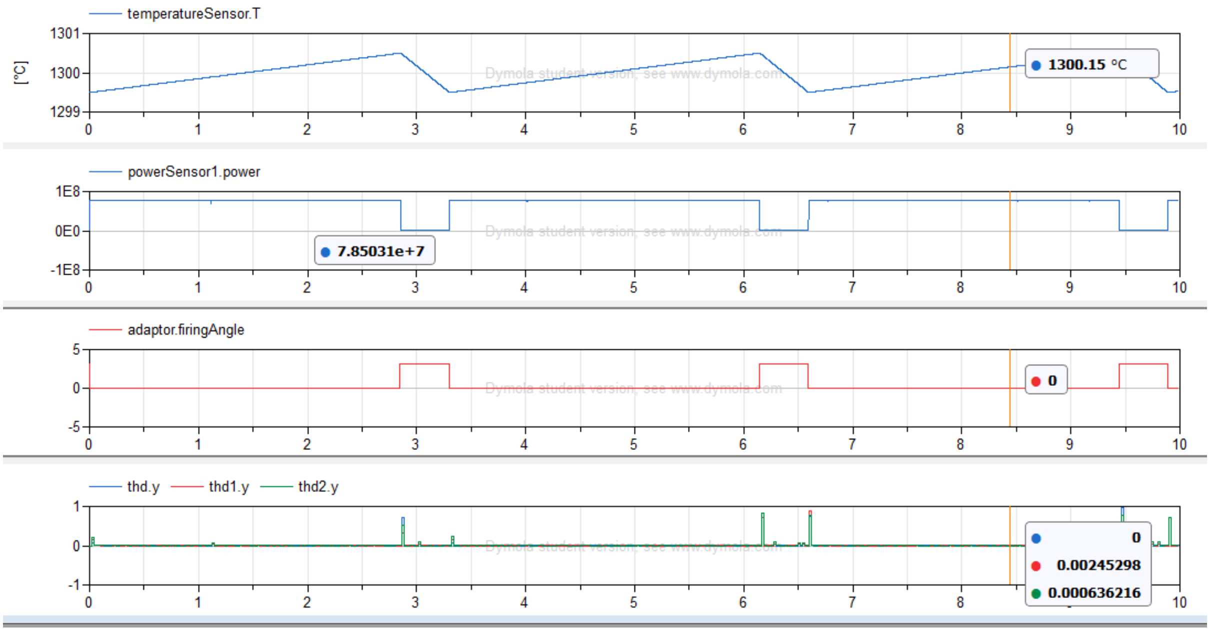


Figure 4-14: on/off method

The result shows no harmonics in the system except for the switching moment. So, it is essential to estimate how much the switching frequency would be if this method is supposed to be used. Switching frequency is dependent on the time constant for heat dissipation in this system. This method may also be applied if the time constant is high enough.

4.3 Harmonics and transformers

In recent years, the use of power electronics in power systems overgrew, such as inverters, converters, phase controllers, etc. initially, this technology increases flexibility and control systems in the field but has some side-effect such as generating harmonics that destroy power quality and therefore impacts power system components such as transformers and cables. This chapter discusses the impact of harmonics on transformers and ways to control them.

Harmonics cause higher r.m.s current, higher peak current and higher frequencies in the power system. Higher r.m.s current will generate more heat and losses in the power system. Higher peak current will cause errors in measurement instruments, and higher frequencies will cause a problem in cables and may cause resonance in the power system.

Here are listed some effects of harmonics on transformers [13]:

- Magnetic core saturation by a change in operating point in a non-linear B-H curve
- Increasing hysteresis and eddy current losses in the core and metallic part which increase the temperature
- Operation with higher audible noise
- Increase in magnetizing current
- Overheating and acceleration in degradation of insulation system oil-paper that shorten the lifetime of the transformer

- Higher ohmic losses due to flowing harmonic current trough transformer
- Reduce the efficiency of the transformer
- Increase in failure risk

Most of the consequences of harmonics on transformers listed above are directly related to the value of current harmonics in the system, which cause higher losses. Losses overheating leads to degradation in the insulation system. Losses in transformers consist of No-load losses plus Load losses.

$$P_T = P_{NL} + P_{LL} \tag{4-2}$$

$$P_{LL} = P_{EC} + P_{OSL} + \mathrm{R}I^2 \tag{4-3}$$

Where:

P_T	-	Total power losses of transformer	[W]
P_{NL}	-	No-load losses of transformer	[W]
P_{LL}	-	Load losses of transformer	[W]
P_{EC}	-	Winding Eddy current losses	[W]
P_{OSL}	-	Other stray losses in the structure of the transformer	[W]
I	-	Current	[A]
R	-	Winding resistance	[Ω]

There is no method to distinguish between eddy current losses and other stray losses. It is common to measure load losses and subtract DC losses ($\mathrm{R}I^2$) from load losses to calculated total stray losses $P_{EC} + P_{OSL}$.

No-load losses are measured by the No-load test at rated frequency and Voltage. These equations are valid for the system without harmonics. When Current harmonics exist in the system, equation(4-2) is invalid. Power losses in new condition is estimated by:

$$P_T = P_{NL} + P_{EC} * \ h^2 + P_{OSL} * h^{0.8} + \mathrm{R}I^2 \tag{4-4}$$

Where h is the order of harmonics, the equation presents direct relation between power losses and harmonics order that increases eddy current losses and stray losses. Any increase in eddy current losses will cause excessive winding losses and overheating. Also, stray losses will heat some metallic parts of the transformer, such as clamps, core, tank, etc., and all will cause an increase in the oil temperature.

4.3.1 How to minimize the effect of harmonics on transformers

There are two main ways for adaption of the transformers with operation in the existence of harmonics:

- Consideration of harmonics in the design stage of transformer in factory
- Derating loading capability of the transformer

In the design process, it is possible to overestimate the size of the core and winding and conductors and cooling system to increase the thermal capability of the transformer in the presence of current harmonics. Analyzing the power system and load condition is vital before the transformer specification for ordering the purchase. K-factor rated transformers withstand the heating effect of harmonic load currents. These transformers are designed for non-linear harmonic generating loads.

IEEE C57.110 provides methods for derating a transformer for non-linear loads that generate harmonics. These transformers are K-factor transformers with additional thermal capacity, allowing operation in non-linear loading conditions. K-factor is applied for the transformer to indicate its suitability for working in the presence of harmonics. The following equation gives K-factor [14]:

$$K - factor = \sum_{h=1}^{h=h_{max}} I_h^2(pu).h^2 \tag{4-5}$$

Where :

h	-	Harmonic order	[-]
h_{max}	-	Maximum harmonic order	[-]
I_h	-	r.m.s value of harmonic current per unit	[A]

The value determines how effectively a transformer can be operated in non-linear loads generating harmonic currents. The value is 1 to 40, and 1 means the transformer can only service linear loads and 40 means that the transformer can service very harsh non-linear loads.

There are some design considerations which is listed:

- The neutral conductor of the transformer is two times oversized compared to ordinary transformers because of third-order harmonics.
- The electrostatic shield might be used between windings and also between winding and core to reduce eddy current losses and heat
- Leads and bushings are larger

- The ferromagnetic core material is less inductive
- Multiple stranded conductors are used in windings to reduce skin effect
- A strong and high-efficiency cooling system is designed
- Multiple smaller conductors are used in the secondary winding of the transformer to reduce the skin effect.

Table 4-3: K-factor for transformer derating [14]

Load type	K-factor
Incandescent lighting (with no solid-state dimmers) Electric resistance heating (with no solid-state heat controls) Motors (without solid-state drives) Control transformers/electromagnetic control devices Motor-generators (without solid-state drives	K-1
Electric-discharge lighting UPS w/optional input filtering Induction heating equipment Welders PLCs and solid-state controls (other than variable speed drives)	K-4
Telecommunications equipment UPS without input filtering Multi-wire receptacle circuits in general care areas of health care, facilities and classrooms of schools, etc. Multi-wire receptacle circuits supplying inspection or testing equipment on an assembly or production line	K-13
Mainframe computer loads Solid-state motor drives (variable speed drives) Multi-wire receptacle circuits in critical care areas and operating/recovery rooms of hospitals	K-20
Multi-wire receptacle circuits in industrial, medical, and educational laboratories. Multi-wire receptacle circuits in commercial office space Small mainframes (mini and micro)	K-30
Other loads were identified as producing very high amounts of harmonics (especially in higher orders)	K-40

So, it is vital to estimate harmonics in the design stage and calculate K-factor for ordering transformer purchases.

But if the transformer was already manufactured, derating is applied for long service conditions.

Even under full load service conditions, power transformers may meet catastrophic fails due to overheating caused by non-sinusoidal current and an increase in eddy losses. To avoid such failures, it is vital to reduce the maximum loading rate of the transformer. In practice, it is called" derating". Derating is a practice to estimate how much reduction in maximum loading capacity of the designed transformer is crucial to keep transformer total power losses less than design value to operate in service for a long time in the presence of harmonics. To achieve this aim, several techniques have been applied last decades. The shared point for all methods is that analysis of the harmonic's spectrum is a must. Industrial transformers typically are loaded much lower than their nominal rating power. So, derating is very affordable and less expensive. European standard introduced an approach to calculate the maximum load capacity in harmonic load current conditions. The expression Factor K is [13]:

$$K - factor = [1 + \frac{e}{1+e} . \left(\frac{I_1}{I_\in}\right)^2 . \sum_{h=2}^{h=h_{max}} [h^q . \left(\frac{I_h}{I_1}\right)]^2] \tag{4-5}$$

Where:

e	-	denotes the ratio of fundamental frequency eddy current losses to DC losses, both at the reference temperature	[-]
q	-	The exponential constant is dependent on the type of winding and frequency. Typical values are 1.7 for transformers with round or rectangular cross-section conductors in both LV and HV windings and 1.5 for those with foil LV winding	[-]
I_h	-	r.m.s value of harmonic current per unit	[A]
I_1	-	the magnitude of the fundamental current	[A]
$I_\in$	-	the magnitude of the total r.m.s load current, including all harmonic components	[A]

Then new loading capability of the transformer is calculated by :

$$S_H = \frac{S_n}{K} \tag{4-6}$$

S_H	-	New loading capacity of the transformer	[KVA]
S_n	-	Rated capacity of the transformer	[KVA]

This derating method is used for oil-immersed transformers.

4.4 Harmonics and vector group of transformers

The non-sinusoidal nature of magnetizing current in three-phase transformers produces sinusoidal flux, which may cause undesirable side effects. Magnetizing current in transformer must contain third harmonics and higher orders to induce sinusoidal flux and Voltage. A Fourier analysis of magnetizing current shows a 60 Hz fundamental and the presence of odd harmonics [24]. The harmonic content of the magnetizing current increases as the level of excitation increases, especially as the core goes into saturation.

To keep phase Voltage sinusoidal for three phases, then phase magnetizing currents in the mathematical form are presented as the following equations

$$I_{Ao} = I_m sin\omega t + I_{3m}\sin(3\omega t + \varphi_3) + I_{5m}\sin(5\omega t + \varphi_5) + \cdots \tag{4-7}$$

$$I_{Bo} = I_m\sin(\omega t - 120) + I_{3m}\sin(3(\omega t - 120) + \varphi_3) + I_{5m}\sin(5(\omega t - 120) + \varphi_5) + \cdots \tag{4-8}$$

$$I_{Bo} = I_m\sin(\omega t - 120) + I_{3m}\sin(3\omega t + \varphi_3) + I_{5m}\sin(5\omega t + 120 + \varphi_5) + \cdots$$

$$I_{Co} = I_m\sin(\omega t + 120) + I_{3m}\sin(3(\omega t + 120) + \varphi_3) + I_{5m}\sin(5(\omega t + 120) + \varphi_5) + \cdots \tag{4-9}$$

$$I_{Co} = I_m\sin(\omega t + 120) + I_{3m}\sin(3\omega t + \varphi_3) + I_{5m}\sin(5\omega t - 120 + \varphi_5) + \cdots$$

It is seen from equations (4-7)to (4-9)that 3rd harmonics are in phase and 5th harmonics have different phases. In other words, due to the nonlinear shape of the B-H curve, odd-harmonic magnetizing currents are required to support sinusoidal induced voltages. If some of the magnetizing current harmonics are not present, the induced voltages cannot be sinusoidal. On the other hand, third harmonics in an electric power system can also cause equipment to overheat and produce voltage distortion. The isolation of third harmonics is an important design consideration in transformers, and some techniques are used to accomplish this issue. Three-phase transformers can be manufactured in different vector groups, and each has some pros and cons regarding harmonic. Four main vector groups are Yy, Dd, Yd and Dy.

4.4.1 Yy connection

In this type of connection, each phase of primary and secondary windings is 120 electrical degrees out of phase with the other two phases. Vectors present it resembles Y in the vector diagram. The common core connects each primary winding to its corresponding phase at the secondary side. In Yy connection, each phase is connected to the neutral point, and it may or not be brought out. Capital Y represents primary winding (HV winding), and the small letter y represents secondary winding (Low Voltage). If the neutral point brought out letter N is added to the expression above, for instance, Ynyn means both neutral points(Neutral bushings) are available. YNy means the neutral point of the primary winding is available, but secondary winding neutral is buried, and vice versa is applied for Yyn.

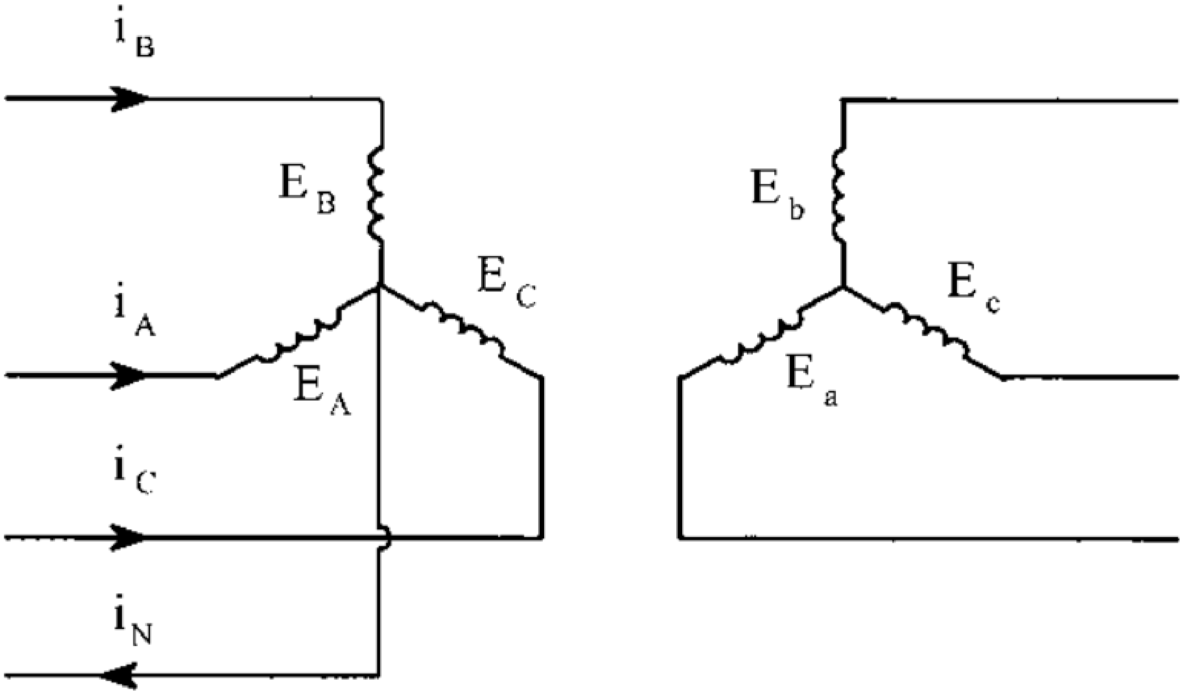


Figure 4-15: YNy Connection with the primary neutral brought out

The magnetizing currents have significant quantities of odd-harmonic components. In the three-phase transformer, the fundamental component of exciting current cancel each other at the neutral point because of 120-degree phase differences between A, B, and C phases, and their sum is zero. But zero-sequence harmonics such as 3rd,6th,9th, and 15th harmonics do not cancel each other and will exist in neutral points. Due to the nonlinear shape of the B-H curve, odd-harmonic magnetizing currents are required to support sinusoidal induced voltages. There is a need for a path to let odd harmonics flow to keep Voltage sinusoidal at terminals. Connecting the neutral of the winding to the ground allows this condition to be met. Suppose the neutrals of both the primary and the secondary are open-circuited, and there is no path for the zero-sequence harmonic currents to flow. In that case, the induced voltages will not be sinusoidal. In figure4-15, it is shown odd harmonics sum up together and create a neutral current i_N Which turns back to the source through the fourth wire, and terminal voltages are sinusoidal. If the neutral point of both sides of the transformer is kept open, even if the primary side voltage is sinusoidal, the secondary voltages will not be sinusoidal. Another problem with a Yy connection is that if an unbalanced phase to-neutral load is connected to the secondary, the load's phase voltages will be unbalanced unless the neutral of the load is connected to the secondary neutral of the transformer[24]. So, it is good practice to have a neutral point of star windings available. There are some advantages and disadvantages regarding Yy connection which are listed here:

Disadvantages:

- Large voltage drops for unbalanced phase-to-neutral loads. phase-to-phase loads cause a voltage drop through the leakage reactance of the transformer, whereas phase-to-neutral loads cause a voltage drop through the magnetizing reactance, which is 100 to 1000 times larger than the leakage reactance
- Series resonance between the third harmonic magnetizing reactance of the transformer and line-to-ground capacitance can result in severe overvoltage
- If a phase-to-ground fault occurs on the primary circuit with the primary neutral grounded, then the phase-to-neutral Voltage on the upfaulted phases increases to 173% of the normal Voltage. This would almost certainly result in overexcitation of the core, with significantly increased magnetizing currents and core losses
- If the primary and secondary neutrals are both brought out, then a phase-to-ground fault on the secondary circuit causes a neutral fault current to flow in the primary circuit. Ground protection relaying in the neutral of the primary circuit may then operate for faults on the secondary circuit

Advantages

- If the neutral point is grounded, the insulation material is reduced
- Phase voltage in star connection id 57.7% line to line voltage, the number of turns in winding is reduced compared to delta connection.
- This configuration makes it possible to construct a more economical and sufficient autotransformer in some applications.

4.4.2 Dy and Yd connection

Delta wye type connection can eliminate some drawbacks of Yy connection. Delta configuration doesn’t have any neutral point and is isolated from the ground and is float.

Figure 4-16 shows the Dyn configuration of a three phases transformer.

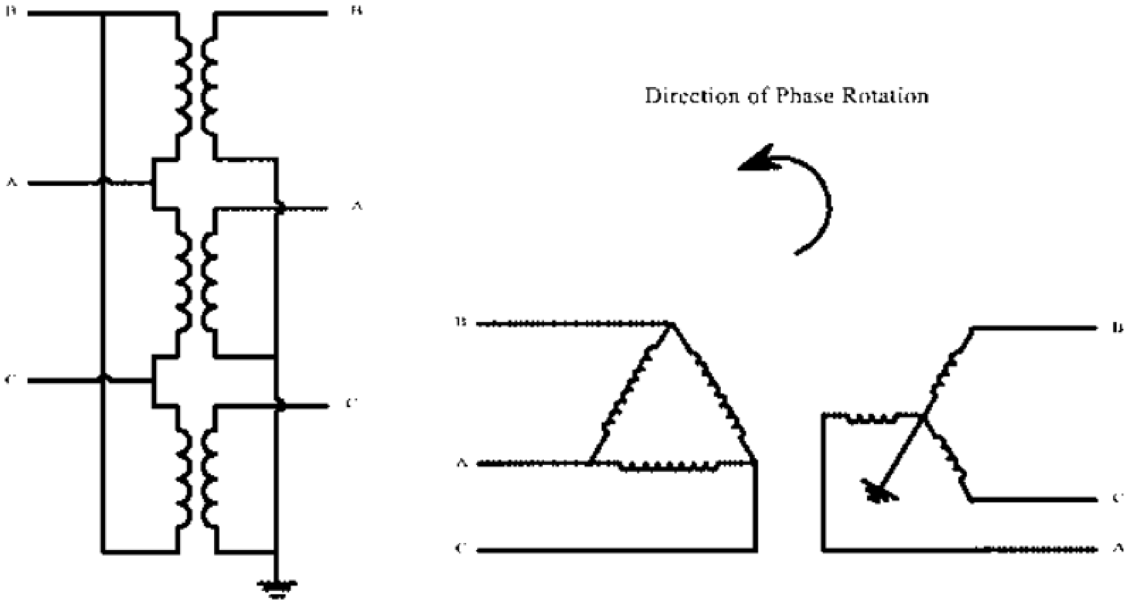


Figure 4-16:Dyn connection

Providing harmonic suppression is one crucial advantage of the Dyn connection transformer.

It is described already that magnetizing current must contain odd harmonics to keep induced Voltage sinusoidal and third harmonics are a dominant component. These third harmonics are in phase in the three-phase system because those are zero sequence currents. In the Ynyn connection, grounded neutral provides a path for the odd harmonics, but in the Dy connection, zero-sequence harmonic currents in delta configuration are equal in amplitude and phase and circulate through the way that Delta winding provides for that.

Moreover, Dyn or YNd connection provides ground current isolation between the primary and secondary circuits. Therefore, if a phase to ground fault event happens on the star side of the transformer connected to the load, it will produce two opposite currents in two phases in the delta circuit, which is float. Nevertheless, compared with the YN yn connection, an unbalanced current in star winding will not affect ground protective relaying applied to the delta circuit. This feature enables proper coordination of protective devices and is a critical design consideration.

The Δ-Y transformer connection is used universally for connecting generators to transmission systems for two significant reasons. First, generators are usually equipped with sensitive ground fault relay protection. The Δ-Y transformer is a source of ground currents for loads and faults on the transmission system. Yet, the generator ground fault protection is wholly isolated from ground currents on the primary side of the transformer. Second, rotating machines can be shaken apart by mechanical forces resulting from zero-sequence currents—the Δ-connected winding blocks zero-sequence currents on the transmission system from the generator.

4.4.3 Dd connection

Delta-delta connection has some advantages and disadvantages, which are listed below

- Dd vector group can be applied for balance and unbalanced load.
- Third harmonics can be buried in delta windings and don't flow to transmission lines, and Voltage at terminals is sinusoidal
- The main disadvantage is the difficulty of phase to ground protection because there is no neutral point in the system.

In conclusion, transformers can only limit or ban the harmonics from flowing from one side to another side, and it is impossible to remove harmonics by the transformer. However, when there are many transformers in the network, it is possible to arrange different vector groups regarding loads and network characteristics to remove some of the harmonics. This method will be explained in the following section.

4.5 Harmonic filter circuits

An effective way to protect electrical components from harmonics is by installing harmonic filters in the power system. The market has two main types of harmonic filters depending on the power, voltage level, and load parameters, including passive harmonic filters and active harmonic filters. Passive harmonic filters are simple in construction, with several passive components such as resistors, inductors and capacitance. Active harmonic filters use active components such as BJTs, IGBTs, MOSFETs and integrated circuits. Harmonic filters are considered safety components of the power system and must be confirmed by international standards [15].

4.5.1 Passive harmonic filters

These are the most common and readily available harmonic filters in the market, and they are affordable. The passive components are used to form a tank circuit. The tank circuit is designed to filter certain harmonic order domains and filter them. They block the unwanted harmonics, convert them to heat, and protect the power system. It can be tuned to a particular domain to block specific order harmonics.

There are four types of passive harmonic filters:

- High pass filter
- Bandpass filter
- C type filter
- Series filter

High pass filter

A high pass filter is used to eliminate high order harmonics, and it provides flexible control over the wide range of frequencies. The primary simple type of high pass filter is constructed of three passive elements resistor, inductor, and capacitance.

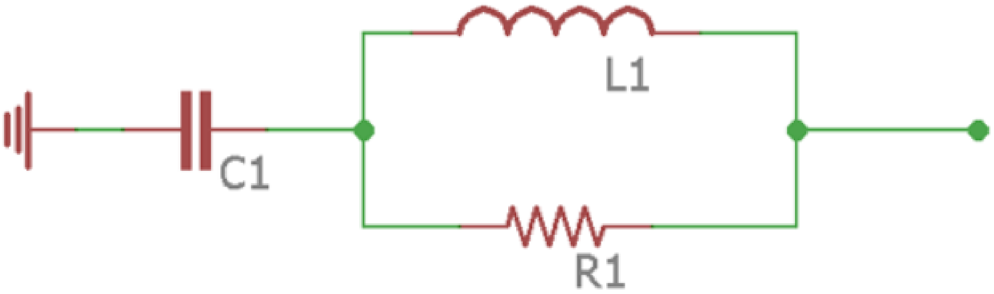


Figure 4-17: High pass filter [15]

The construction diagram shows resistor and inductor are in parallel and both series with a capacitor. This filter produces flat impedance characteristics in the high-frequency domain. It is mainly used for filtering 5th harmonic or higher orders. The impedance curve with the frequency is shown below.

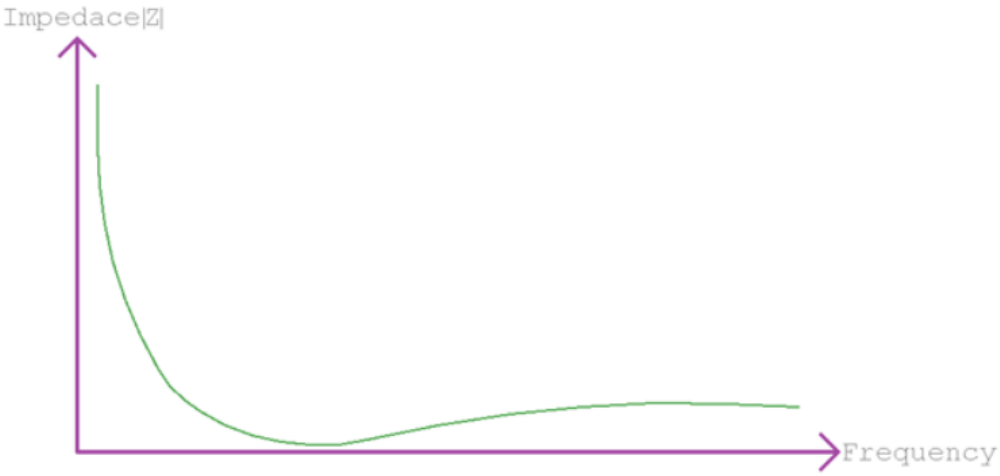


Figure 4-18: Impedance vs frequency of high pass filter

Bandpass filter

Bandpass filter works as a double-tuned filter and is used for high order harmonic filtering purposes.

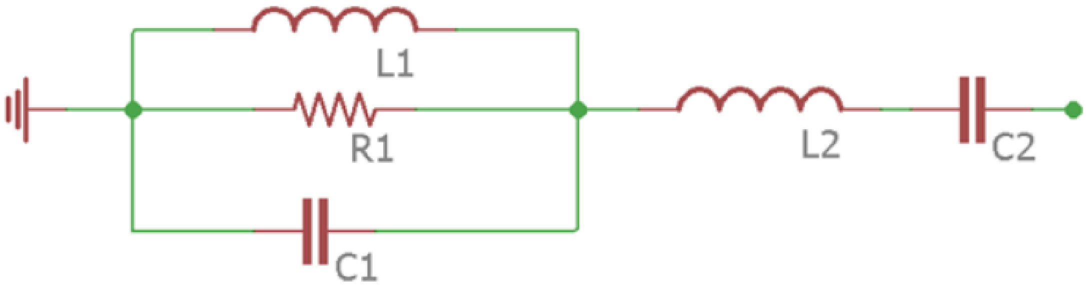


Figure 4-19: Bandpass filter circuit [15]

The impedance curve with the frequency is shown below.

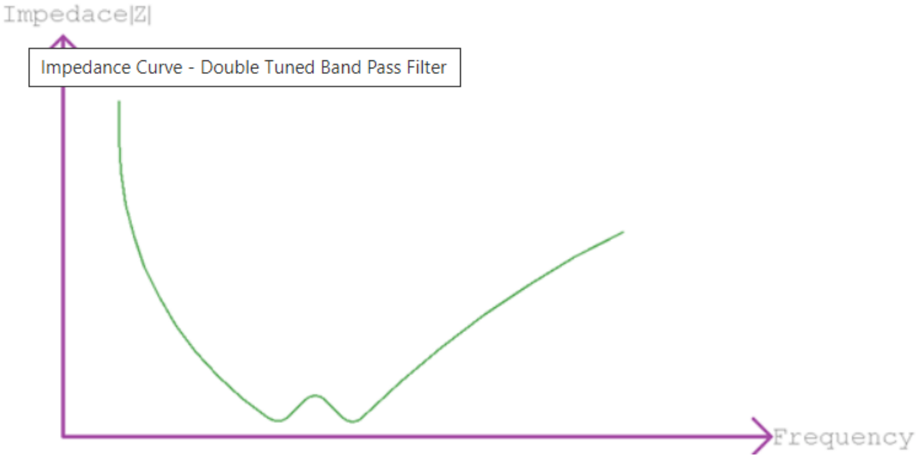


Figure 4-20: The impedance vs frequency [15]

C type filter

Lowe order harmonics, such as third-order harmonics, are eliminated by C type filter. This filter has lower loss over Bandpass and series type filters.

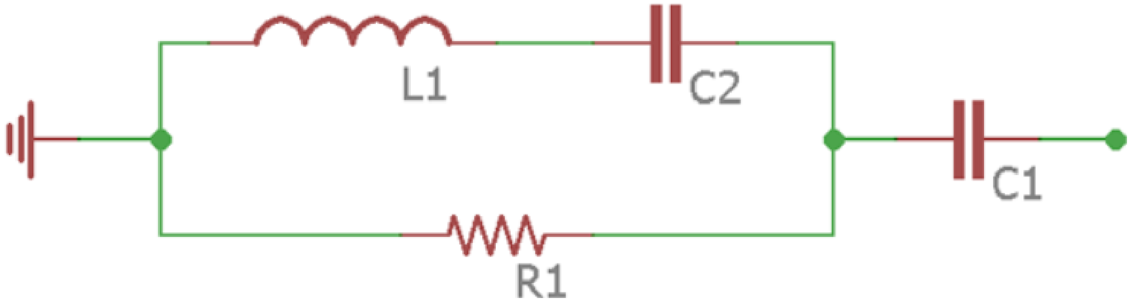


Figure 4-21:C type filter [15]

The resistor surpasses the fundamental current created by the oscillated inductor and capacitor. The impedance characteristic curve is shown below.

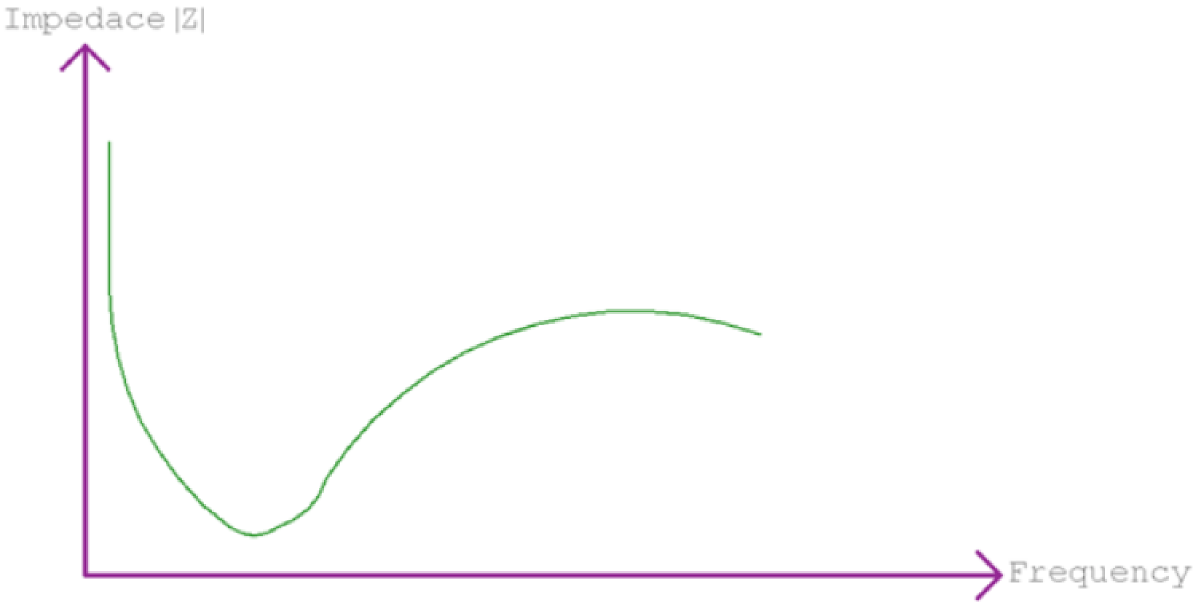


Figure 4-22: impedance characteristic curve of C type filter [15]

Series filter

The series filter eliminates single specific order harmonic in a particular frequency. This filter has the most straightforward construction

Figure 4-23: Series filter [15]

The impedance characteristic is shown below:

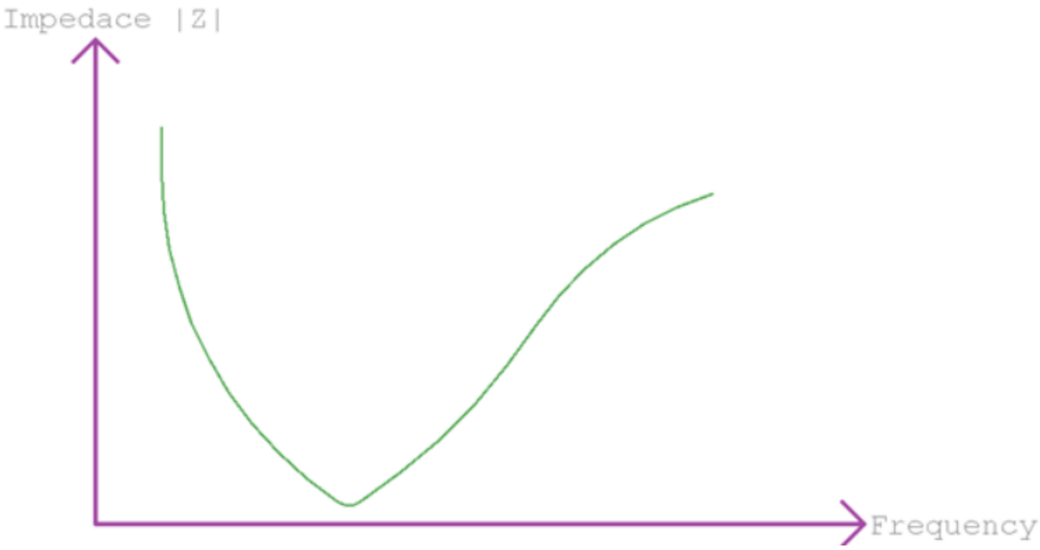


Figure 4-24: Impedance characteristics of a series filter [15]

4.5.2 Active Harmonic Filters

Passive harmonic filters are a good fit for transmission lines. However, the filter design is complicated and needs more load and apparent power information. It also adds poor power factor operation for load conditions. Active filters are much better and handle power line harmonics without reactive power dependency of the fundamental frequency. Active filters produce harmonic components and inject them into the power lines in the opposite direction of the harmonics in the system and cancel them. Different topologies are used, and some common standard methods are listed below

- Voltage source inverters using various power switches
- Sampling and control reference from the power line
- PWM system

Active filters consist of some semiconductors and need the power to operate.

4.6 Harmonic filtering

As it is seen from the harmonics analysis that harmonics orders 5th and 7th are the main orders which SCR in this system produces. To reduce the effect of harmonics, these harmonic orders must be filtered between load and transformer buses. A series filter is a convenient and straightforward filter available in the market and common to apply in power systems.

The current-voltage amplitude in 5th order current harmonic is 9932 A & 325 V.

We need a passive filter that can absorb this harmonic current. The estimated power of the filter is [16]:

$$Q_f = I_h . V_h \tag{4-10}$$

Q_f =9932*325=3.2279 MVar

The impedance of the filter is determined by;

$$X_f = \frac{V^2}{Q_f} \tag{4-11}$$

Or

$$X_f = \qquad |X_c - X_L| \tag{4-12}$$

$$X_f = \frac{352^2}{3227900} = 0.038385\Omega$$

$$X_c = h^2 . X_L \tag{4-13}$$

$$X_c = \frac{X_f . h^2}{h^2 - 1} = \frac{0.038385 * 5^2}{5^2 - 1} = 0.039984\ \Omega$$

$$\mathrm{C} = \frac{1}{2.\pi.f.X_c} \tag{4-14}$$

$$\mathrm{C} = \frac{1}{2.\pi.f.X_c} = \frac{1}{2.\pi.50.0.039984} = 0.079611\ \mathrm{F}$$

$$X_L = \frac{X_C}{h^2} \tag{4-15}$$

$$X_L = \frac{0.039984}{5^2} = 0.0016\ \Omega$$

$$\mathrm{L} = \frac{X_L}{2.\pi.f} \tag{4-16}$$

$$\mathrm{L} = \frac{0.0016}{2.\pi.50} = 5\mathrm{e}{-6}\ \mathrm{H}$$

Where:

X_f	-	Filter reactance at the fundamental frequency	[Ω]
X_L	-	Inductor reactance at the fundamental frequency	[Ω]
X_C	-	Capacitor reactance at the fundamental frequency	[Ω]
I_h	-	the amplitude of the maximum harmonic current in a certain order current	[A]
V_h	-	the magnitude of load voltage at the certain harmonic	[V]
Q_f	-	Filter rated power	[Var]
C	-	Filter capacitance	[F]
L	-	Filter inductance	[H]

f	-	Fundamental frequency	[Hz]
V	-	Maximum load voltage	[V]

After adding this filter to the system, simulation results showed a significant drop in the 5th harmonic. Figure4-25 shows the comparison of the result before and after installing the 5th filter. The blue bars indicate harmonics amplitude before installing the filter, and the orange bars indicate harmonics after installing the 5th filter. The fundamental current is removed from the plot to have a clear resolution of other harmonics.

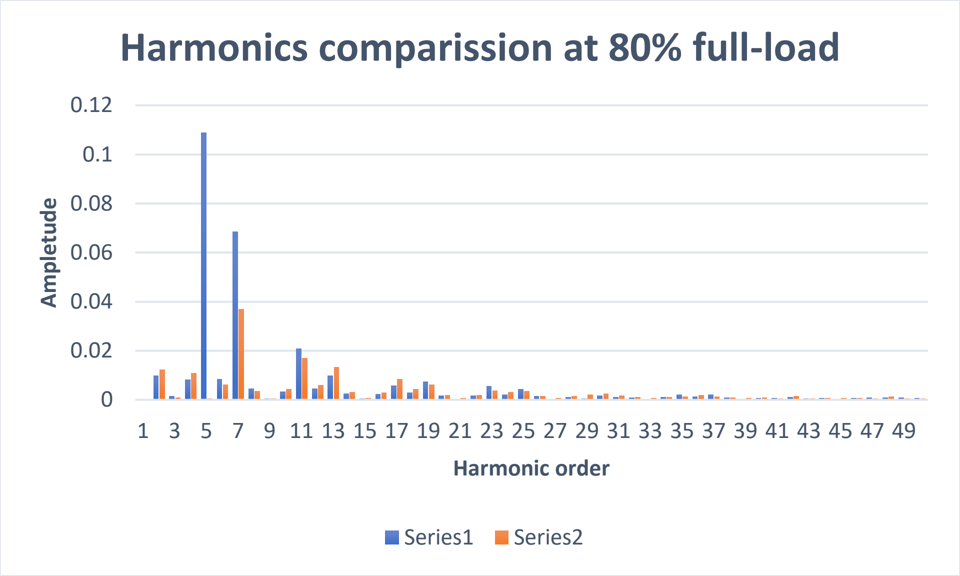


Figure 4-25: After filtering 5th harmonics by passive filter

The table shows the THD in different scenarios after installing the 5th filter.

Table 4-5: THD in different scenarios after installing the 5th filter

	THD %			
	Current	Voltage	Current	Voltage
Load	HV	HV	LV	LV
100%	0	0	0	0
95%	2.1	0	2.1	9.7
90%	3.2	0	3.2	13.7
85%	3.9	0	3.9	15.7
80%	4.6	0	4.6	17.9
75%	5.7	0	5.8	20

The same approach is applied to design 7th order harmonic filter in the system.

$$Q_{f7} = I_{h7}.V_{h7}$$

Q_{f7} = 6153*325=2 Mvar

The impedance of the filter is determined by;

$$X_f = \frac{V^2}{Q_f}$$

Or

$$X_f = |X_c - X_L|$$

$$X_{f7} = \frac{352^2}{2000000} = 0.061952\Omega$$

$$X_c = h^2.X_L$$

$$X_{c7} = \frac{X_f.h^2}{h^2-1} = \frac{0.061952*7^2}{7^2-1} = 0.0632426\ \Omega$$

$$C = \frac{1}{2.\pi.f.X_c} = \frac{1}{2.\pi.50.0.0632426} = 0.05033\ F$$

$$X_L = \frac{X_C}{h^2}$$

$$X_{L7} = \frac{0.0632426}{7^2} = 0.00129\ \Omega$$

$$L = \frac{X_L}{2.\pi.f}$$

$$L = \frac{0.00129}{2.\pi.50} = 4.1e\text{-}6\ H$$

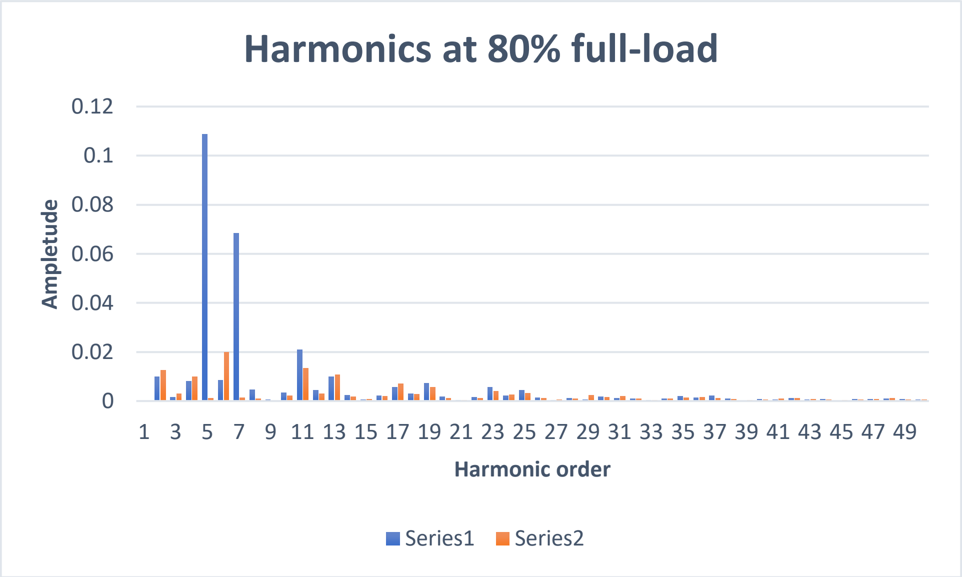


Figure 4-26: Harmonic comparison after installing 5th and 7th order filters

There is a significant reduction in the 7^{th} harmonic after installing the filter. Results show the current harmonic and voltage harmonic in the HV side of the transformer is under limit according to standard. There is a relatively higher voltage harmonics on the LV side of the transformer. Since there is no other use from the LV side of the transformer, it doesn’t cause any trouble. The harmful current harmonics are omitted by installing these filters. Table4-6 shows THD on both sides of the furnace transformer after installing filters.

Table 4-6: THD content on both sides of the furnace transformer

	THD %			
	Current	Voltage	Current	Voltage
Load	HV	HV	LV	LV
100%	0	0	0	0
95%	0.8	0	0.8	6
90%	1.5	0	1.5	9.5
85%	1.8	0	1.8	11.5
80%	2.2	0	2.2	13

4.7 Power factor

Power factor is a term or expression that is related to energy efficiency. It is associated with an AC circuit and power system. It is desirable to have a maximum power factor while consuming AC power since it is related to energy efficiency. PF presents the power factor in power system studies, and the value is between 0 to 1. To understand it well, first, we need to know active power(P), reactive power(Q) and apparent power(S). Different components are used in an AC circuit, such as capacitors, inductors, and resistors. Phasors are rotating vectors with an angular velocity equal to the angular frequency of the power system, used to represent voltage and current in an AC circuit. The type of loads and components in the power system (Capacitive, Inductive, Resistive) changes the phase angle ($\emptyset$) between voltage and current vectors. Consider v(t) as the source voltage in an AC circuit, and i(t) is the current [17].

$$v(t) = v_0 \sin(\omega t) \tag{4-17}$$

$$i(t) = i_0 \sin(\omega t + \emptyset) \tag{4-18}$$

Where:

$\boldsymbol{v_0}$	-	The maximum voltage of the source	[v]
$\boldsymbol{i_0}$	-	The maximum current of the Source	[A]
ω	-	Angular velocity	[rad]

The phase angle of an AC circuit is defined by ($\emptyset$)

The power factor of the circuit is defined as cosine$(\emptyset)$. Therefore, to calculate the power factor of an AC circuit:

$$PF = cos(\emptyset) \tag{4-19}$$

The maximum value is called the unity power factor(PF=1). In a resistive load power factor is unity. It means the phase angle is zero. In a purely inductive load phasor diagram, $(\emptyset)$ is 90 degrees or π/2 rad. It means the current lagging the voltage phasor byπ/2 rad. Therefore power factor of the system is zero. In reality, there is no pure inductive load. The current phasor will lead to the voltage phasor by 90 degrees when the load is purely capacitive. The power factor of the pure capacitive load is also zero. In real systems, the phase angle is less than 90 degrees, and the optimal is to get close to zero degrees which gives maximum power factor and efficiency.

Power factor also is defined in terms of active and reactive power. Active power is denoted by P, and it is the power which is dissipated in the power system and produces valuable work or heat. The unit of power factor is wat(w). Active power is calculated by:

$$\mathrm{P} = \mathrm{V.I.}\cos(\Phi) \tag{4-20}$$

Reactive power moves between the source and load of the circuit. This power doesn’t cause any useful work on the load. Q represents the reactive power, and its unit is Var. this reactive power is always present in the power system, absorbed by transformers and other inductive loads in the system. Electronic loads can produce reactive power. It is essential to keep the reactive power of the power system at an acceptable level to have an efficient system.

$$\mathrm{Q} = \mathrm{V.I.Sin}(\Phi) \tag{4-21}$$

Apparent power is the product of total rms current and rms voltage, neglecting the phase angle. The apparent power is called demand and is expressed as kilovolt ampere (kVA). Apparent power is the amount of power required to run machinery or equipment. But this amount of power given by the source is not entirely used for useful work. Only a part of power is used for useful work called active power. The apparent power is denoted by the letter S. The formula to calculate the apparent power of a circuit is given by:

$$\mathrm{S} = \mathrm{V.I} \tag{4-22}$$

The power factor of an AC circuit can be defined by the ratio of active power to apparent power.

$$\mathrm{PF}=\mathrm{P}/\mathrm{S} \tag{4-23}$$

This relation is shown in a triangle called the power triangle, which describes the relationship between apparent power, reactive power and active power. Figure4-27

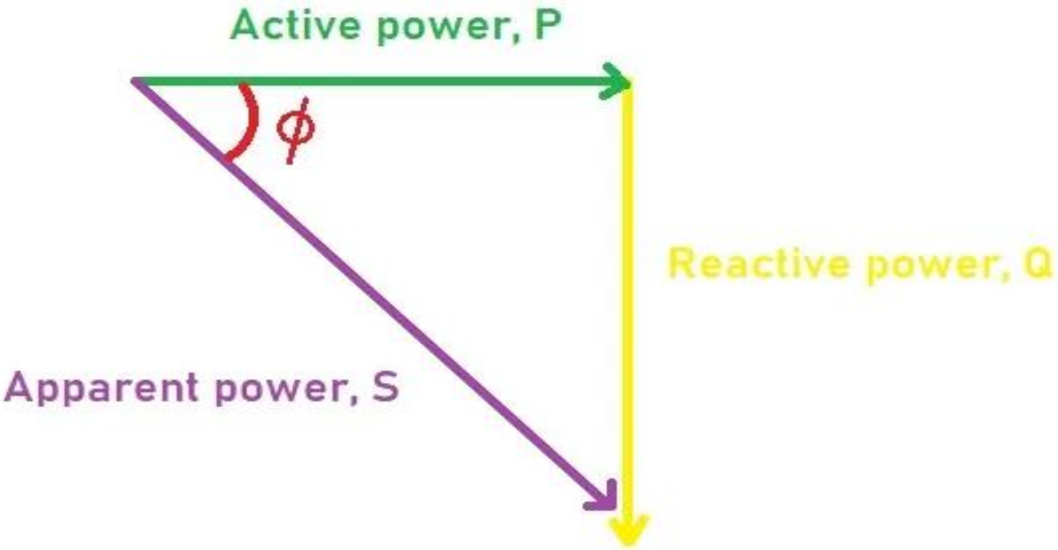


Figure 4-27: Power triangle [18]

Also, equation (4-24) presents this relationship

$$S = P^2 + Q^2 \tag{4-24}$$

It is essential to estimate the power factor of any design in a power system. Therefore, a power factor study is done for the proposed system.

When the system is working on full load condition and firing angle is zero, the power factor is almost unity as shown in the figure4-28.

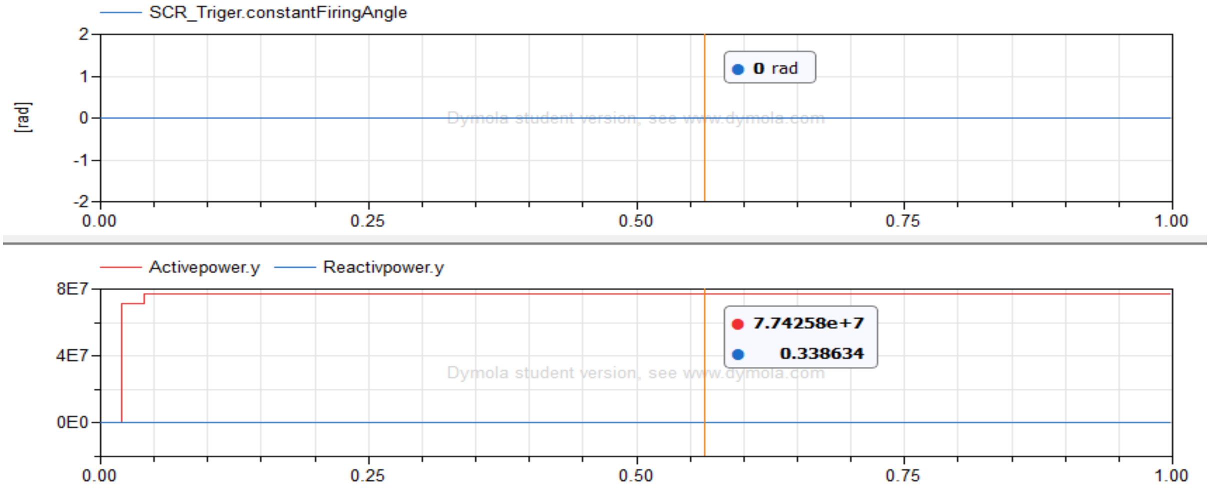


Figure 4-28: active and reactive power in full load

But when the SCR is activated, it produces reactive power as expected. Figure 4-29 shows the simulation result when 80% load is loading.

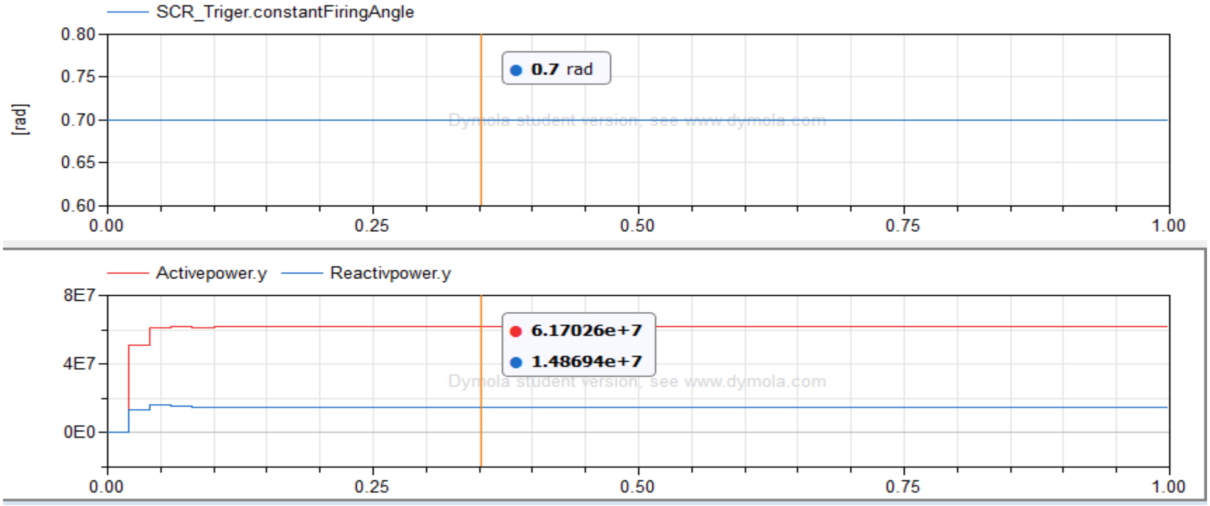


Figure 4-29: Active and reactive power at 80%of load

Power factor is calculated by equations (4-23) and (4-24).

$$S = 61.7^2 + 14.8^2 = 63.45\text{MVA}$$

PF=P/S= 61,7/63.45=0.972

This power factor is measured after installing filters.

5 Grid

5.1 Short-Circuit study

For accurate calculation of the system's short-circuit capacity, short-circuit impedance in the connection point to the grid is needed. The data usually is provided by the local electrical company and applying the exact value will help to estimate the actual short-circuit level. The Actual short-circuit level is generally lower than the theoretical calculation and impacts cost estimation directly. In this study, this data is not available and short-circuit calculation is done in the typical way of using transformer data.

Short-circuit study is done to estimate the fault's current magnitude and results are essential to use for:

- Procure substation equipment rated to withstand
- Determine trip setting for relays
- Perform other studies such as bus calculation and ground grid study

Fault current at the primary side of furnace transformer is obtained by [19]:

$$I_{sc}=\frac{FLA*100}{Z_t\%} \tag{5-1}$$

Where:

I_{sc}	-	short-circuit current	[A]
FLA	-	Full load current	[A]
Z_t	-	Transformer impedance UK%	[%]

Of course, for more accurate results, source impedance must be provided. If the source impedance is available, the equation is changed to:

$$I_{sc}=\frac{FLA*100}{Z_t\%+Z_s\%} \tag{5-2}$$

Where Z_s Is source impedance at the connection point to the grid. Power transformer's typical impedances are around 15% in this power. By this assumption, short-circuit current is estimated using equation (5-2). First, we need to calculate the full load current of the main power transformer, which is supposed to connect to the grid in the substation. A transformer is 100MVA, and the voltage ratio is 230/20KV. Also, cable resistance is ignored.

$$\text{FLA}=\frac{100000}{\sqrt{3}.20} = 2887\text{ A}$$

$$I_{sc}=\frac{2887*100}{15} = 19.25\text{kA}$$

This is the fault current that circuit breakers and cables must withstand between the main transformer and furnace transformer. The fault current will decrease if the source impedance is added to the calculation. Higher the fault current, the higher the cost of the project. So, it is vital to obtain source impedance from the local authority.

5.2 Power transmission by cables

A cable is a conductive path that allows power transmission with minimum power losses between two locations. The local grid delivers power at high voltage to the factory because of the high-power demand(100MVA). The substation inside the factory reduces the voltage level to 20kv. The distance between the substation transformer and furnace transformer is more than 1 km. We use cable to connect two transformers. According to the transmission space, cables can be installed underground, overhead, or together. The overhead line type is cheaper than the underground system. However, running an overhead line system inside the factory might be challenging. In this study, the distance between two transformers is assumed to be 1 km, and the underground system is applied.

5.2.1 Electrical cable sizing

Because of the high current capacity of the load, the Furnace transformer must be installed close to the furnace as much as possible. The estimated distance between the substation and furnace transformers is at least 1km. XLPE cables can be a solution for this power transmission. Overhead line and underground method together may be applied.

First, it is essential to have some data about the power supply capacity, Installation surrounding, loading, Voltage level, Power factor and the selected cable characteristic, such as current carrying capacity and voltage drop per ampere meter. Some expressions used in cable sizing are presented below:

- Current carrying capacity: The current carrying capacity of a cable is the maximum current that can flow continuously through a cable without damaging the cable's insulation and other components. It is sometimes also referred to as the continuous current cable rating.
- Base Current Ratings: International standards and manufacturers of cables will quote base current ratings of different types of cables as several tables. Each of these tables pertains to a specific type of cable construction and a base set of installation conditions. It is important to note that the current ratings are only valid for the quoted types of cables and base installation conditions.
- Installed Current Ratings: When the proposed installation conditions differ from the base conditions, de-rating (or correction) factors can be applied to the base current ratings to obtain the actual installed current ratings. International standards and cable manufacturers will provide de-rating factors for a range of installation conditions, for example, ambient/soil temperature, grouping or bunching of cables, soil thermal resistivity, etc. The installed current rating is calculated by multiplying the base current rating with each de-rating factor.
- Voltage Drop: A cable's conductor can be seen as an impedance, and therefore whenever current flows through a cable, there will be a voltage drop across it, which can be

derived by Ohm's Law (i.e. V = IZ). The voltage drop will depend on the current flow through the cable – the higher the current flow, the higher the voltage drop. And, Impedance of the conductor – the larger the impedance, the higher the voltage drop. The cable impedance is a function of the cable size (cross-sectional area) and the length of the cable. Most cable manufacturers will quote a cable's resistance and reactance in Ω/km.Calculating voltage drops based on the load power factor is commonly used for AC systems. Full load currents are normally used. For a three-phase system

$$\Delta V\ \%(3ph) = \sqrt{3}L.I_{fL}\frac{R\ \cos\emptyset + X\sin\emptyset}{Vn} * 100 \tag{5-3}$$

Where:

ΔV	-	Voltage drop	[%]
I_{fL}	-	Nominal full load current	[A]
X	-	The reactance of the cable	[Ω/km]
φ	-	Load power factor	[pu]
V_n	-	Nominal voltage	[V]
R	-	Resistance of the cable	[Ω]

System Characteristics**:**

- Cabling From: 230/20kV, 100 MVA
- Cabling To: HV side of 20kV Furnace transformer
- Length: approx1000 meters
- Laying configuration: in the air & on a Ladder and buried
- Ambient temperature: 20 °C
- Power factor: 0.9

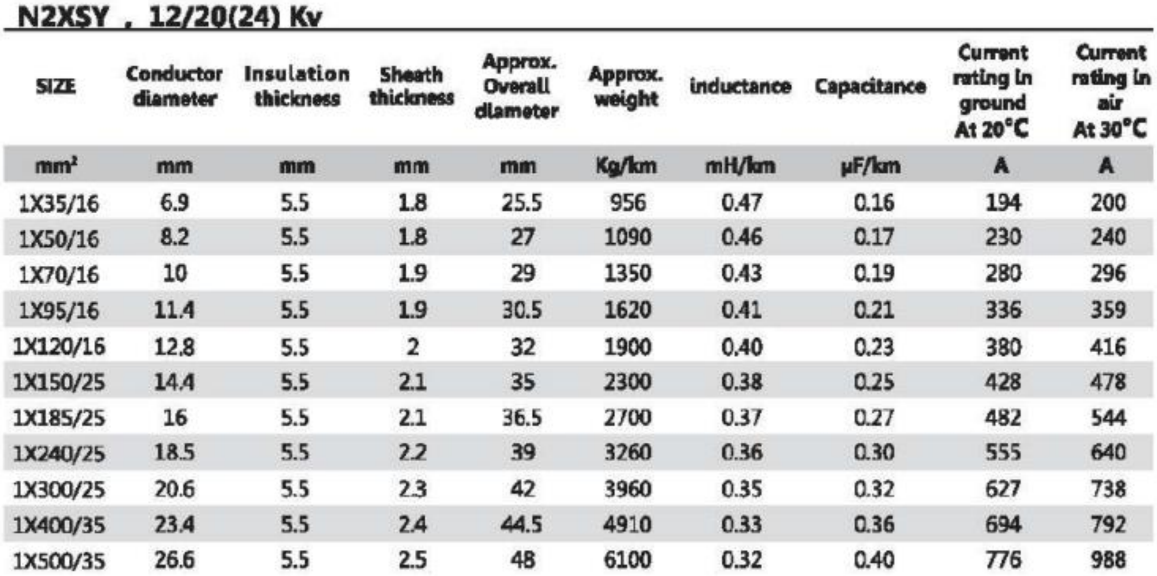
Cable main Construction:

- Conductor material: Copper
- Insulation type: XLPE (Cross-linked polyethene)
- Maximum short-circuit temperature 250°C
- Short-circuit time maximum 1sec

N2XSY XLPE PVC 12/20(24) kv cable is considered to start the calculation. It is a stranded copper conductor and has a semi-conductive material layer with screen copper and sheathed by PVC. Its rating temperature is -20°C to 90 °C [10].

Figure 5-1: XLPE type cable

Table 5-1: electric characteristics of N2XSY XLPE cable [10]



N2XSY , 12/20(24) Kv

SIZE	Conductor diameter	Insulation thickness	Sheath thickness	Approx. Overall diameter	Approx. weight	inductance	Capacitance	Current rating in ground At 20°C	Current rating in air At 30°C
mm²	mm	mm	mm	mm	Kg/km	mH/km	µF/km	A	A
1X35/16	6.9	5.5	1.8	25.5	956	0.47	0.16	194	200
1X50/16	8.2	5.5	1.8	27	1090	0.46	0.17	230	240
1X70/16	10	5.5	1.9	29	1350	0.43	0.19	280	296
1X95/16	11.4	5.5	1.9	30.5	1620	0.41	0.21	336	359
1X120/16	12.8	5.5	2	32	1900	0.40	0.23	380	416
1X150/25	14.4	5.5	2.1	35	2300	0.38	0.25	428	478
1X185/25	16	5.5	2.1	36.5	2700	0.37	0.27	482	544
1X240/25	18.5	5.5	2.2	39	3260	0.36	0.30	555	640
1X300/25	20.6	5.5	2.3	42	3960	0.35	0.32	627	738
1X400/35	23.4	5.5	2.4	44.5	4910	0.33	0.36	694	792
1X500/35	26.6	5.5	2.5	48	6100	0.32	0.40	776	988

Some assumptions regarding the environment surrounding the cables are considered to provide this table:

- The air temperature is 30°C
- The ground temperature is 20°
- Specific ground thermal resistance 1km/W
- Cable laying dept 0.7m to 1.2 mThe cable sizing is based on the following criteria:

Cable sizing steps

- The current carrying capacity of cable after applied derating factors
- Voltage drop calculation in cable within acceptable limit
- Cable short-circuits rating capability

The current-carrying capability of the cable must be larger or equal to the continuous maximum load current. Current carrying capacity is calculated by:

$$I_c = k_0 . k_1 . k_2 . k_3 . I_0 \tag{5-4}$$

Where:

I_c	-	Installed Current carrying capacity of cable at site condition	[A]
k_0	-	Cable derating factor for variation of the surrounding temperature	[-]
k_1	-	Cable derating factor for variation of thermal resistivity of soil in the ground	[-]
k_2	-	Cable derating factor for dept of laying	[-]
k_3	-	Cable derating factor for cable arrangement	[-]
I_0	-	Cable current capability at the typical standard condition	[A]

If the condition is different, then some de-rating factors must be applied.

- Short Circuit Withstand Rating of cables

  The short circuit current withstands the capability to measure the short circuit current a device can tolerate without being damaged when a fault is let through the device. Short-circuit current event has a short quick duration, and the heat losses during short-circuit have no time to transfer and almost entirely dissipate in the main conductor. The cable size must be calculated such as temperature rise during short-circuit event doesn’t cross the permissible limiting temperature, which damages the cable. The capability of the cables or cable short circuit rating to withstand the short circuit current shall be verified by the following formula [20]:

$$I_{sc} = \frac{K.S}{\sqrt{t}} \tag{5-5}$$

Where:

I_{sc}	-	Allowable short-circuit current of given cable size	[KA]
k	-	Insulation material type coefficient of the cable	[-]
S	-	The cross-section area of the cable	$[mm^2]$
t	-	Short-circuit duration	[s]

For copper conductor XLPE cable, K is 143.

If the accurate fault clearing time or short-circuit duration time is not available, recommended fault clearing time in table9-3a/b/cd/e of IEEEStd242 can be used.

The short circuit current calculation is done in the next chapter, estimated at 19.245kA. Protection time is set to 1s. The cross-section of the cable is calculated through the equation(5-5).

$$S \geq \frac{I_{sc}.\sqrt{t}}{k} = \frac{19245*1}{143} = 134.5\ mm^2 \rightarrow 150 mm^2$$

From table 5-1 cable with 150 mm^2 is selected. The number of cables is calculated by:

$$N_c = \frac{I_{fl}}{S} \tag{5-6}$$

$$N_c = \frac{2887}{150} = 6.7 -\!\!\rightarrow 7$$

Seven cables for each phase are estimated. In total, 21 cables are needed to transmit the power from the main transformer to the furnace transformer.

The voltage drop of the proposed system is calculated by using equation (5-3). If the project design hasn't specified any value, a maximum of 2 % for the main feeder cable is considered. To estimate voltage and drop, the impedance of the cables must be calculated using information from the table.

Cable resistance :0.1056 Ω/km

R=1.72e-8.1000/0.0001628=0.1056 Ω/km

Cable inductance: 0.119 Ω/km

X=2.π.f.L→ X=2*3.14*50*0.38e-3=0.119 Ω/km

Since four cables are used, these values are divided by 4 in the equation.

$$\Delta V\ \%(3ph) = \sqrt{3} * 1 * 2887 \frac{0.1056\cos 25.84 + 0.119\sin 25.84}{20000*7} * 100 = 0.52\%$$

The voltage drop between two transformers is almost 0.5% which the main substation transformer tap-changer can regulate.

Depending on the installation condition and cable manufacturer catalogue, this calculation result can differ.

5.3 Study on the impact of skin effect and inductance

The distribution of the AC current over the cross-section surface of a conductor is not uniform. It means the concentration of current density is nearer the outer surface of the conductor than the core of the conductor. More current flows close to the skin of the conductor, which will cause an increase in the effective resistance of the conductor. This phenomenon is called the Skin effect. The main electric current flows through the skin and the level of the diameter of the conductor, which is called the skin depth.

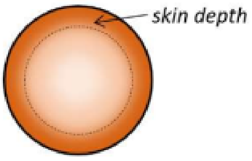


Figure 5-2:Skin effect

5.3.1 Why does the skin effect occur?

Consider a conductor made up of several concentric cylinders. When AC current flows through the conductor, the magnetic flux induces inside it. The linking magnetic flux of cylindrical elements near the center is greater than the elements near the surface. Because both internal and external flux surrounds the inner cylindrical elements while external fluxes only sound the outer elements, this condition will provide more inductive reactance in the inner part of the conductor and less inductive reactance in the outer surface of the conductor. So, the AC current tends to flow near the skin of the conductor. So, the changing magnetic field causes skin effects [21]. The alternating magnetic field induces a skin effect. Skin depth is calculated by:

$$\delta = \sqrt{\frac{2r}{\mu\omega}} \tag{5-7}$$

μ - Permeability of the conductor [H/m]

ω - Angular frequency [rad/s]

r - Resistivity of conductor [Ω-m^2/m]

Some factors impact the skin effect:

- Frequency: Skin effect will increase with the increase in frequency
- Diameter: expanding the diameter of the conductor will improve the skin effect
- Permeability: increasing permeability of the conductor will increase the skin effect
- The shape of conductor: The skin effect is more in solid conductors rather than strands conductors because of the large surface area in the solid conductors.

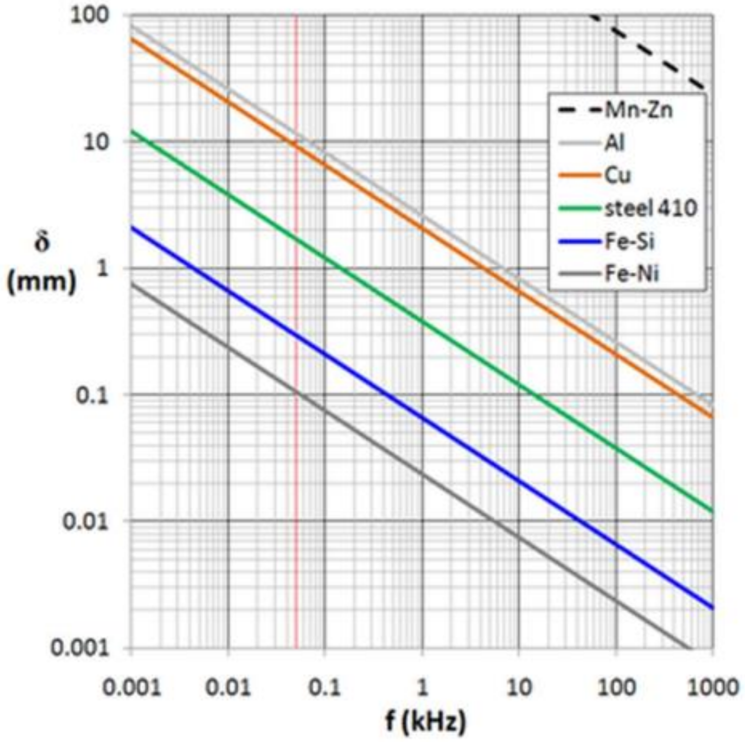


Figure 5-3:Relation between skin depth and frequency in different conductors [21]

Skin effect in the cables considered according to their rating current in production phase by manufacturer.

5.4 Connection to Grid

When a business or industry with a high-power demand is established, and there is not enough power infrastructure, it is the case for building a power substation close to the load. If a remote substation supplies the new load, efficiency is reduced because of high power losses in transmission lines. Higher voltage means lower currents, and low current cause low losses, which is very important in power transmission. A circuit breaker isolates the substation from transmission lines in case any fault event happens.The furnace transformer is designed up to 100 MVA to deliver 77 MW and active power in this project and to withstand overloading and harmonic issues. The factory also has some extra demand, estimated at 10 MVA. In total, 100 MVA or even more power is required. At this level, the routine voltage level for transmission is 230 kv. Therefore, the main substation transformer might be 100MVA,230/20 kv, YNd11.HV side of the transformer is connected to the 230kv bus, which connects the substation to the grid by a circuit breaker. LV side of the transformer connected to 20 kv bus which is disturbance feeder of the factory. One grounding transformer is connected to this bus to determine the phase to ground faults since the LV side of the main transformer is a Delta connection.The furnace transformer is supplied by using cables at 20 kv level from this bus. Also, other demands of the factory can be supplied from this feeder. For different voltage levels, a different distribution transformer is required.Figure 5-4 shows the single line diagram of the proposed system.

Grid

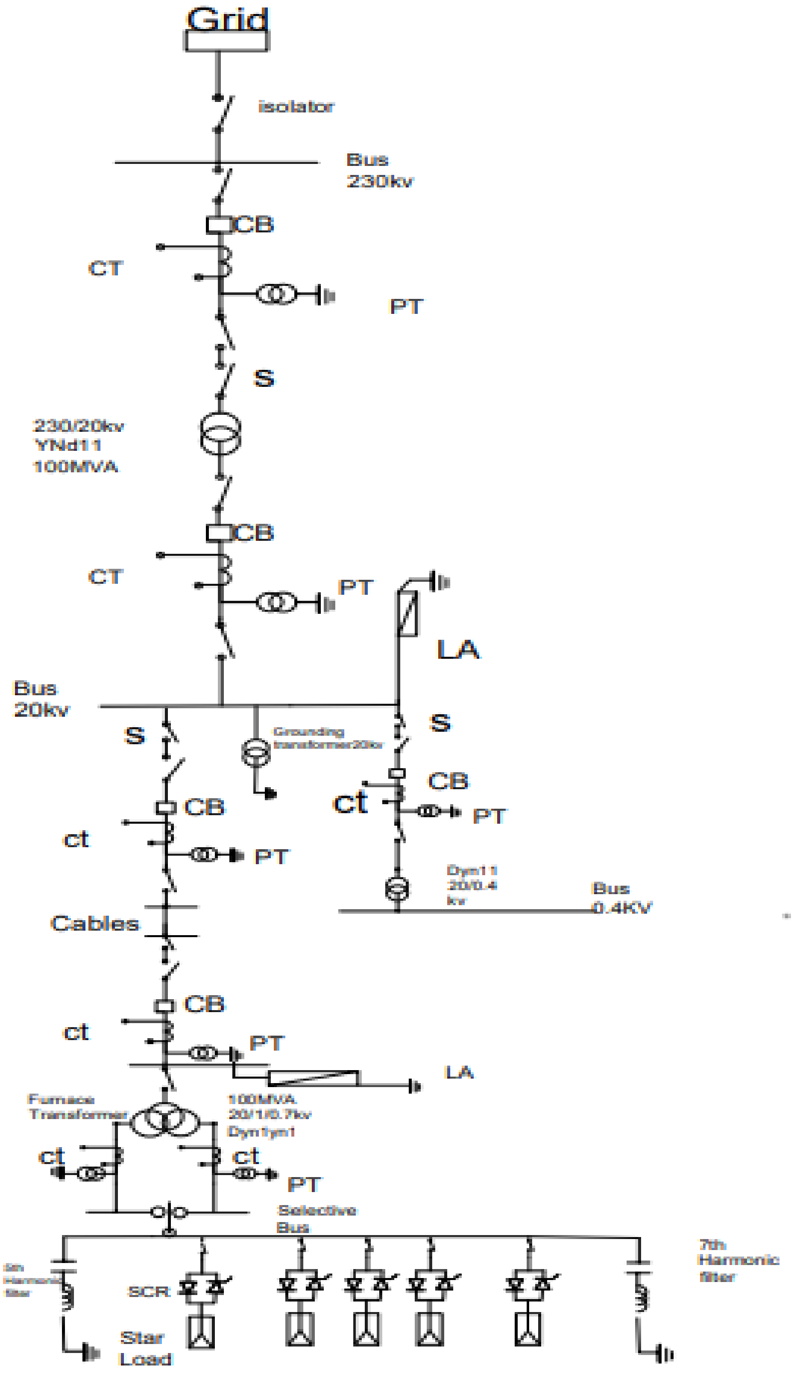


Figure 5-4:SLD of power supply

CB:	Circuit breaker	PT:	Potential transformer
Ct:	Current transformer	S:	Isolator switch
LA:	Lightning arrester	SCR:	Phase control thyristors

6 Risk assessments

Identifying hazards that could negatively impact a business or production process is called risk assessment. These assessment helps determine the severity of the risks and provide measures, process, and controls to reduce the consequence of the risks. Risk assessment can be done differently depending on the type of business and faults. In general, there are five steps [22]:

- Identify the hazards
- Determine who or what can be harmed.
- Evaluation of risk and developing control measures
- Record the findings
- Review and update the risk assessment

Maintenance strategy, condition assessment and technical diagnosis are essential in the power industry and give us valuable data for risk assessment and management. in this chapter, risks from high voltage and high current are studied.

6.1 High voltage and high current

In a live system that is working correctly, there is no harm for anyone if they don't touch the live part of the electrical system. However, all electrical equipment has its lifetime and eventually will fail. This event can harm operators and also has a vast economic consequence.

In the proposed system, insulation breakdown in transformers, cables, heating elements, and busbars may be risky. Breakdowns usually lead to short-circuit events that can damage the system severely. Fortunately, most electrical assets can withstand short-circuit events for a short time, which allows the protection system to shut down the power system to prevent the assets. The protection system in the power industry advanced rapidly, and it is vital. However, it is not 100% efficient, and sometimes the protection system also fails to protect the system because of wrong setting, wrong design, operator mistakes etc. So, the identification of hazards and harms is vital.

Economic risk

Industries highly consider the economic consequence of every design. That is important to know the result of any failure in the system because that makes it possible to provide measures and plans.

Here is a prioritized list of assets and equipment according to their economic consequence:

- Furnace transformer: This asset is the heart of the power supply. If it meets severe failure, production may stop for at least six months to one year. Replacing a transformer is not simple, and it takes a long time to manufacture and deliver.
- Cables: a breakdown in cables also will cause a pause in production. Depending on the transmission system, over-head or underground, repair time can be varied.
- Heating elements: Losing Heating elements will cause an unbalanced load current and reduce the heating system's efficiency.

- SCR/Thyristors: Thyristors act as a switch in the power supply. Any failure in the thyristor will affect the power control system.

The power supply consists of many assets and equipment, and every piece must keep its good working condition to avoid an unpredictable pause in the production system. Condition assessment and planned maintenance are practical solutions to achieve this goal and avoid failures. There are many detailed instructions for diagnosis and condition assessment in related international standards introduced for any electrical asset such as transformers, cables, protection systems etc. The condition assessment and diagnosis aim to predict any weakness in the system and plan maintenance or replacement activity to reduce the risk and economic cost. The insulation system of the assets must be tested according to the maintenance program to monitor the deterioration speed of the insulation system.

Moreover, to increase the system's reliability, some companies provide spare parts and assets to reduce maintenance and repair time according to their product strategy and economic issues. For instance, providing an extra transformer or utilizing two transformers instead of one, increases reliability. When it comes to reliability, it is always expanding the cost. Adding reserve cables to the transmission line is a solution for an emergency condition. Various techniques can be applied beyond basic standard requirements when it comes to protection, which increases reliability.

Safety

Grounding and earthing are very important to increase the safety of operators. Loading current is too high, and it must be isolated well enough not to flow to earth, increasing the voltage in metal bodies and ground. The grounding system must always monitor and feed by conductive materials to keep its low resistivity as much as possible. One protection way is to isolate the calcination metal frame from the rest of the production structures. The furnace body must be adequately earthed, and one measuring instrument should be applied to measure the current flow from the body to the earth to trip the system in case of any current flow.

The voltage of the power supply is not too high and can be isolated by bus-duct between feeder and heating element connection point.

6.2 Dielectric breakdown risks if raw meal particles are present between the heating elements

Initially, the raw material cannot cause any breakdown between heating elements because the raw material is not conductive. Also, the potential energy between heating elements per phase is zero. Suppose the raw material is located between two phases. In that case, the maximum voltage is 1200 V. Inside the furnace, the temperature is too high, and there is no conductive path on the surface of the raw material, such as moisture. However, the raw material can be burned on the surface of the heating elements and form impurities on the surface of the heating elements. This impurity can cause a hot spot and may lead to disconnection of the element at that point.

7 Conclusion

Comparison between AC and DC power resulted in selecting AC power because there is no difference in heating efficiency. Since the cost of DC power supply is higher than AC, the solution is AC. Priority of DC power supply may be less harmonic but needs more investment.

The heating element study showed better efficiency in Sic element regarding Kanthal APM. The main reason is higher wat density and higher operating temperature. The drawback is variations in resistivity of the elements by time in service, which continually increases. So, this needs a 100% voltage reserve. Another drawback is the high cost of the elements and the fact that these elements have to be replaced after a few years. Also replacing new elements with used or failed elements has another issue. The new element’s resistance is lower than the rest of the elements which are in the system, and they might be overloaded. The economic efficiency of the project must be studied more.

Delta and star connection of elements is applicable, and it must be decided on the design stage. The efficiency of both models is equal. The power supply's current and voltage are related to this arrangement, and it is decided as the first step in power supply design.

Using a furnace transformer and SCR/thyristor together is a solution for the project. Three winding transformers are applied to provide reserve voltage and OLTC-Tap changer equipped transformer will make for variation in the resistivity of elements and cause for slight firing angle of the SCR system. A slight SCR firing angle will result in less harmonic.

In full load operation firing angle is zero, and there is no harmonic in the system. To have an optimal operation, it is desirable to provide a zero or minimum firing angle condition.

Therefore, heating elements are divided into five units around 15MW load. The maximum variation of the load is limited to 20%. In case of a more decrease in load, it is possible to switch one unit of the loads, and it helps to reduce firing angle and decrease harmonic.

SCR power control system causes 5th and 7th harmonics. These current harmonics are intended to flow throughout the furnace transformer and cables to the grid. Installing a series filter on the LV side of the furnace transformer absorbs this current harmonic.

XLPE cables do transmission of power to furnace transformer. However, there is a lack of information about the distance between the furnace transformer and the proposed substation location.

There is a need for more research and study about power delivery to the factory and power substation. Also, installing furnace transformer near to calcination process is one of the challenging issues. The size of the transformer is estimated to be 3*7*3 meters and 200 tons in weight.

Thyristors in this study are considered ideal thyristors. For more accurate analysis, actual data is needed.

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