A Study on Reduction of Harmonic Distortion caused by AC Arc Furnaces

Venkata Mani Gadiraju
Louisiana State University and Agricultural and Mechanical College

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A STUDY ON REDUCTION OF HARMONIC DISTORTION CAUSED BY AC ARC FURNACES

A Thesis
Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering

in

The Department of Electrical Engineering

by
Venkata Mani Gadiraju
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ABSTRACT

In AC arc furnaces, arc ignition is stabilized by inductors which are connected across its supply lines. They cause power factor degradation in the system. When furnaces are modelled as linear RL load, the arc nonlinearity reduces the impact of this degradation to a significant extent. Furnace Power factor is improved by the DC voltage on the arc.

In this research study, power factor of AC furnaces is estimated on the assumption that DC voltage on the arc is constant and furnace operates in steady state. Primary objective of this research was to determine the power factor of the furnace in steady state. However, other states of operation such as bidirectional arc and unidirectional arc ignition were also taken into consideration while computing the power factor of the furnace.

Secondary objective of this research was to understand the effects of harmonics on arc furnace and design filter parameters to mitigate the impact of harmonics caused by the transient operation of the furnaces. Random extinction and ignition of individual arc furnaces help reduce current distortion of ultra-high-power ac arc furnaces using resonant harmonic filters. This operation can be conducted in condition of fast varying parameters of the furnace.

On the other hand, this resonant harmonic filter can be built practically only as a constant-parameters device. Filters built on fixed parameters cannot be well coordinated to the furnace. This discrepancy can cause a decline in the filter’s efficacy of harmonics reduction. A reference model using MATLAB was developed to simulate different conditions on the circuit. Also, use of different resonant filters to reduce these harmonics was performed to find the most efficient filter that will increase the efficacy of this process.

This efficiency was investigated, specifically, in a melting mode of an arc furnace operation. A reference arc furnace was used in this study which enabled to draw some qualitative and quantitative conclusions on possibilities of current harmonic reduction at a supply of ultra-high-power furnaces by resonant harmonic filters.
CHAPTER 1. INTRODUCTION

The arc furnaces, whether AC or DC, are high-power systems with power above 750 MVA, and cause maximum load on the distribution system. It is predicted that in future, we can have arc furnaces with power as high as 1GVA. Energy consumption of single arc furnace is approximately 100 GWh. As arc furnaces have high power loads, their power consumption can be compared with power consumption of half a million consumers and therefore, the annual bill of arc furnaces can be estimated as hundred million dollars (Czarnecki and Bhattarai 2016). Hence, their power factor is of prime importance as its degradation contributes to this bill. Moreover, this value is considered as a standard reference point for designing reactive compensators required for the power factor improvement.

Arc furnace operates in three modes, boring mode, melting mode and refining mode. In the refining mode of a furnace operation, when the whole furnace charge is melted and a relatively flat steel surface is created, the arc furnace is at a relatively balanced load. The refining phase is the least distorted phase, since a homogeneous mixture forms in creating a balanced load. All arcs are ignited, and only some asymmetry in electrodes added to the varying length of arcs could contribute to arc imbalance. The power factor still declines in this mode of operation, because there is reactance in the electrodes’ supply lines and arc nonlinearity (Martell et al. 2015).

Melting mode is a relatively random phase where distortion is at maximum as some of the electrodes are not ignited. This phenomenon is observed for half-cycle of period or whole period generating imbalance in the system which creates unbalanced current and reduces power factor. In the melting mode, when the furnace load is distributed randomly and changes position during the melting process, some arcs are found to be not ignited. This phenomenon may apply to the whole- or half-period of the supply voltage. Consequently, the furnace becomes no longer balanced. An unbalanced current occurs in the supply lines which is the main cause of the power factor decline. Once an arc fires over only half of the voltage period, the furnace line current loses its negative symmetry with respect to values shifted by T/2. Thereby, harmonics of the even order, DC component, and the 2nd order harmonic occur in supply lines. Also, when arcs are no longer symmetrical due to arc extinction, the zero sequence harmonics and the 3rd order harmonic have a different value in particular lines. Additionally, these harmonics can accompany the even order harmonics (Martell et al 2015).
1.1 Causes of Harmonics

The waveform distortion of supply current is negligible when the current is to be supplied to a smaller area because the consumption is predictable and the system compensation is easy since it can operate at power factor close to unity. However, when we consider a big city with substantial power load, the nature of power demand becomes random which results in random, distorted, and asymmetric supply current. As a result, the power factor of the system reduces to level of 0.4. This reduction wastes a lot of energy. Since there is current asymmetry and distortion, the arc furnace becomes the source of major disturbances in the system. To reduce this occurrence, arc furnaces are generally equipped with harmonic filters and compensators. They reduce the distortion in the system and improve the power factor \textit{(Czarnecki and Bhattarai 2016)}. \[ \]

The stabilization of arcs in arc furnaces depends solely on the inductors installed in supply lines. Interestingly, the power factor will be extremely low in this furnace operation. For improving the power factor, harmonic filters are installed that act as compensators of reactive power. Generally, these compensators are installed on the primary side of AF transformers because of various technological reasons. In the following Fig.1, the transformer of arc furnace assembly affected by low power factor is described. Further, current harmonics were also generated by furnace arcs. Low power factor coupled with current harmonics can not only lead to increased energy loss in the transformer, but it can also alter transformer power ratings.

\[ \]

Figure 1. A structure of an AC arc furnace with a transformer
Generally, the harmonic distortion as well as power factor of any AF current were evaluated and/or measured on the primary side of furnace transformer. On secondary side, the current harmonic distortion as well as the source of power factor degradation are partially hidden and affected by transformer. Hence, to have specific evaluation of effect of arcs on the power factor, we focused on the secondary side of AF Transformer.

It is understood that while in boring and melting modes of AF operation, arc ignition and extinction are random processes. This randomization is caused by the movement of AF charge and turbulences in arc plasma. Accordingly, the power factor of the AF also changes randomly. Due to this random process, we can eventually specify the arc performance as an electrical load by using some statistical measures. However, we can have a cognitive merit with respect to the knowledge on the state of arc furnaces on the power factor. The Arc Furnace operation can be classified in the following types:

a) Three arcs ignited condition
b) Two arcs ignited condition
c) Two bidirectional arcs ignited condition and
d) Unidirectional arc ignited condition.

With the above different states of AF operation, the power factor value and the furnace current distortion differs substantially. Non-linearity in the electric arc is dependent on two factors namely, the arc plasma resistance $R_p$ on the arc current and the Voltage needed for the arc ignition $U_0$.

Arc current RMS value and plasma space properties are the key factors that influence plasma resistance. Hence, we can presume with respect to a single period $T$ of supply voltage variability, the plasma resistance $R_p$ is a slowly varying parameter of the arc. $U_0$ Voltage needed for arc ignition depends on the distance of electrode from the melted charge of the furnace. With the movement of charge $U_0$ there will be change in voltage which can also change with each period $T$. Based on these facts, we can understand that with ignition of arcs there will be a ground that assumption of parameters of arc furnace do not change over a single period $T$.

In this study, we tried to evaluate power factor of AF, by modeling a steady state furnace in a single period $T$. We considered to investigate three different states of arc furnace namely,
a) With three bidirectional arcs i.e. balanced operation
b) When operated with only two bidirectional arcs and
c) When operated with two bidirectional arcs and one unidirectional arc

We observed that the measure of electric parameters of arc furnace is an uphill task as these are known with very low accuracy especially when they rapidly change during Arc Furnace operation. Modeling the furnace with fixed electric parameters is the innovative idea we adopted in our study. Hence, we can regard the values of the power factor obtained as approximation to true values only. However, with this approach of modeling derives a far approximate information on the change of power factor as well as on the effect of the furnace state.

1.2 Current Methodology

The electrical properties of low-power arc furnaces can be improved using switching compensators like Insulated Gate Bipolar Transistors (IGBT). However, when we are dealing with ultra-power systems, switching compensators are of no use as they are able to compensate the distorted current. Thus, we use reactive compensation.

1.3 Objective and Scope

The objective of this study was to understand the effects of harmonics on Arc Furnace and computation of furnace power factor for which we designed a reference model in MATLAB and simulated different operating conditions of the furnace. Furthermore, we used different resonant filters to reduce these harmonics to determine the best filter to increase the efficiency of the process.

1.4 Report Outline

This thesis report is divided into 5 chapters including this introductory chapter (Chapter 1). It explains the main motivation behind this research and the objective of the study. Chapter 2 provides a literature review report stating the current methods used in the field to overcome the problem. Next, Chapter 3 describes the methodology used to fulfill the objective. Chapter 4 presents the evaluation of data analyses results of all projects. Finally, Chapter 5 summarizes the study and explains the further possible scope of this research.
CHAPTER 2. LITERATURE REVIEW

A detailed literature review was conducted to identify studies dealing with the proposed research objectives and activities. The following section presents summaries of the findings.

2.1 Basic Structure of Arc Furnace

Arc furnace operates in 3 phases: bore down phase, melting phase and refining phase. Various phases of arc furnace result in different effects. In the bore down phase, the scrap is added to the system. In melting phase, the hole in scrap is achieved using charges supplied by electrodes. In this phase, maximum distortion is observed since there is non-linearity in arc. The refining phase which is a liquid phase has homogeneous mixture, and it is the most stable one of all three phases. The rapid change of arc furnace current during different stages of steel making process are highly co-related with arc length variation. This arc length variation in turn depends on scrap material, gases produced during the process, electromagnetic forces & position of electrodes. These produced harmonics can damage the system due to flicker problem. Harmonics may be the reason for losses in the transformer as transformers are frequency sensitive devices. When a transformer dispenses power to an electric arc furnace, it is the only load on that transformer, and no other loads are connected to it. Due to the harmonics, the current actually increases beyond the expected value which may be dangerous for the system (Czarnecki and Bhattarai 2016).

![Figure 2. A simplified structure of an AC arc furnace](image)

Inductors shown in Fig.2 connected in the supply lines for stabilization of arcs. Symbols $u$ and $i$ represents vectors of instantaneous values of the supply voltages and the furnace supply current. Conventionally, power factor improving equipment along with harmonic filters are
installed on the primary side of the furnace transformer. This installation provides with a benefit of reduction in rated current of such device. However, furnace transformer is still subjected to the effects of low power factor and harmonic distortion of arc furnace currents. Hence, the attention of this research is directed on the power factor improvement on the secondary side of the furnace transformer where line inductors are installed. This eliminates an effect of the transformer on the power factor value, especially, harmonics of the zero sequence are trapped in transformer secondary windings; configured usually in delta.

A prediction of the arc furnace’s power factor in this mode of operation is needed for development of equipment needed for the power factor improvement.

The electric arc, specifically inside of the arc furnace cage where its observation and measurements are limited, is an exceptionally complex phenomenon. Moreover, it is affected by several random factors beyond a control of the furnace operator. In effect, arc furnaces regarded as electrical loads can be described only in stochastic terms. It applies to powers, power factor, and current distortion. There are a lot of published reports on stochastic properties of arc furnaces (Agah 2010, Jagiela et al. 2010, Gol et al. 2010, Esfahani and Vahidi 2012).

2.2 Basic Evaluation of Electric Arc Furnace (EAF) Model

Martell et al (2015) in their research tried to analyze the arc furnace after applying the CPC power theory. In the paper, it is concluded that the CPC helps us in calculation of electric parameters. These decompositions of current in CPC helps us to understand the process more thoroughly which enables us to develop control algorithms for efficiency improvement. The following model was studied.

Figure 3. EAF Model
The typical power curves for these three phases – three wire system with time varying and nonlinear loads is seen below.

![Typical Power Curves](image)

Figure 4. Typical Power Curves

### 2.3 Parameters That Affect EAF Operation

Yacine et al. (2013) explained the effect of various parameters that affect arc furnace operation. Some of the parameters that affect EAF are electrode positions, the materials that are used as scrap, short circuit power of the feeder, electrode arm control. These parameters make power, current and voltage non-linear.

### 2.4 Methods of Compensation

In this research study, the LC parameters of reactive balancing compensator were calculated using CPC power theory. To calculate the parameters, the basic circuit without compensation was studied. Using CPC power theory, new parameters were calculated and plugged (figure). However, in the paper, it is concluded that this compensator cannot be directly plugged in the arc furnace as further harmonic study needed to be conducted on the system before plugging (Czarnecki and Bhattarai 2016).
Surapong et al. (2000) discussed minimization of harmonic effects in which the thermal efficiency of arc furnace operation, effects of harmonics, and voltage flickering are discussed. In this paper, the thermal profiles of arc furnace operation are studied to explore the minimization techniques of harmonics.
CHAPTER 3. METHODOLOGY

3.1 Arc Furnace Models

Detailed arc furnace analysis includes development of an equivalent model to evaluate its electrical characteristics. Such a model is a result of an approximation of real properties by simplified ones. Because of this approximation, results are simplified and easier for interpretation. The physical phenomena inside cage of an operating arc furnace are complex; possibilities of their observation and measurement are very limited. Therefore, results obtained from analysis, even simplified models, could have both cognitive and practical merits.

Properties of electric arc are so crucial for the furnace performance, that there were numerous attempts aimed at piercing the random shell of the arc to reach its physical fundamentals (Zheng et al. 1998, Ozgun and Abur 1999, Alonso Donsion 2004). In effect of these investigations, arcs were described by some deterministic models of varying complexity. Regardless, when the furnace currents and powers are calculated, sometimes the arc was approximated even by short-circuit (Suh et al. 2010, Cassie 1939, Mayr 1943, Ravenscroft 1960, Yan et al. 2014, Samet et al. 2015). As shown in Fig. 5, the nonlinearity of the plasma resistance does not have to be ignored.

3.2 A Linear Model

It is evident that the operating of arc furnace and observing its physical phenomena inside the cage is complex. Also, the possibility of measuring the parameters is quite limited. With this understanding, for the arc analysis or modeling an equivalent circuit of the Arc Furnace is to be considered.

The main parameter of such model will be the furnace line resistance $R$. This $R$ is self-possessed of the supply line and the inductor resistance $R_0$, the arc plasma resistance $R_p$ and the resistance of the current path in the steel charge below electrodes, denoted by $R_s$.

Hence, the line resistance is

$$R = R_0 + R_p + R_s.$$  

(1)
Out of the above parameters the plasma resistance \( R_p \) is the most important component of the line resistance \( R \).

Presently, there are two methods available to evaluate the resistance of the arc plasma and they are described in research studies by Cassie (Cassie 1939) and Mayr (Mayr 1943). However, the results obtained by these methods could portray certain inaccuracies. Metrological experiments (Zheng et al. 1998, Suh et al. 2010, Mayr 1943) on arc furnace operation can only specify near credible values with respect to these resistances. Even though the plasma resistance is included in the resistance \( R \), occasionally while calculating furnace current and power values the arc will be estimated even by short-circuit (Suh et al. 2010, Cassie 1939, Mayr 1943, Samet et al. 2015).

![Figure 6. An equivalent circuit of an arc furnace with the arc approximated by a short circuit](image)

To maintain arc current continuity, inductors are connected in the supply lines of arc furnace. These inductors’ resistance \( X \) will be generally observed to be similar with line resistance \( R \). For all practical purposes, reactance generally has a fixed value, whereas line resistance changes with respect to current RMS value. However, the condition cannot be satisfied with some level of control on reactance.

The Fig.6 which represents a linear model of the furnace can be considered as an equivalent circuit of arc furnace. This model will be utilized for the fundamental analysis of performance of Arc Furnace as an electrical load. With respect to inductance value \( L \) when selected such that \( \omega_0 L = R \), then at such approximation point the power factor of Arc Furnace in a balanced mode of operation will be \( \lambda = P/S = 0.71 \). In our study, this value will be utilized later as a reference \( A \). At this juncture, it is necessary to determine whether this value of power factor is lower or higher than the true value of power factor of AF with real nonlinear arcs? Or does the arc nonlinearity reduces inversely with the value of power factor?
3.3 A Basic Nonlinear Model of the Arc

The voltage between electrode and charge has to reach a certain appropriate level for ignition of the arc. Once ignited, the voltage between furnace charge and electrode comprises of AC component which is equal to the product of arc current, DC current, and plasma resistance $R_p$. Interestingly, there will be a minimal decrease in DC voltage with increase in arc current from the constant value, which we denote as $U_0$ (Samet et al. 2015). This decrease is particularly dependent on arc length. To thoroughly analyze this understanding, we have estimated the arc (Zheng and Makram 2000, Hariyanto et al. 2014) as depicted in Fig.7, assuming the constant voltage on arc as $U_0 = 300$ V.

![Figure 7. A circuit (b) that approximates the arc (a)](image)

Thus, the simplified relation between the arc voltage and current are clearly depicted in the equivalent circuit in the above Fig.7. It clearly specifies the salient feature of the relationship between arc voltage and current. However, unless arc voltage reaches an appropriate value the arc cannot be ignited.

3.4 Reference Arc Furnace Model

Studies in this area of research are performed with an intention that derived conclusions could be applicable for ultra-high power furnaces with the consideration that transformer and furnace power properties are comparable. Assumptions in this study include 1) approximating transformer power rating as twice higher than that of the furnace, 2) Transformer secondary voltage rms value was selected as $E=700$V and 3) the ratio of reactance and resistance is $X_s/R_s = 5$.

Modelling of ultra-high power arc furnaces which constitute arc furnace currents of thousands of amperes would be a cumbersome. Hence, analysis and modelling in this study were carried out on a low power furnace regarded as a ‘Reference arc furnace model’, which estimated as a mathematical proportion of an ultra-high power arc furnace parameters.
Referring various studies on arc furnace models (Czarnecki and Ginn 2005) conclude that arc ignition voltage is maintained at $U_0 = 300\text{V}$, and the DC component of the arc voltage remains constant irrespective of fluctuations in the furnace currents. Line resistance $R$ is assumed to be $0.25\ \text{ohms}$. After simulation studies, we observed that furnace operates at a power factor of $0.7$ considering line reactance $X = 1.0\ \Omega$. Results of the modelling are depicted in fig.8.

![Diagram of arc furnace model](image)

Figure 8. The results of modeling of a furnace (operates at the PF $\lambda = 0.71$ in state $s0$)

Waveforms of voltage and current in line ‘R’ are observed in balanced mode of operation, i.e., in state 0.

![Waveforms](image)

Figure 9. Waveforms of voltages, current in line R at furnace balanced operation (state $s0$)

When furnace operates with unidirectional arc, for example line ‘S’ is not ignited, implies furnace operating in State 1. Arcs in this state are connected in series and supplied with line-to-line voltage $e_{RT}$.
When furnaces operates in state S2 alterations in voltages and currents are observed as shown in fig.10.

Ultra-high power AC arc furnaces are observed to be large sources of voltage and current distortion. For convenience in this study, their modelling is carried out on the assumption that they are supplied by sinusoidal symmetrical voltage.

Vector representation of arc furnace line current is presented in *(Nikolaev et al. 2014)* as a sum of harmonics.
\[
\mathbf{i} = \begin{bmatrix} i_R \\ i_S \\ i_T \end{bmatrix} = \sum_{n=0}^{\infty} i_n \approx \begin{bmatrix} I_{R0} \\ I_{S0} \\ I_{T0} \end{bmatrix} + \sqrt{2} \text{Re} \sum_{n \in N} \begin{bmatrix} I_{Rn} \\ I_{Sn} \\ I_{Tn} \end{bmatrix} e^{jn\omega t}
\]

Wherein \( N \) represents the set of current harmonics of order \( n \), including fundamental harmonic \( n = 1 \). Arc Furnace current can be decomposed further into a vector of fundamental harmonic current \( \mathbf{i}_1 \) and a harmonic current \( \mathbf{i}_h \), namely

\[
\mathbf{i} = \mathbf{i}_1 + \mathbf{i}_h.
\]

The current distortion is specified as \( \delta_i \)

\[
\delta_i = \frac{\|\mathbf{i}_h\|}{\|\mathbf{i}_1\|}
\]

Where a vector in double bars \( \|\| \) denotes a three-phase rms value of that vector, defined as

\[
\|\mathbf{a}\| = \sqrt{\|x_R\|^2 + \|x_S\|^2 + \|x_T\|^2}
\]

The results of modeling of the arc furnace under consideration in the states \( s_0, s_1, s_2 \) are compiled in Table 1.
Table 1. Results of arc furnace modeling

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>State 0</th>
<th>State 1</th>
<th>State 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>u</td>
<td>$</td>
<td>V</td>
<td>854</td>
</tr>
<tr>
<td>$</td>
<td>i</td>
<td>$</td>
<td>A</td>
<td>575</td>
</tr>
<tr>
<td>$P$</td>
<td>kW</td>
<td>350</td>
<td>229</td>
<td>302</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>-</td>
<td>0.71</td>
<td>0.58</td>
<td>0.61</td>
</tr>
<tr>
<td>$\delta i$</td>
<td>-</td>
<td>2.2</td>
<td>7.5</td>
<td>40.7</td>
</tr>
<tr>
<td>$</td>
<td>i_0</td>
<td>$</td>
<td>A</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>i_1</td>
<td>$</td>
<td>A</td>
<td>574</td>
</tr>
<tr>
<td>$</td>
<td>i_2</td>
<td>$</td>
<td>A</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>i_3</td>
<td>$</td>
<td>A</td>
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<td>$</td>
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<td>-</td>
</tr>
<tr>
<td>$</td>
<td>i_7</td>
<td>$</td>
<td>A</td>
<td>5.6</td>
</tr>
</tbody>
</table>

3.5 Power Factor ($\lambda$) at a Balanced Mode

During this operation, we can observe that in the equivalent circuit of Arc furnace, DC voltage on the arc is having substantial effect and can’t be ignored due to shifting of plasma resistance $R_p$ from the arc to the line resistance $R$.

If we approximate the arc as above in Fig.6, accordingly the equivalent circuit of the Arc Furnace will have as depicted Fig. 12.

Figure 12. An equivalent circuit of an arc furnace with the arc approximated (ref. Fig. 6)
All arcs are ignited and line currents are continuous at adequately high line inductances \( L \). There will DC voltage \( a_x U_0 \) with coefficient \( a_x = \pm 1 \) (\( x = R, S, T \)), which is totally dependent on the current sign in each line, if \( i_x > 0 \), then \( a_x = 1 \), if \( i_x < 0 \), then \( a_x = -1 \).

If \( G = 1/R \) represents line conductance, then voltage \( v_0 \) of joining point of arc i.e. the melted steel, which has to satisfy for a DC voltage, then the nodal equation will be

\[
v_{A0} = -\frac{Ga_R U_0 + Ga_S U_0 + Ga_T U_0}{3G} = -\frac{1}{3}(a_R + a_S + a_T)U_0.
\]

Thus, in a three-wire system

\[
i_R(t) + i_S(t) + i_T(t) = 0 \quad (7)
\]

Hence, minimum one-line current must be negative which indicates there should be at least one coefficient \( a_x \) as negative i.e. \( a_x = -1 \). If in one period \( T \) each of line currents changes their sign twice, then the voltage at the joining point of arcs will be

\[
v_{A0} = \pm \frac{1}{3}U_0 \quad (8)
\]

And the sign changes occur six times in one period \( T \), as depicted in Fig. 13 below.

![Figure 13. Variation of the voltage at the joining point of arcs](image)

Considering the variation of voltage at the joining point of arcs, the voltage on the arc in line R is
Accordingly, the variation of the voltage \( v_R \) is described below Fig. 6.

Figure 14. Variation of the voltage at the arc in line R

By critical examination, we found that since the arc plasma resistance \( R_p \) is included in the line resistance \( R \), the voltages \( v_R, v_S \) and \( v_T \), as explained above in Fig.4 are not actually the voltage of arc furnace electrodes. Hence, we can presume that these voltages are false values only. Practically, we found that no physical points in furnace that represents such voltage values. However, these fictitious voltages give us a lead to differentiate two main features of arcs nonlinearity, namely,

i) A DC voltage on the arc and

ii) Change in the arc plasma resistance with a change in current value.

Accordingly, there will be two different mechanisms in the arc with respect to release of heat. Thus we can find that the release of energy in the furnace on this resistance is relative to the arc power i.e.

\[
P_p = 3R_p \| i_R \|^2
\]

\[
\text{(10)}
\]

Hence, DC voltage on arcs causes energy release proportional to the active power

\[
P_d = 3 \frac{1}{T} \int_0^T v_R(t) i_R(t) dt
\]

\[
\text{(11)}
\]
Illustration 1:

Generally, with respect to electrical supply perspective the arc furnace assemblies differ with varying furnace power, the power of the furnace transformer, and supply voltage RMS value. If the power built in arc furnaces reaches 750 MVA, then the supply voltage RMS value in furnace varies in the range between 400V to 1300V. In such a condition of high power in the furnace, the transformers can have a power comparable to the power of furnace or a few times higher than the power of furnace.

In our study, we tried to determine more feasible conclusions with respect to the effect of arc nonlinearity on the power factor. In this case, the power of the furnace is not considered for our studies, because it is more convenient to analyze the furnace having relatively low power. Further, it was presumed in our assignment as detailed in Illustration 1, that the line resistance $R = 1 \, \Omega$. The inductor for the arc stabilization has a reactance for the fundamental frequency $X = R = 1 \, \Omega$. Moreover, it was assumed that the furnace is supplied with a transformer on the secondary side with a voltage of RMS value $U = 700 \, V$ as well as the power ratings are two times higher than the apparent power of furnace. Also, the ratio of reactance-to-resistance of the transformer was considered as $X_t/R_s = 5$. Accordingly, the arc furnace with electrical parameters and transformer as considered above is depicted below in Fig.14.

![Diagram of Arc Furnace and Transformer Parameters](image)

Figure 15. Arc furnace and transformer parameters in illustration 1

Accordingly, a computer model was designed as depicted below in Fig.15, and waveforms of internal voltage of supply system were determined with respect to secondary side of operation of transformer $e_R$, the voltage on the supply terminals of the furnace $u_R$, the fictitious voltage $v_R$ and the line current $i_R$. 

18
Figure 16. Waveforms of voltages and currents in line R

We adopted a new discrete approach of calculation in this study as the voltage and currents are non-sinusoidal in the studied circuit. In this approach, we were calculating values of $K$ equidistance samples of the current $i_R$ and the voltage $v_R$. When once we obtained these samples $i_{Rk}$ and $v_{Rk}$, and assuming that $K = 32$, then the active power $P_d$ could be defined by eqn. (11) is equal to,

$$P_d = \frac{3}{T} \int_{0}^{T} v_R(t) i_R(t) dt \approx 3 \frac{1}{K} \sum_{k=0}^{K-1} v_{Rk} i_{Rk} = 198.0 \text{ kW} \quad \text{………………………………………(12)}$$

Here, the current RMS value in line R is

$$\|i_R\| = \sqrt{\frac{1}{T} \int_{0}^{T} i_R^2(t) dt} \approx \sqrt{\frac{1}{K} \sum_{k=0}^{K-1} i_{Rk}^2} = 245.7 \text{ A} \quad \text{………………………………………………………(13)}$$

Accordingly, the active power of the arc furnace resistance is equal to

$$P_r = 3R \|i_R\|^2 = 181.1 \text{ kW} \quad \text{………………………………………………………………………..(14)}$$

It is clearly evident from Fig. 15, that the line current has some level of distortion. Hence, the total harmonic distortion (THD) can be defined as

$$\delta_i = \frac{\|i_h\|}{\|i_i\|} = \sqrt{\sum_{n, n \neq 1}^{\infty} (\frac{I_n}{I_1})^2} \quad \text{………………………………………………………………………..(15)}$$
and, is equal to 2.6%.

During that point of low level of distortion, the apparent power $S$ of the arc furnace is almost equal to the apparent power of the fundamental harmonic $S_1$

$$\approx S_1 = 3U_1I_1$$

Further, the complex RMS (crms) values $U_1$ and $I_1$ of the voltage and current fundamental harmonic in this illustration are

$$U_1 = U_1e^{j\alpha_1} = 578.1e^{-j11.1^\circ} \text{V}, \quad I_1 = I_1e^{j\beta_1} = 245.6e^{-j38.2^\circ} \text{A}$$

Accordingly, the apparent power at fundamental harmonic

$$S_1 = 3U_1I_1 = 425.9 \text{kVA}$$

Approximate power factor of furnace can be estimated by

$$\lambda = \frac{P}{S} \approx \frac{P_r}{S_1} = \frac{P_r + P_d}{S_1} = 0.89$$

Hence, we can safely conclude that in a balanced mode of operation of Arc Furnace the power factor of the furnace is significantly higher than that calculated under assumption stating arc is regarded as a short-circuit. This electrical energy conversion is the net result not only because of DC voltage on the arc but also the current flow through the arc plasma resistance.

3.6 Power Factor at Two Arcs

In this type of operation i.e. boring or melting mode of AF, extinction of one arc only could take place due to furnace charge movement. Based on this, an action may be required from operator to return to balanced mode of operation and to restore the arc. Ignition of arc, again, may be due to lowering the electrode to touch melted steel. Simultaneously, the furnace operates with two arcs only affecting the furnace power and value of power factor. We will try to evaluate the value of power factor under such a mode of operation without igniting arc in line S.

Let us assume that ignited arcs are regarded as short-circuits, as depicted below in Fig. 16.
Figure 17. An equivalent circuit of an arc furnace with two arcs approximated by short-circuit

It is evident from one study (Alonso et al. 2004) that arithmetic and geometric definitions of apparent power results in an erroneous value of power factor when a load is unbalanced. The definition of apparent power $S$ as suggested by Buchholz (Buchholz 1922) should be utilized as an alternative, namely

$$S = \sqrt{U_R^2 + U_S^2 + U_T^2} \sqrt{I_R^2 + I_S^2 + I_T^2} \quad \text{.................................(18)}$$

The power factor of the furnace during two arcs mode of operation can be evaluated by the assumption that the supply voltage is symmetrical.

Hence, it is

$$\lambda = \frac{P}{S} = \frac{2RI_R^2}{\sqrt{3}U_R\sqrt{2}I_R} = \sqrt{3} \frac{R}{U_R} I_R =$$

$$= \sqrt{\frac{2}{3}} \frac{R}{U_R} \frac{\sqrt{3}U_R}{\sqrt{(2R)^2 + (2X)^2}} = \frac{1}{\sqrt{2}} \frac{R}{\sqrt{R^2 + X^2}} \quad \text{.................................(19)}$$

When $X = R$, i.e. the reactance is equal to the line resistance, then the power factor is $\lambda = 0.5$.

Let us consider that the arc is estimated as discussed above instead of considering as short-circuit. Then the arc may be as shown in Fig. 6. The equivalent circuit of the furnace at two arcs mode of operation is depicted in Fig. 18.
Figure 18. An equivalent circuit at two arcs mode operation

The voltage $v_{RT}$ by considering that the line inductance is adequately high to preserve the current continuity, which is equal to

$$v_{RT} = 2a_R U_0 \quad \text{(19)}$$

Since not only the voltage $v_{RT}$ is a fictitious voltage and AF operation is under balanced mode, the arc plasma resistance $R_p$ was moved to line resistance $R$. The variation in the voltage $v_{RT}$ is depicted below in Fig.18.

Thus, the active power is proportional to the energy released on the arcs due to DC voltage present on them.

$$P_a = \frac{1}{T} \int_{0}^{T} v_{RT}(t) i_R(t) \, dt \quad \text{………………………………………………………………………………(20)}$$

Further, the electric energy released in arcs plasma resistance is proportional to

$$P_p = 2 R_p \|i_R\|^2 \quad \text{………………………………………………………………………………(21)}$$

Illustration 2:

With the same parameters as specified in Illustration 1 of an arc furnace and its supply when it is under two arcs mode of operation, the waveforms of voltages and the line R current are as per Fig. 19 depicted below:
Suppose, we assume that $K = 32$, then we have samples $I_{Rk}$ and $V_{RTk}$, and the active power $P_d$ is equal to

$$P_d = \frac{1}{T} \int_0^T V_{RT}(t) \cdot i_R(t) \, dt = \frac{1}{K} \sum_{k=0}^{K-1} V_{RTk} \cdot I_{Rk} = 99.1 \text{ kW}$$

Then the line R current RMS value is equal to

$$\|I_R\| = \sqrt{\frac{1}{T} \int_0^T i_R^2(t) \, dt} \approx \sqrt{\frac{1}{K} \sum_{k=0}^{K-1} i_{Rk}^2} = 188.1 \text{ A}$$

Such that, the active power at the furnace resistance

$$P_I = 2R\|I_R\|^2 = 70.8 \text{ kW}.$$
The line S is not loaded, so that

$$\|u_S\| = 700 \text{ V}$$

While for line T

$$\|u_T\| = \sqrt{\frac{T}{T}} \int_0^T u_T^2(t) \, dt \approx \sqrt{\frac{1}{K} \sum_{k=0}^{K-1} u_{Tk}^2} = 673.3 \text{ V}.$$ 

Here, the formula [22] results with such rms values into the apparent power of furnace during two-arc operation. Then, $S = 298.9 \text{ kVA}$ and accordingly the power factor is equal to

$$\lambda = \frac{P}{S} = \frac{P_r + P_d}{S} = 0.57$$

Thus, we can find that the power factor now derived is higher than the previously derived one. This increase is the result of our consideration of arcs as short-circuits.

Likewise, the DC voltage on the arc does its part to higher value of power factor of AF, as in case of a balanced operation.

### 3.7 Power Factor at Unidirectional arc

Generally, existence of bidirectional arcs is usually common during quiet mode of arc furnace operation. In this mode of operation, we can estimate line currents with more precision by quantities having negative symmetry with respect to the values shifted by half of the period $T$ i.e.

$$x(t-T/2) = -x(t) \…………………………………………………………………………………………………………………(23)$$

These quantities with the above explained property generally do contain harmonics of the even order $n$. In addition to this, third order harmonics cannot occur in the supply current because of three-wire lining with lack of neutral in supply lines and current symmetry. This lack of occurrence results into lower order harmonic as 5th order.

Experiments, measurements performed on arc furnaces (Dionise 2014, White et al. 2010), indicates that the arc current contains harmonics of even order. Furthermore, it is found that the second order current harmonic could reach (White et al. 2010) above the level of 50% of fundamental harmonic. However, we can understand that with the intervals of time when the AF is in unidirectional condition, the validity of equation [23] is not possible.
In this context, per our previous assumption, the AF with one i.e. unidirectional arc for example S with a positive current can be estimated as Fig. 20 depicted below

![Figure 20](image)

Figure 21. An equivalent circuit of an arc furnace with unidirectional arc in line S

The furnace when operated in a balanced load with voltage $v_A$ of the joining point of arcs is depicted in Fig.13. When the current in line S reaches zero that means when the arc in line S is not in ignited condition, then DC voltage at joining point of arcs will be zero since coefficients $a_R$ and $a_T$ have to be of different sign, and accordingly,

$$v_{A0} = - \frac{Ga_RU_0 + Ga_TU_0}{2G} = - \frac{1}{2} (a_R + a_T) U_0 = 0. \quad \text{.................................(24)}$$

Since AC voltage only occurs at this point A during the state of the operation of furnace, the CRMS value of this voltage fundamental harmonic is

$$V_{A1} = \frac{Y_1 E_R + Y_1 E_T}{2Y_1} = \frac{1}{2} (E_R + E_T) = - \frac{1}{2} E_S \quad \text{.................................(25)}$$

Meaning, it changes as $- e_S(t)/2$.

At this voltage the time interval ends while the distribution system interval voltage $e_S(t)$, approaches the summation value of $v_A + U_0$. As a result, the arc in line S is again ignited. The current in line S and the time variance of voltages are depicted in Fig.15.
The changes in voltage $v_A$ of the joining points of arcs are influenced by the state of the arc in one line because it affects other lines too. Especially, when the arc in line S is unidirectional with a positive current, then the changes in the current of the arc in line R are depicted in Fig.23 below:

Figure 22. Waveforms of voltages and current in line S at unidirectional arc

Thus, we can understand that the energy released on arcs due to the DC voltage is proportional to the active power

$$P_d = \frac{1}{T} \int_0^T (v_R i_R + v_S i_S + v_T i_T) dt$$

(26)

While on the arcs plasma resistance

$$P_p = R_p \|\mathbf{i}\|^2$$

(27)

Where

$$\|\mathbf{i}\| = \sqrt{\|i_R\|^2 + \|i_S\|^2 + \|i_T\|^2}$$

(28)
“\(i\)” is the furnace current three-phase RMS value.

Then, the active power of the total resistance \(R\) of the furnace is

\[
P_r = R||i||^2 \\
\]  

………………………………………………………………………………

(29)

So that, the power factor of the furnace is

\[
\lambda = \frac{P}{S} = \frac{P_r + P_d}{||i||||i||} \\
\]  

………………………………………………………………………………(30)

Illustration 3:

With the same parameters of arc furnace and its supply as mentioned in Illustration 1, we have calculated discrete values of particular voltages and currents – quantities that specify the power factor, while assuming \(K = 32\).

\[
P_d \approx \frac{1}{K} \sum_{k=0}^{K-1} [v_{Rk} i_{Rk} + v_{Sk} i_{Sk} + v_{Tk} i_{Tk}] = 152.7 \text{ kW} \\
\]

\[
||i|| \approx \sqrt{\frac{1}{K} \sum_{k=0}^{K-1} [i_{Rk}^2 + i_{Sk}^2 + i_{Tk}^2]} = 361.7 \text{ A} \\
\]

Therefore, \(P_r = R||i||^2 = 130.8 \text{ kW}\)

\[
\text{As} \quad ||i|| \approx \sqrt{\frac{1}{K} \sum_{k=0}^{K-1} [u_{Rk}^2 + u_{Sk}^2 + u_{Tk}^2]} = 1067.5 \text{ V} \\
\]

The power factor at unidirectional arc is approximately equal to

\[
\lambda = \frac{P_r + P_d}{||i||||i||} \approx 0.73 \\
\]

3.8 Resonant Harmonic Filters

Generally, during first cycle of steel production we observed that Furnace operates in the balanced mode i.e., S0. During this operation, line reactance was chosen in a way so as to obtain the power factor as 0.7, which implied that reactive power \(Q\) approximately equals the level of Active Power in \(P\) in the system. Due to the presence of arc nonlinearity, line reactance \(X\) was
selected higher than the furnace resistance $R$ ($X >> R$). For this study, furnace resistance of Reference arc furnace $R$ was chosen as 0.25$\Omega$ and line reactance was selected as 1.0$\Omega$. To obtain $Q=P$ i.e., line reactance was chosen 4 times larger than furnace resistance ($X >> 4R$).

In balanced state of operation, we did not observe substantial distortion of supply current. As we had symmetrical supply during balanced state S0, presence of 3rd order harmonic was not possible due to symmetrical line currents in the system. Hence, 5th order harmonic current was the lowest order harmonic that we could observe. But in State S1, as a result of asymmetry, we observed 3rd order harmonic in the supply current. Drastic increase of furnace current distortion in unidirectional operation was observed i.e. in state S2 and S3 because of DC component and even order harmonics $n=2, 4, 6…$

In literature there is inadequate documentation regarding occurrence of unidirectional arc in the furnace operation. However, occurrence of such a state was quite evident from the presence of even order harmonics in the system, mainly 2nd harmonic. These harmonics, however, could not occur in state S0 or S1.

Switching compensators, traditionally observed as active power filters, are usually built-in with power transistors. These filters, however, have limited switching power capability which further creates a limitation of their usage in mitigating current harmonics in ultra-high power arc furnaces. Hence, we use Resonant Harmonic filters to serve this purpose. These have to be connected permanently to the furnace. There is limited technical means to switch them ON/OFF based on furnace operation states.

Conventional structure of filter connected per phase is as shown,

![Figure 24. A resonant harmonic filter structure](image)
Configuration can be Y/Δ based on operation. However the selected structure of filter impacts the mitigation of harmonics (Zero sequence), filter parameters and also capacitor grounding. However, these were ignored in this study, and for analysis we used Δ configuration. The objective of this study was however focus on effectiveness of RHF in harmonic reduction, and not their design. Hence, single branch filters which were separately tuned to most dominant harmonics 2\textsuperscript{nd} and 5\textsuperscript{th} and their effectiveness were subsequently studied.

Detuning of filters was not required (Czarnecki and Ginn 2005, Czarnecki 1988) for this study as we assumed that the distribution voltage harmonics were quite negligible as compared to that of harmonics generated by the furnace. Hence branches were later tuned to the following frequencies.

\[
\frac{1}{\sqrt{L_n C_n}} = n \omega_1, \quad n = 2, 3, 5. \quad \text{....................................................}(31)
\]

Another assumption (Steeper and Stratford 1976) consisted reactive power \(Q\) of equal amount was compensated by each filter branch. Hence, in a \(K\)-branch filter, a single branch compensated reactive power of \(Q1/ (3K)\). Thus, for \(n\)\textsuperscript{th} order harmonic, Susceptance at fundamental harmonic is computed as

\[
B_{in} U_1^2 = \frac{\omega_1 C_n}{1 - \omega_1^2 L_n C_n} U_1^2 = \frac{1}{3K} Q_1 \quad \text{...............................................}(32)
\]

Therefore, filter parameters are computed as

\[
C_n = \frac{1}{3K} \left(1 - \frac{1}{n^2}\right) \frac{Q_1}{\omega_1 U_1^2} \quad \text{....................................................}(33)
\]

\[
L_n = \frac{1}{n^2 \omega_1^2 C_n} \quad \text{....................................................}(34)
\]

Resistance \(R_n\) in fig 24 indicates equivalent resistance of inductor. It is, however, computed from quality factor \(q\), defined as

\[
q = \frac{\omega_1 L_n}{R_n} \quad \text{....................................................}(35)
\]

For our research and modelling we approximated it as \(q=50\).
At fundamental frequency, Susceptance of RHF is equivalent to capacitance. Reactive current at fundamental harmonic was compensated by this capacitance. Hence, it improved power factor of the system.

State S0 occupied the highest time interval of arc furnace operation. As a result of this, arc stability power factor of furnace remained 0.7. Filters parameters could be chosen in a way that power factor during balanced mode of operation was improved to almost unity. In this case, however filter operated as a compensator to reduce the reactive current because harmonics generated by furnace currents were at a lower degree that did not impact supply current.

Crucial branches of RHF were tuned to the most dominating harmonics 2\textsuperscript{nd} and 3\textsuperscript{rd} order. Entire filter branches must be tuned to 5\textsuperscript{th} and 7\textsuperscript{th} order but their contribution to the problem was minimal. Hence, they were ignored for our studies.
CHAPTER 4. RESULTS AND DISCUSSIONS

Three-phase rms values $|\mathbf{i}_{\text{rms}}|$ of the Currents’ Physical Components of the supply current of the reference arc furnace, with parameters shown in Fig. 13, in situations as assumed in Illustrations 1, 2 and 3, are compiled in Table 2.

Table 2. Three-phase rms values of the supply current physical components

<table>
<thead>
<tr>
<th>Illustration:</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\mathbf{i}_{a1}</td>
<td>$ A</td>
<td>378.9</td>
</tr>
<tr>
<td>$</td>
<td>\mathbf{i}_{r1}</td>
<td>$ A</td>
<td>193.1</td>
</tr>
<tr>
<td>$</td>
<td>\mathbf{i}_{u1}</td>
<td>$ A</td>
<td>0</td>
</tr>
<tr>
<td>$</td>
<td>\mathbf{i}_{G}</td>
<td>$ A</td>
<td>7.1</td>
</tr>
<tr>
<td>$P_1$ kW</td>
<td>380.3</td>
<td>170.4</td>
<td>287.1</td>
</tr>
<tr>
<td>$P_G$ kW</td>
<td>0.01</td>
<td>0.05</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Results compiled in this Table show that at the balanced operation of a furnace the reactive current is the main cause of the power factor degradation. At two arcs operation of a furnace, the unbalanced current is the main cause of this degradation, while at operation with unidirectional arcs this degradation is mainly caused by current harmonics generated in the arc furnace.

Apart from a change in the unbalanced current $i_{u1}$ rms value, the modes of a furnace operation differ substantially with the harmonic content of the furnace current. Three-phase rms values of the supply current harmonics, up to order $n = 7$, in situations as assumed in Illustrations 1, 2 and 3, are compiled in Table 3.

Table 3. Three-phase rms values of the arc furnace current harmonics

| Illustration | $|\mathbf{i}_0|$ | $|\mathbf{i}_1|$ | $|\mathbf{i}_2|$ | $|\mathbf{i}_3|$ | $|\mathbf{i}_4|$ | $|\mathbf{i}_5|$ | $|\mathbf{i}_6|$ | $|\mathbf{i}_7|$ |
|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|              | A               | A               | A               | A               | A               | A               | A               | A               |
| 1            | -               | 425             | -               | -               | 11.0            | -               | 4.6             | -               |
| 2            | -               | 266             | -               | 25.5            | -               | 9.0             | -               | 4.6             |
| 3            | 151             | 363             | 55.8            | 9.4             | 19.4            | 6.4             | 5.3             | 2.9             |
It should be noticed that a dc current which occurs at unidirectional arcs cannot be transformed to the primary side of the transformer, but it can saturate its core. This saturation in turn can cause additional distortion of the transformer primary side current.

Single RHF connected permanently to the furnace tuned to 2nd order harmonic affects furnace supply as shown in Table 4.

Table 4. Results of modeling with RHF tuned to 2nd order harmonic

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>s0</th>
<th>s1</th>
<th>s2</th>
</tr>
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<tbody>
<tr>
<td>$</td>
<td>u</td>
<td>_0$</td>
<td>V</td>
<td>1083</td>
</tr>
<tr>
<td>$</td>
<td>i</td>
<td>_0$</td>
<td>A</td>
<td>518</td>
</tr>
<tr>
<td>$P$</td>
<td>kW</td>
<td>560</td>
<td>316</td>
<td>540</td>
</tr>
<tr>
<td>Q1</td>
<td>kvar</td>
<td>0</td>
<td>-964</td>
<td>-232</td>
</tr>
<tr>
<td>$\lambda$</td>
<td></td>
<td>0.999</td>
<td>0.21</td>
<td>0.65</td>
</tr>
<tr>
<td>$\delta$</td>
<td>%</td>
<td>0</td>
<td>0</td>
<td>77</td>
</tr>
<tr>
<td>$</td>
<td>i</td>
<td>_1$</td>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>$</td>
<td>i</td>
<td>_2$</td>
<td>A</td>
<td>518</td>
</tr>
<tr>
<td>$</td>
<td>i</td>
<td>_3$</td>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>$</td>
<td>i</td>
<td>_4$</td>
<td>A</td>
<td>0</td>
</tr>
<tr>
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<td>i</td>
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<td>0</td>
</tr>
<tr>
<td>$</td>
<td>i</td>
<td>_7$</td>
<td>A</td>
<td>0</td>
</tr>
<tr>
<td>$</td>
<td>i</td>
<td>_8$</td>
<td>A</td>
<td>0</td>
</tr>
</tbody>
</table>

The supply current three phase RMS value $|i|$ in state S0 is reduced by the filter. Thereby, we observe increase in the voltage of furnace terminals. Hence, the active power. i.e. an increase in the energy delivery, thereby reduces melting time. Supply current in this state does not have harmonics. In state S1, where only one arc is ignited, both 2nd order harmonics and all other harmonics are reduced. This is explained by the low pass filtering characteristics exhibited by RHF along with transformer Inductance. A drastic increase of RMS value of current is observed. This is caused by furnace overcompensation as a result power factor drops to a significantly low value.

Filter branches tuned to 3rd order harmonics effects parameters as shown in the table:
Table 5. Results and Modelling of RHF tuned with 3rd order harmonic

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
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<th>s1</th>
<th>s2</th>
</tr>
</thead>
<tbody>
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<td>V</td>
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<td>1162</td>
<td>1237</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>517</td>
<td>933</td>
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</tr>
<tr>
<td>P</td>
<td>kW</td>
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<td>541</td>
</tr>
<tr>
<td>$Q_1$</td>
<td>kvar</td>
<td>0</td>
<td>−977</td>
<td>−213s</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>-</td>
<td>0.999</td>
<td>0.21</td>
<td>0.65</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>%</td>
<td>0.6</td>
<td>0</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>414</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>516</td>
<td>933</td>
<td>524</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>2.7</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>1.7</td>
<td>0</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 6. Results of modelling when two Filters are tuned to 2nd and 3rd order harmonics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>s0</th>
<th>s1</th>
<th>s2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V</td>
<td>1091</td>
<td>1664</td>
<td>1228</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>518</td>
<td>941</td>
<td>666</td>
</tr>
<tr>
<td>P</td>
<td>kW</td>
<td>564</td>
<td>294</td>
<td>536</td>
</tr>
<tr>
<td>$Q_1$</td>
<td>kvar</td>
<td>0</td>
<td>−988</td>
<td>−988</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>-</td>
<td>0.999</td>
<td>0.19</td>
<td>0.65</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>%</td>
<td>0.86</td>
<td>0.4</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>412</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>518</td>
<td>934</td>
<td>527</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0</td>
<td>0.5</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0</td>
<td>0.4</td>
<td>0.1</td>
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<td></td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>5.3</td>
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<td>A</td>
<td>3.7</td>
<td>3.0</td>
<td>2.8</td>
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<td>A</td>
<td>0</td>
<td>0</td>
<td>2.7</td>
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<tr>
<td></td>
<td>A</td>
<td>2.2</td>
<td>1.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Filter branches of two filters tuned to 2nd and 3rd order harmonics are compiled above. Results shown above demonstrates the problem of overcompensation in the furnace operating states S1 and S2. However, one should notice that all the studies that carried out apply for the steady state operation of the furnace. Alteration in the furnace states of operation causes transients. These are beyond the scope of this research. As an illustration, consider transient in line R when filters are tuned to 2nd and 3rd order harmonics when furnace switches to state S0 as depicted below.

![Figure 25. Current and voltages in line R](image)

For parameters computed in this study, transients are considered to occur over a time period of approximately 5 periods of T.
CHAPTER 5. CONCLUSIONS AND FUTURE SCOPE

This study emphasized on electric energy decomposition into two phenomena namely, 1) heat dissipated in arc plasma because of its resistance and 2) presence of DC voltage on the arc. Increase in the power factor as well as active power can be attributed mainly due to the DC voltage on the arc. This attribution is, however, attenuated by the reactive power.

Arc furnace modelling was based on approximation that furnace parameters remains constant over a single time period T. Hence, they remain fixed in all states of operation. Based on time intervals of random duration, states can alter randomly or remain constant. However, we observed transients when furnace operation states were altered. On the other hand, power factor and powers computed varied randomly. Presented studies can give us a rough estimate of currents’ RMS values and harmonics in each designated states of furnace operation.

Over-compensation in the furnace was observed to have caused in state s1 and s2 by connection of Resonant Harmonic Filters directly to furnace terminals. Substantial increase in the voltage of furnace terminals was caused by over-compensation and furnace transformer had high inductance when furnace operated at ultra-high power. Also, a huge increase in the DC component in states S2 were observed. Therefore, over-compensation of RHF should be handled by any means of adaptive compensation strategies to maximize the benefits of such a filter installations.
REFERENCES


Ozgun O. and A. Abur. (1999). Development of an arc furnace model for power quality studies. DOI: 0-7803-5569-5/$10 C IEEE.


Three Phase Arc Furnace Model
Vr and Ir of R-Phase in Balanced mode of Arc furnace operation
Vs and Is of S-Phase in Balanced mode of Arc Furnace Operation
Vt and It of T-Phase in Balanced mode of Arc Furnace Operation
Vr and Ir of R-Phase in Two-Arc Mode of Arc furnace operation
Vs and Is of S-Phase in Two-Arc Mode of Arc furnace operation
Vt and It of T-Phase in Two-Arc Mode of Arc furnace operation
Vr and Ir of R-Phase in Uni-directional-Arc Mode of Arc furnace operation
Vs and Is of S-Phase in Uni-directional-Arc Mode of Arc furnace operation
Vt and It of T-Phase in Uni-directional-Arc Mode of Arc furnace operation
VITA

Venkata Gadiraju was born in June 1992 in Bapatla, Guntur, India. Gadiraju has been resident of the beautiful city widely known as “The city of destiny” Visakhapatnam located in the Andhra Pradshesh state of India. He received his Bachelor of Science degree in Electrical and Electronics Engineering (B. Tech EEE) from Vignan’s Institute of Information Technology, Visakhapatnam in May 2013. Gadiraju then received his Post Graduate Diploma Degree from NPTI-PSTI-Bangalore, and worked as a Jr. Electrical Engineer in Elpro International Ltd. in Pune, India.

He then joined Louisiana State University, Baton Rouge in The United States of America to pursue his master’s degree in Electrical Engineering in the spring semester of 2016. Gadiraju expects to receive the degree of Master of Science in Electrical Engineering (MSEE) in Fall 2018.