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Arc Furnace Power Quality Compensation Using SVC: A case study in IRAN

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***Abstract*—Due to increased demand of electrical energy and also importance of power quality in distribution system, the reactive power and power quality compensation is needed in today power systems. Reactive power can cause abnormality in power quality which may harm sensitive loads.**

One of the most harmful equipment in distribution system is arc furnace. This device widely used in melting steels. They need huge amount of reactive power and also cause approximately all of power quality disturbances like harmonics, flicker, unbalancy, transients, sag, swell. Therefor compensating both reactive power and power quality is very important in distribution system contains arc furnace. One of the most common and effective devices for this aim is using Static Var Compensators (SVC).

In this paper design of elements and control strategy for a SVC which is used in a real steel factory in IRAN is proposed to compensate both reactive power and power quality simultaneously. Simulation results in PSCAD/EMTDC and experimental results are compared and show the effectiveness of the method.

Keywords: Power Quality, Reactive power, Arc furnace, Distribution system, harmonics

I. Introduction

Nowadays, using electric power in steel and metal casting industry is so prevalent that the energy needed for melting and maintaining molten material temperature is provided by electric power through diverse approaches. Arc furnace is utilized for melting and refining metal pieces. Thanks to nature of arc and sudden fluctuations in active and reactive power with relatively high amplitude, power quality problems for the grid, steel producers and other users are made. Flicker, harmonic problems and voltage imbalance is such problems [1], [2], [3]. with the purpose of efficient use of electric power in arc furnace used in steel factories, some problems must be solved especially maintaining voltage, correcting power factor and harmonic filtering issues. Maintaining voltage improves arc furnace performance significantly. This improvement either increases maximum power and consequently the production of steel or provides furnace with an ability to decrease the arc length at the same power and consequently voltage flicker will be decreased. Methods used for maintaining voltage includes connecting furnace to a grid with higher voltage, using synchronous condensers and high-speed modern compensators of thyristor-controlled reactor type and saturable reactor. Connecting furnace to a higher voltage grid is often costly and sometimes impractical and on most occasions using thyristor-controlled compensator or saturable reactor is economically and technically advantageous. The first presence of SVC in electrical industry world dates back to 1960 that was used to compensate arc furnace and prevent voltage flickering. But it was widely used for other applications because of its advantages [4], [5], [6]. In this paper, analyzing furnace disadvantages and proposing a model for it is considered. Furthermore the presence of SVC for compensating electric arc furnace problems and reducing harmonic is evaluated using EMTP in a real steel complex in Iran.

II. Arc Furnace Modeling and Performance

Behavior of arc in furnace is dependent on several variables that not all of them have been known, so a precise model has not been proposed. Typically electrical behavior of arc is determined by its voltage and current. Figure 1 depicts voltage versus current of an electric arc furnace [1]. Arc is normally instable and completely nonlinear. This instability and nonlinearity is intensified especially when melting cool wreckage. By passing melting interval, arcing becomes stable but still has low frequency fluctuations. Waveform of the voltage is approximately square and its amplitude depends on the current.

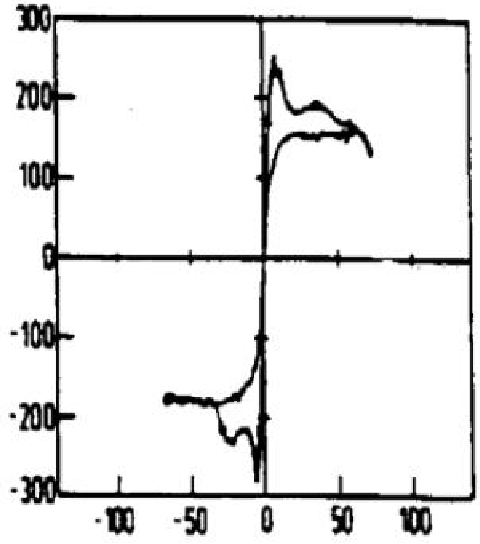

Figure 1: Electric arc furnace characteristic

Electric arc can be illustrated as a variable resistor in single phase equivalent circuit of electric furnace and its source, as in figure 2. Although this model is very simple but represents furnace performance according to mean values. For simplicity, all other resistors except arc resistor can be ignored. Reactance X is the sum of all reactance serried by the arc which is including reactance of the cables, bus bars, electrode arm, electrodes, furnace transformer, the main transformer and short circuit reactance of the source grid. All reactance are transferred into the secondary winding of the furnace transformer. Short circuit reactance of the source grid is about 15% to 20% of all reactances, while cable reactance from the secondary terminals of the furnace transformer to graphite electrodes is 70%. E is the open circuit voltage of the terminals of furnace transformer and accompanied with X indicates thevenin equivalent of the electric arc source. It can be seen that in a circuit like figure 2, delivered power to the load (electric arc) with variations in R is limited by the maximum power per phase below [7]:

$$P_{max} = \frac{E^2}{2X} \qquad (1)$$

In the condition of maximum power, R is

$$R_{pmax} = X$$

Furthermore the current relating to maximum power is:

$$I_{pmax} = \frac{E}{\sqrt{2}X}$$

So voltage drop over electric arc equals the one over reactance X which is $E/\sqrt{2}$.

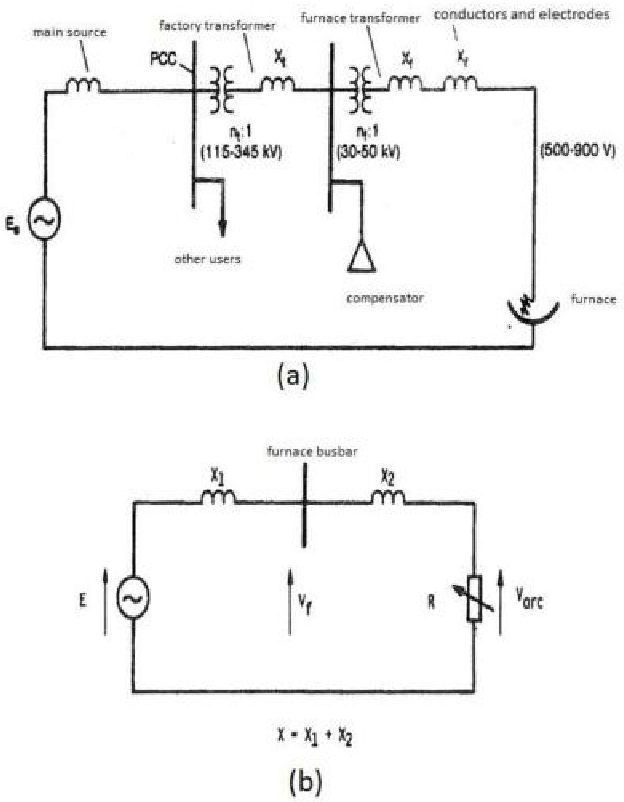

Figure 2: Single phase equivalent circuit for characteristics of electric furnace performance

Arc stability is acquired in the maximum power point. Although Currents less than I_{pmax} leads to higher power factor, it reduces power and stability of the arc. On the other hand, the more current, the less power and power factor, which uneconomical utilization is implied. These considerations offer desirable operation around maximum power point. As a matter of course, operation of the furnace is constrained with corrosion of its inner sidewall. Maintenance expenditure of inner sidewall of furnace is a major portion of steel production expenses. And its importance grows as input power of furnace in a specific diameter increases. At a specific level of power, corrosion rate is approximately proportional to electric arc length. Length of electric arc is exclusively depends on voltage of the arc and is approximately independent of its current. For a maximum length of arc and a desirable maximum power of arc P_{max}, reactance X must not exceed $\frac{V_{arc}^2}{P_{max}}$. If X exceeds this value, furnace have to work in a higher current to produce arc. This method is not practically atypical but reduces both power and power factor. Reducing X leads to reduction in electric arc length at all levels of power, not only the maximum one. In many cases, smaller reactance is acquired by reinforcing factory source, i.e. by connecting it directly to a grid with higher voltage which has higher level of short circuit capacity and lower short circuit reactance [7]. Needless to say, one of the desirable conditions of a power grid it its voltage regulation at the nominal range. As electrical devices like large machineries, welding machines and arc furnaces start using the grid, it causes sudden changes in the grid current and consequently fluctuations in voltage; which its effect appears in incandescent lamps in the form of rising and falling of light. This phenomenon is known as flickering. In addition, flickering of electric arc furnaces can cause harmonic and mid-harmonic problems so that it is known as one of the most important sources of harmonic in distribution feeders [2], [3].

III. ADVANTAGES OF COMPENSATING

It is obvious how a compensator can provide us with advantages that reducing X does. Compensator might be connected to the furnace busbar, as in figure 2. If compensator can maintain voltage, X_1 can be efficiently eliminated. Among all compensators, only reactive compensators with high-speed characteristic are able to maintain voltage and fulfill the above advantages. These compensators include saturable reactor, thyristor-controlled reactor and thyristor-switched capacitor compensators. These compensators like synchronous condenser, are connected in parallel with furnace busbar. In other words, the principle is such that reactive power of electric furnace is measured at a possible pace and compensator is controlled in a way that sum of reactive power of furnace and of compensator is balanced as much as possible. For eliminating harmonics, utilization of harmonic filters is often necessary. In fact, compensator plays the role of reactive power compensation and voltage maintenance only at fundamental frequency. In addition to harmonics generated by furnace, TCR type compensators do the same [7].

Distortion in waveform (i.e. harmonics) is resulted from switching. Harmonics generated from electric furnace, unlike static power converter, are unpredictable because electric arc differs from one cycle to another, especially when new wreckage is entered. Since current of arc is aperiodic, spectrum analyzing of electric furnace distorted current does not lead to discrete-order harmonic components, but it is a continuous spectrum which its amplitude is in reverse proportion to the frequency. However, for determining nominal values of electric furnace, obtaining spectrum amplitudes of integer multiples of the fundamental frequency is of great importance. These filters usually become homophonic for 2, 3, 4, 5 and 7 order harmonics [7].

IV. DESIGNING VIAN STEEL COMPLEX SYSTEM

In this paper VIAN steel complex which is located in Iran is considered as a real case study for design, analyse and compensation study. The system is modeled, all components is designed and then simulation will performed for analyzing the effectiveness of SVC for power quality improvement.

IV-1: VIAN STEEL COMPLEX SCHEMATIC

Figure 3 shows the schematic diagram of Vian steel complex with SVC installed on PCC.

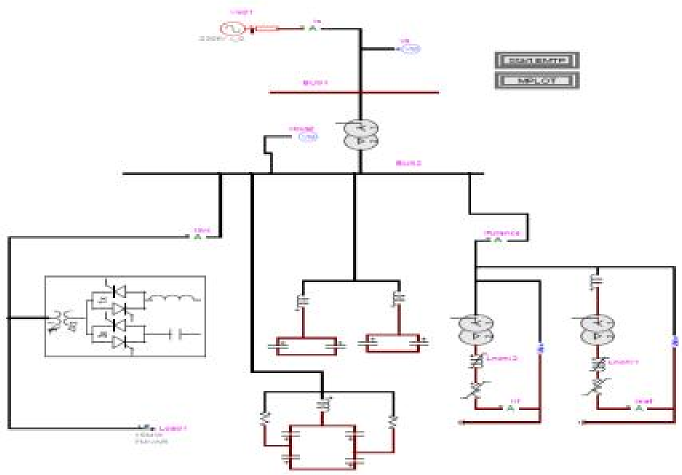

Figure 3: Vian steel complex Electrical schematic

IV-2: GRID CHARACTERISTICS

Data at 230Kv bus (PCC):

$$S_{min} = 2111\ MVA$$
$$S_{max} = 7661\ MVA$$

33KV busbar load:

Electrical Arc Furnace: $60MVA\ cos\emptyset = 0.8$

Ladle Furnace: $12MVAcos\emptyset = 0.8$

IV-3: SVC CAPACITY CALCULATION

$$Q_{EAF} = S_{EAF} \times sin\,\emptyset = 60 \times 0.6 = 36MVAr$$
$$P_{LF} = S_{LF} \times \cos\emptyset = 12 \times 0.8 = 9.6MW$$
$$Q_{LF} = S_{LF} \times \sin\emptyset = 12 \times 0.6 = 7.2MVAr$$
$$Q_{DYN} = \sqrt{(Q_{EAF} \times 0.7)^2 + (Q_{LF} \times 0.2)^2} = 25.2MVAr$$
$$Q_{TR} = \frac{P^2 \times U_K}{S_{TR}} = \frac{57.6^2 \times 0.12}{75} = 5.3MVAr$$
$$Q = Q_{EAF} + Q_{LF} + Q_{DYN} + Q_{TR} = 36 + 7.2 + 25.2 + 5.3 = 73.7MVAr$$

So an SVC with capacity of 80MVAr must be chosen.

IV-4: SVC SECOND-ORDER-HARMONIC FILTER CALCULATION FOR VIAN STEEL COMPLEX

Predicted characteristics of devices for second-order-harmonic filter

A: 2nd HF reactor 57.77 mH
385/397A 3PH
B: 2nd HF Capacitor 625 KVAr 29.23 µF 63 Seel.

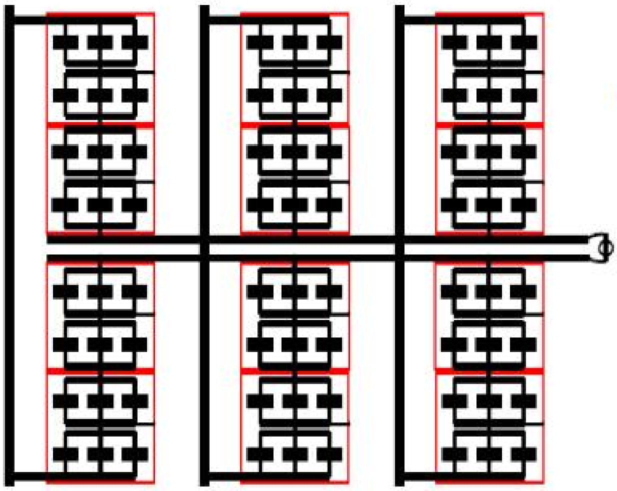

Figure 4: Combination of connecting capacitors in second-order harmonic

Sample calculations are considered for one phase.

A. Filtering operation of circuit for second-order harmonic $2 \times 50 = 100Hz$

According to combination of capacitors, equivalent capacitor for one phase is:

$$C = 29.23 \,||\, 29.23 = 14.615 \,||\, 29.23 = 9.743 \,||\, 29.23 = 7.3 \times 3 = 21.929 \times 2 = 43.85\, \mu F$$

Reactor impedance:

$$X_L = 57.77 \times 10^{-3} \times 3.14 \times 2 \times 50 = 36.279\, \Omega$$

Capacitor reactance:

$$X_C = \frac{1}{C} = \frac{1}{43.85 \times 10^{-6} \times 2 \times 3.14 \times 2 \times 50} = 36.31\, \Omega$$

Thanks to equality of reactor impedance with capacitor bank impedance in each phase at 100 Hz frequency, circuit resonates and passes currents of second-order harmonic and filters them.

B. Reactive operation of filter set (capacitor and reactor) and power factor correction of second-order harmonic filter at fundamental frequency of 50Hz:

Inductor impedance:

$$X_L = 57.77 \times 10^{-3} \times 3.14 \times 2 \times 50 = 18.139\, \Omega$$

Impedance of capacitor set:

$$X_C = \frac{1}{C} = \frac{1}{43.85 \times 10^{-6} \times 3.14 \times 2 \times 50} = 72.62\Omega$$

Total impedance of circuit:

$$Z = X_L - X_C = -54.481$$

Current passed through second-order harmonic filter in one phase:

$$I = \frac{U}{Z} = \frac{33kv}{\sqrt{3} \times 54.481} = 350.125A$$

Capacitive reactive power for each phase of second-order harmonic filter:

$$Q = U \times I = (350.125 \times 54.481) \times 350.125 = 6678690\, VAr$$

Three phase reactive power of filter:

$$3 \times 6678690 = 20036070\, VAr$$

So the predicted filter set for second harmonic, along with considered devices, are able to filter 2nd harmonic destructive current and inject 20036070 VAr capacitive reactive power (at 50Hz frequency) in order to correct power factor of Vian Complex.

IV-5: CALCULATIONS OF SVC THIRD-ORDER HARMONIC FILTER FOR VIAN STEEL COMPLEX

Predicted characteristics of devices for third-order harmonic filter:
A: 3rd HF Reactor 14.73 mH, 576/632A 3PH
B: 3rd HF capacitor 848.06 KVAr 29.17µF 72 Seel.
Combination of capacitors: two Y-connected three phase sets, each phase containing four parallel circuits, each circuit having three capacitors in series.
Sample calculations are considered for one phase.

A. Filtering operation of the circuit for 3rd harmonic $3 \times 50 = 150Hz$

According to the combination of capacitors, equivalent capacitance of each phase is: 77.786µF
Reactor impedance:

$$X_L = 13.875\Omega$$

And impedance of capacitors:

$$X_C = 13.647\Omega$$

IV-6: SAMPLE CALCULATIONS OF SVC FORTH-ORDER HARMONIC FILTER FOR VIAN STEEL COMPLEX

Predicted characteristics of devices for forth-order harmonic filter:
A: 4th HF reactor 7.93mH, 578/597A 3PH
B: 4th HF capacitor 848.06KVAr 35.188µF 63 Seel.
Combination of connecting capacitors: two Y-connected three phase sets, in the first set each phase having four parallel circuits and each circuit has three serried capacitors. The second set contains three parallel circuits, each of these circuits containing three serried capacitors.
Sample calculation is considered for one phase.

A. Filtering operation of circuit for forth-order harmonic $4 \times 50 = 200Hz$

According to combination of connecting capacitors, equivalent capacitance of one phase is: 82.098µF
Reactor impedance:

$$X_L = 9.9\Omega$$

And impedance of capacitors:

$$X_C = 9.8\Omega$$

4-7 TCR AND SVC CURRENT CALCULATIONS OF VIAN STEEL COMPLEX

$$L = 4949 = 98mH$$

And TCR current is 1072A furthermore according to Y-connection of TCR, current is 1540A.

V. SIMULATION

V-1: grid, busbar and electric arc furnace voltages are shown below in the absence of SVC.

ggg

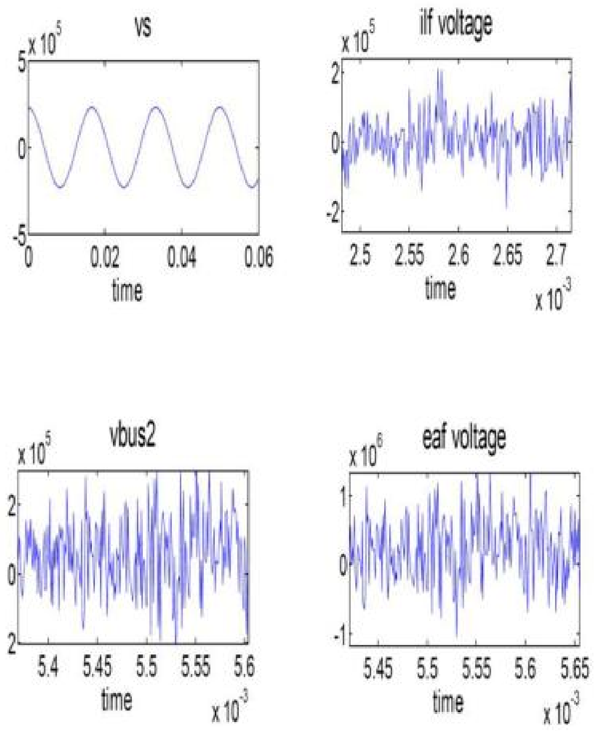

Figure 5. Voltages before compensating
Furnace and grid currents before compensating

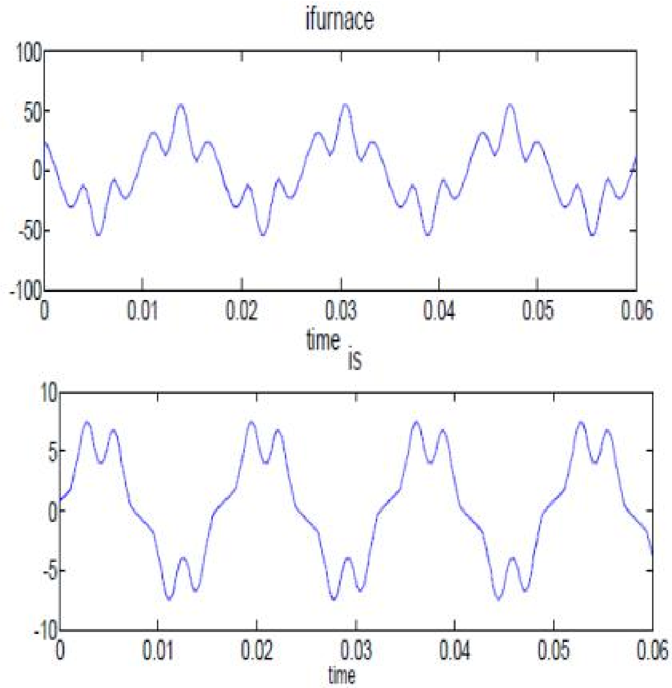

Figure 6. Currents before compensating

V-2: VOLTAGES AND CURRENTS AFTER COMPENSATING AND PRESENCE OF SVC

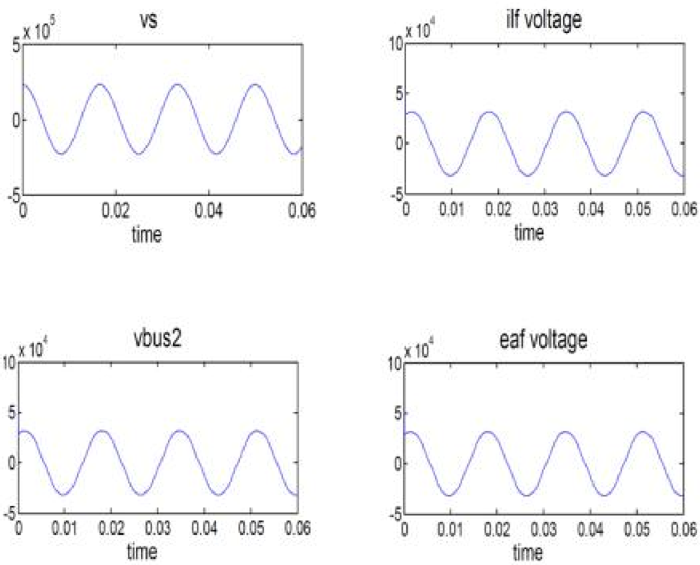

Figure 7. Voltages after compensating

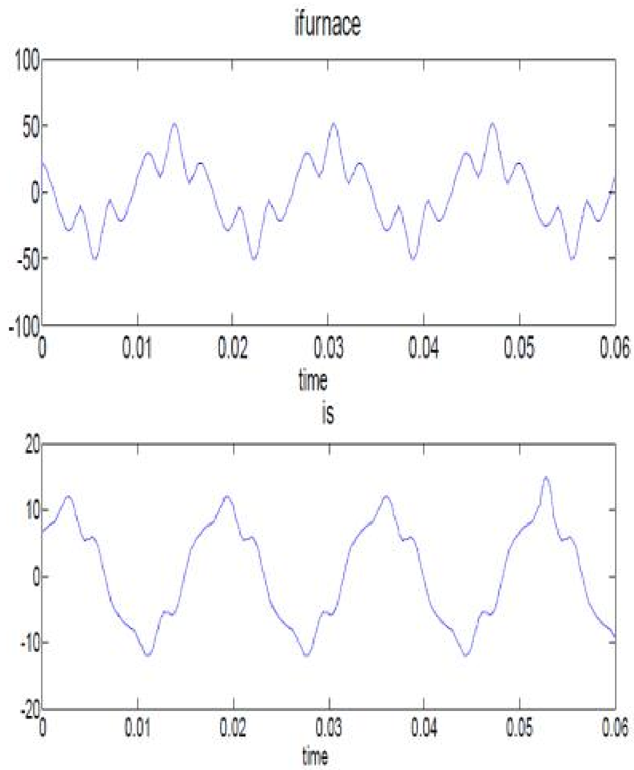

Figure 8. Currents after compensating

VI. SIMULAT`ION RESULTS

As stated above, electric arc is a nonlinear and stochastic phenomenon so it is time-variant. Nonlinearity of furnace causes harmonics in the grid. Furthermore, its time-variability causes changes in current at fundamental frequency and changes in voltage of furnace busbar. Sudden changes in active and reactive power has led to utilization of SVC compensator for improving power quality problems. After simulation and comparing the results, it can be concluded that by SVC installation, because of its high-speed response, voltage fluctuations have been reduced significantly and also harmonics generated by SVC and furnace have been corrected to some extent.

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