# Installation, Startup and Performance of a Static Var Compensator for an Electric Arc Furnace Upgrade

Sam Morello, PE
ARM EnerTech Associates, LLC
Johnstown, PA
Senior Member, IEEE

Thomas J. Dionise, PE
Eaton Electrical Group
Power Systems Engineering
Warrendale, PA
Senior Member, IEEE

Thomas L. Mank, PE
Standard Steel, LLC
Burnham, PA

*Abstract*—**This steel maker upgraded the Electric Arc Furnace (EAF) Melt Shop to increase production and improve metallurgical quality of their product. The increased electrical load and harmonic generation for the new furnace operation necessitated the installation of a 80 MVAR static var compensator (SVC) to meet utility interconnect requirements. This paper is a follow-up and companion to [1] that documented comprehensive analysis to specify the SVC. This paper describes the sequence of events during the installation, commissioning and operation of the SVC. It will assess the performance of the SVC compared to the electrical requirements of the utility for voltage regulation, flicker, harmonics and power factor. Power quality measurements during EAF operation without the SVC established a baseline to from which to show improvements provided by the SVC as well as compliance with the utility limits. Additionally, events encountered during the commissioning are shared as lessons learned.**

*Keywords-static var compensator (SVC), Electric Arc Furnace (EAF), Ladle Melt Furnace (LMF), harmonic analysis, harmonic filtering, flicker, IEEE Std 519-1992, IEEE Std 18-1992, IEEE Std 1453-2011*

## I. INTRODUCTION

Sumitomo Metals / Standard Steel upgraded the Electric Furnace Melt Shop at their Burnham, PA plant to increase production and improve metallurgical quality of their product. The upgrade described in detail in [1] and highlighted here consisted of upgrading the EAF#4 to 50MVA, supply of a new swing type Ladle Furnace/Vacuum Degasser (LD/VD) station, reuse of an existing 15 MVA transformer for a new Ladle Melt Furnace (LMF) and restoration of EAF#2 to meet increased demand for steel. The interconnect requirements put forth by the utility for the 230 kV point of common coupling (PCC) necessitated the application of an 80 MVAR SVC with integral 3-stage harmonic filter bank.

A series of comprehensive analytical power studies including Load Flow Analysis, Flicker Analysis and Harmonic Analysis were conducted to specify the ratings for the SVC needed to mitigate the increased electrical load and harmonic generation of the new EAF#4 operation to meet utility interconnect requirements for voltage regulation, flicker, harmonic distortion and power factor [1]. Upon completion of the studies, sharing the results with the utility and obtaining their approval, Standard Steel procured and installed the SVC over a period of approximately 2 years. Startup and commissioning took place in early 2015.

## II. OVERVIEW OF THE SYSTEM

### A. PCC at Utility 230kV at Yeagertown Substation

The PCC is the 230 kV primary two (2) 46 kV step down transformers in the utility Yeagertown Substation. Two 46 kV lines 1YSS and 2YSS from Yeagertown Substation supply the Standard Steel melt shop. The lines enter the plant at Sub 4 and the 46 kV is distributed from this substation throughout the plant for Arc Furnace service. Other plant circuits are supplied by another Standard Steel Sub-station and a utility feed not associated with the Yeagertown 230 kV. Fig. 1 shows an aerial view of major plant power distribution for Arc Furnace loads.

### B. Upgraded Electric Arc Furnace 4 (EAF#4)

A new Indoor Electric Arc Furnace Transformer rated 50/56 MVA was installed to replace the existing 30 MVA transformer as shown in Fig. 2. EAF#4 was installed ahead of the SVC installation. The utility agreed to allow operation without the SVC at a reduced operation of the new transformer rating. The revamp of the existing EAF#4 included the supply of a new swing type LF/VD Station to the power system as shown in Fig. 2. Along with furnace process improvements, the new swing type design LF/VD station allows two ladles of steel to be processed at the same time and also allows for arc reheating after vacuum degassing if required. The new LF/VD station was located existing EAF #3 position shown in Fig. 2.
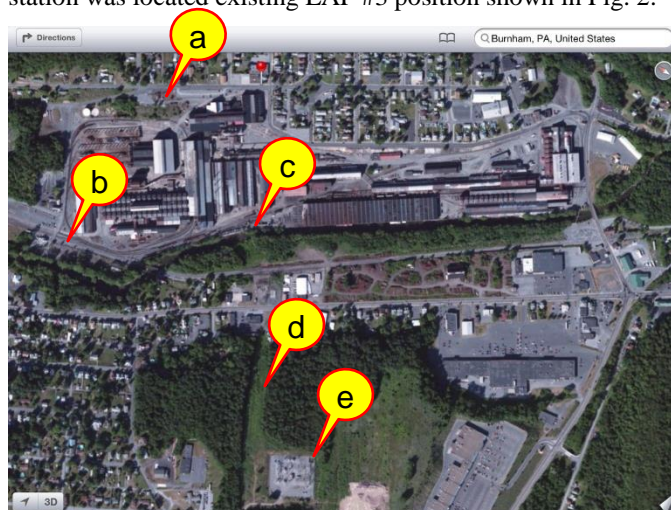


Figure 1. Aerial View of Major Plant Power Distribution for Arc Furnace Loads: a) Sub 19 46kV, b) Sub 4 to Sub 19 46kV Line, c) Sub 4 46kV, and d) 1YSS and 2YSS 46kV Lines, and e) Yeagertown Sub 230kV/46kV
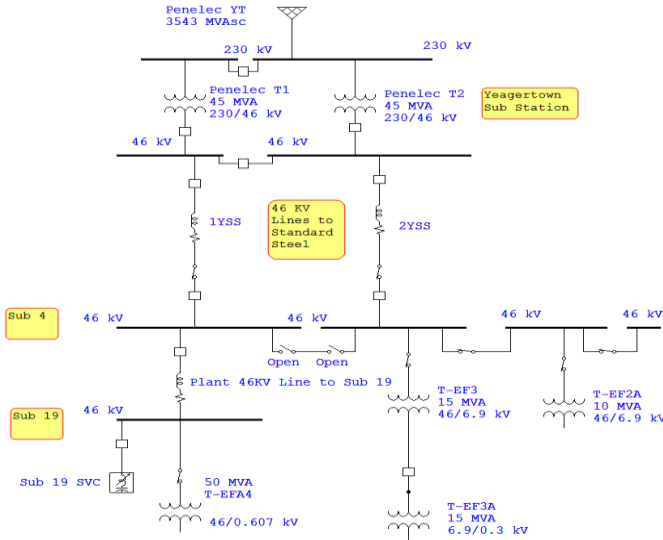
Figure 2. Simplified One-line Diagram for the Standard Steel Showing the New SVC, Upgraded EAF, New LMF and Retained EAF#2

### C. Reused Existing 15MVA Transformer Pair For New Ladle Furnace

The existing 15 MVA step-down transformer was re-used along with the existing ladle furnace transformer for the new LMF operation. Operationally, the new LMF required an increase of EAF#4 to be operated at the newly designed MVA to maintain productivity. The new LMF was commissioned about the same time as the new SVC.

### D. Electric Arc Furnace 2 (EAF#2)

Original plans called for Electric Arc Furnace 2 (EAF#2) and associated transformers of Table I to be retired. As the upgrade project progressed, they were restored back into service and added to the power supply bus. Restoration of EAF#2 to operation was required for the plant to meet steel demand because the SVC installation lagged behind the start-up of EAF#4 and the new LMF. Standard Steel requested an analysis of this additional furnace load be presented to the SVC vendor. With the nature of the load and the analysis, the SVC vendor agreed to maintain the original design in that it would comply with the SVC design specifications and utility interconnect requirements. The utility also was informed and gave permission to continue forward with the original design.

### III. UTILITY REQUIREMENTS

The interconnect requirements of the utility for the 230 kV PCC are given Table II. These requirements comply with flicker defined and limits specified in [4] and harmonic voltage and current limits specified in [2]. These voltage regulation,

TABLE I. EAF#2 TRANSFORMERS

| Specification | Rating |
|---|---|
| Power Rating | 10/11.25/14 MVA |
| Primary Voltage | 46,000 V |
| Secondary Voltage | 6900 V |
| Power Rating | 10/12.5 MVA |
| Primary Voltage | 6,900 V |
| Secondary Voltage | 275 V |
| Tap Changer | On-load, motor operated |

TABLE II. UTILITY INTERCONNECT REQUIREMENTS

| Specification | Rating |
|---|---|
| Voltage Regulation | 92 - 10% |
| Flicker | |
| PST | 0.8 |
| PLT | 0.6 |
| Harmonics | |
| VTHD | 1.50% |
| individual harmonic voltages | 1% |
| ITHD | 3.80% |
| individual harmonic currents (odds) | 3% |
| individual harmonic currents (evens) | 0.75% |
| power factor | .97 lag to .99 lead |

flicker and harmonics limits must be met during normal and single transmission element outage conditions including a generating unit outage. The flicker requirement further stipulates the connected facility shall be designed and operated such that short-term perception $P_{ST}$ does not exceed 0.8 and long-term perception $P_{LT}$ does not exceed 0.6 for more than 1% of the time (99% probability level) using a minimum assessment period of one week.

### IV. CONFIGURATION OF CONSTRUCTED SVC

Standard Steel installed an 80 MVAR SVC in the area of Sub 19 which supplies 46 kV directly to EAF#4 as shown in Fig. 3. This substation is directly connected to Sub 4 via a dedicated line. Sub 19 was selected since it was above the flood plain and an available track of open space was present. The SVC consists of a Thyristor Controlled Reactor (TCR) rated 80 MVAr and a three (3) stage harmonic filter bank rated 80 MVAc with specifications in Table III. The filter banks are tuned to 2nd harmonic (20 MVAc), 3rd Harmonic (25 MVAc) and 4th Harmonic (35 MVAc). See Fig. 4 for a one line diagram of the SVC and Fig. 5 for a physical plan view of the SVC.

TABLE III. SVC SELECT ELECTRICAL SPECIFICATIONS

| Specification | Rating |
|---|---|
| Nominal system Voltage | 46kV |
| Maximum Continuous Voltage | 49.2kV |
| | |
| Thyrister Contolled Reactor | |
| TCR Rating | 80 Mvar @ 639 Amps |
| TCR Short Time Overload Rating | 100 Mvar @ 725 Amps |
| | |
| TCR Switch Thyristor Type and size | |
| Thyrsitors in Series | 24 (1 redundant) |
| TCR Switch Rated Current | 580 Amps |
| | |
| Filter Bank 3-stage | |
| 2nd Harmonic Filter Rating | 20 Mvar |
| 3rd Harmonic Filter Rating | 25 Mvar |
| 4th Harmonic Filter Rating | 35 Mvar |
| Filter overall Rating | 80 Mvar |
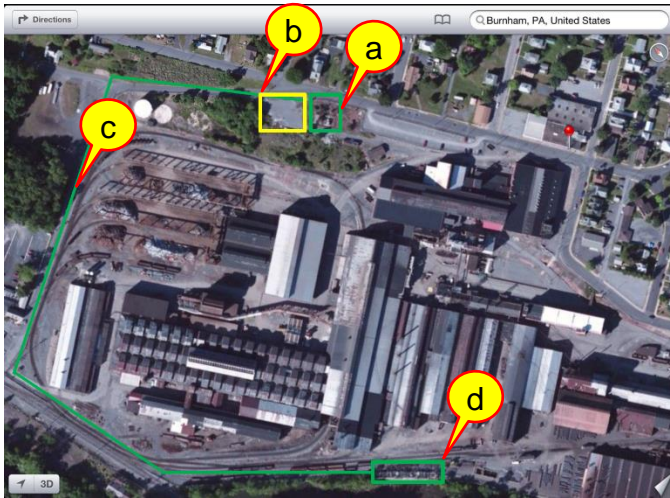
Figure 3. Aerial and Ground View a) Standard Steel Sub 19, b) Sub 19 Site for SVC, c) Sub 4 to Sub 19 46kV Line, and d) Standard Steel Sub 4 46kV
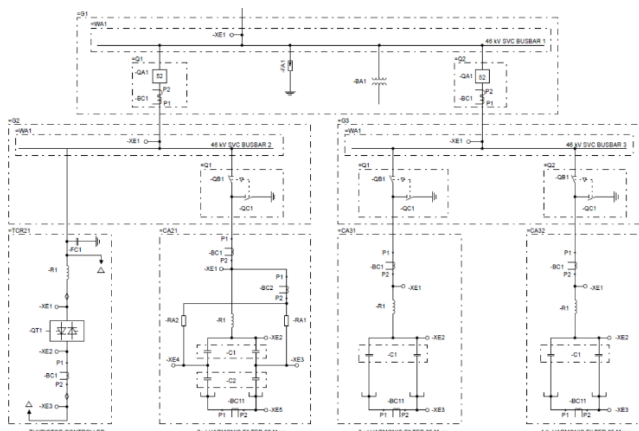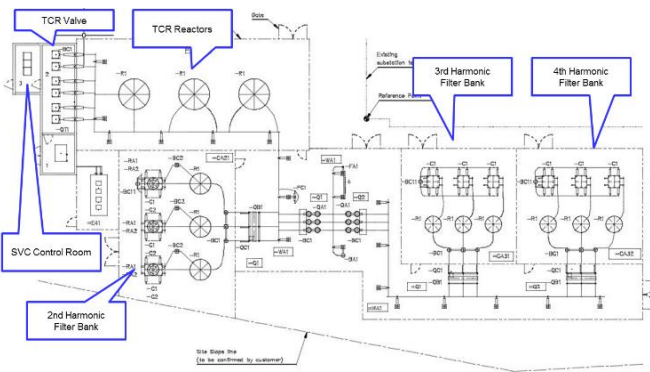


Figure 4. SVC One Line Diagram



Figure 5. SVC Physical Plan View

## A. Harmonic Filters

A Filter Circuit is a tuned circuit, which consists of capacitor banks (capacitance) and tuned reactor coils (inductance) connected in series. At the fundamental frequency (60Hz), the filter circuits behave like capacitors and provide power factor improvement. In the presence of harmonics, as those produced by the electric arc furnace, the filter circuits will reduce the negative influence of the loads like harmonic distortion and poor power factor. See Fig. 6 showing Standard Steel 2nd Harmonic Filter.



Figure 6. Standard Steel 2nd Harmonic Filter – C- Type Filter viewing Capacitors, Tuning Reactor and Damping Resisitor

## B. Thyristor Controlled Reactor (TCR)

The TCR consists of thyristor devices in series with reactors directly connected to the power system. The TCR will reduce the negative influence of the loads like flicker, voltage fluctuation, and voltage unbalance. The control system regulates the SVC so that the resulting reactive power to the load can be continuously controlled within the designed range of the SVC, at nominal voltage. The control system processes the input signals, calculates the phase-angle for triggering of thyristors and converts them to control pulses for the TCR thyristor valve (shown in Fig. 7) which change the amount of the main reactors (shown in Fig. 8) inserted in parallel to the harmonic filters. Each phase-to-phase TCR valve consists of one stack of Bidirectional Control Thyristors (BCT). Control pulses are transmitted to the BCTs via redundant fiber optic strands as shown in Fig. 9.



Figure 7. TCR Switch View – Two (2) Stacks of Twelve (12) Tyhristors per Assembly for a Total of Twenty-four (24) per Phase

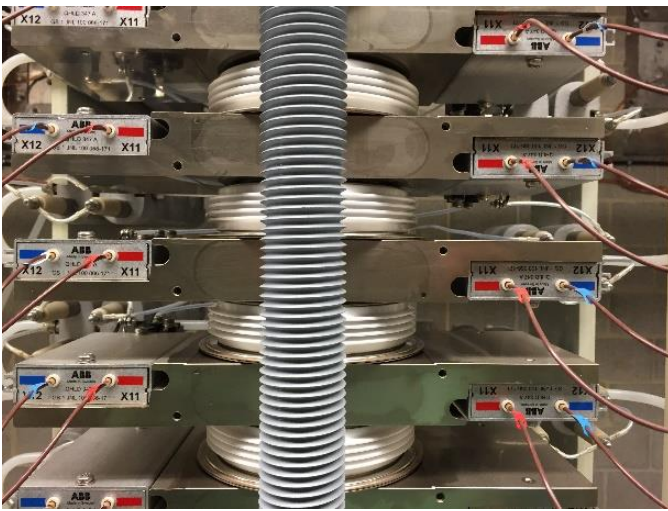Figure 8. TCR Reactor view – Presenting three (3) Main Reactors, one per phase, located outside the TCR Swich Room



Figure 9. Thyristor, Heat Sink and Fiber Optic Control

## V. ELECTRIC FURNACE AND SVC COMMISSIONING HISTORY

### A. New EAF#4 Operation Prior to SVC Commissioning

EAF#4 installation was completed prior to SVC construction. The utility for Standard Steel allowed operation of the new furnace, at reduced power levels for the new transformer. This was accomplished by operation at reduced power taps of the new transformer. The reduced operation point is shown as point a in Fig. 10 which was equivalent to power levels typical of the old EAF#4. This operation caused poor productivity for the furnace and with the SVC construction schedule lagging, the utility granted Standard Steel permission to ramp furnace power to near top tap prior to SVC commissioning shown as point b in Fig. 10. When the SVC finally came online, the furnace was operated at the top tap which resulted in less current but higher MW shown as point c in Fig. 10.

### B. SVC Commissioning

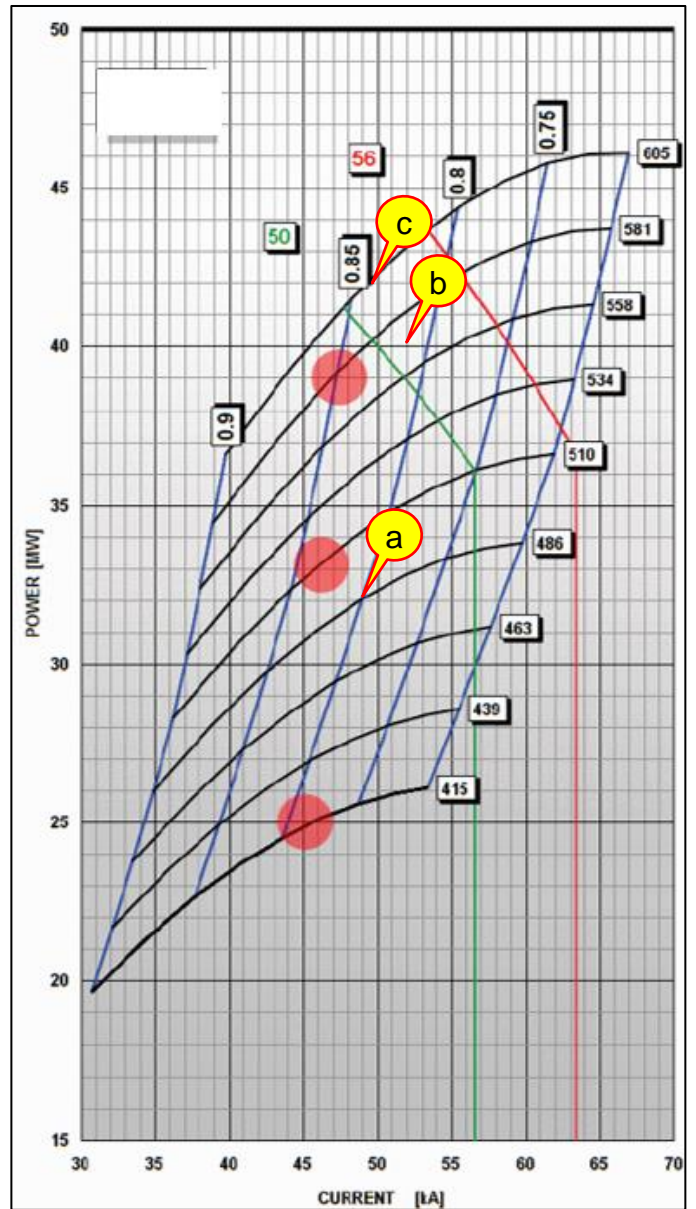Once SVC construction was completed, a commissioning



Figure 10. Power Curve for EAF4: a) 30MVA Loading without SVC, and b) 50MVA Loading without SVC, and c) 50MVA Loading with SVC

team of vendor and Standard Steel engineers was assembled. Commissioning procedures were scheduled over a three week period. A full simulation of the control system was conducted at the vendor factory prior to delivery of equipment. Commissioning procedures consisted of approximately 75% static checks and testing and 25% energized system testing. Examples of static checks included confirmation of all components as in Fig. 11 including capacitors, reactors and thyristors met specified values and tolerances. Prior to the SVC sub-station being energized at 46 kV, the system control was fully verified by energizing at 480 V. The only control issue of significance that did not function properly was the current transformer input feedback for the added EAF#2. The furnace current transformers were on the secondary of the step-down 46 kV transformer, which had a 30° phase difference. During the commissioning period, the vendor engineers were not able to solve the issue via software changes. It was decided not to utilize the EAF#2 current feedback as a controlling reference due to the small magnitude of the furnace.

Figure 11. SVC 2nd Harmonic Commissioning – Verifying Capacitors

## C. SVC Start-up with EAF #4 High Power Implementation with LMF

Once the SVC was commissioned and deemed operational, furnace EAF#4 was ramped-up to its highest operation tap as shown in Fig. 10. The initial operation of the increased power had immediate productivity changes, with an average decreased tap to tap time of approximately 5 minutes over a typical 90 minute production cycle. The increased power was the result of stable voltage at the 46 kV bus. Fig. 12 exhibits stable 46 kV bus voltage operating at approximately 48 kV during furnace operation for a period of about 1 hour. During this time period, the furnace reached power levels of 50 MW also shown in Fig. 12. The completed SVC Substation is shown in Fig. 13.
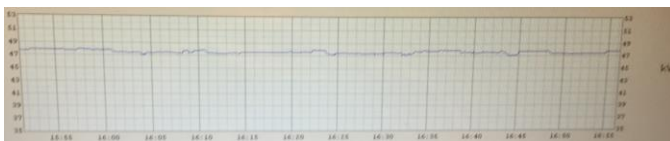
MW and MVAR loading of the two 46 kV lines (1YSS and 2YSS) from the Yeagertown Substation were very close in magnitude to the load flow predicted in [1]. Table IV reveals actual peak utility meter values for power flows as compared to predicted values illustrated with yellow shading. Because the meters are on the secondaries of the Yeagertown 45 MVA, 230/46 kV transformers, they also confirmed the predicted MVAR flow from the SVC, i.e. up through line 1YSS and back down through line 2YSS to the LMF and EAF#2. During the commissioning, it was determined that the utility meters are not configured to read negative MVAR flow, which is indicated by a zero value. As a result, the utility conceded they will be required to make a billing adjustment for reactive charges since the meters are not configured to report net MVARs. Section VI will review the electrical performance of the SVC to regulate voltage, control flicker and mitigate harmonics to within the utility required limits.

### D. SVC Operation Post Commissioning

Two significant events occurred during the SVC operation and post commissioning. In the first event, the EAF#4 furnace transformer suffered a major fault at the secondary furnace bus delta closure. Fig. 14 shows the damage to the bus and insulation due to short circuit current levels on the order of 400kA. The initial evaluation was that the fault may have been caused by insulation failure due to increased voltage being supplied by the SVC. However, after investigation and analysis, it was determined the fault was caused by incorrect insulation and bus support which was subsequently redesigned, fabricated and installed prior to re-energization.

TABLE IV.     PREDICTED LOAD FLOW VERSUS UTILITY PEAK METER VALUES

| Load Flows with SVC On Line - Predicted from Study [1] | | | | | |
|---|---|---|---|---|---|
| | MW | Mvar | MVA | PF | V% |
| Yeagertown Sub | 56.4 | 0.7 | 56.4 | 1.00 | 99.8 |
| 1YSS | 43.4 | -12.1 | 45.1 | 0.96 | |
| 2YSS | 12.9 | 10.3 | 16.5 | 0.78 | |
| SVC | -0.7 | 41.5 | 41.5 | -0.02 | |
| EF4 | 42.6 | 26.4 | 50.1 | 0.85 | 99.8 |
| LMF | 12.8 | 8.9 | 15.6 | 0.82 | 94.4 |
| EF2 | 0.0 | 0.0 | 0.0 | N/A | N/A |
| SVC On Line - Peak Utility Meter Values - 5/27/15 | | | | | |
| 1YSS | 37.5 | 0.0 | 37.5 | 1.00 | |
| 2YSS | 14.0 | 13.8 | 19.7 | 0.71 | |

Note: Yellow denotes utility peak meter values.



(a)



(b)

Figure 12. SVC a) 46 kV Bus Voltage Trace showing stable voltage at 48 kV, and b) EAF#4 real power in MW



Figure 13. Completed SVC Substation – View encompasses Incoming 46 kV from plant, TCR Reactors and filter banks in background

Figure 14. EAF#4 Delta Closure damage shortly after SVC went online

In the second event, the normally closed 46 kV tie breaker failed at the utility Yeagertown Sub. The utility allowed operation without the tie breaker isolating the SVC to only the EAF#4 load on line 1YSS. Operating without the tie breaker and the utility system operator's inexperience with the new SVC, over voltage faults were consistently experienced due to utility operation of the on-load tap changer along with SVC operation. The OLTC slower voltage control conflicted with the SVC real-time voltage control. As a consequence, Standard Steel decided to operate without the SVC until the tie breaker was put back into service.

## VI. SVC PERFORMANCE ASSESSMENT

### A. Voltage Regulation

A well regulated voltage is important to arc furnace operation because it allows higher power into the furnace reducing the elapsed time for a given heat. Reduced tap-to-tap times for a heat allow more heats per day and increased production. A well regulated voltage also benefits the utility and other customers it serves. As stated in detail in [1] and summarized in Sec. III, the utility requires voltage regulation of 92 to 105% of nominal under normal and single transmission element outage conditions, i.e. single contingency. Table V and Fig. 15 give the voltage regulation during operation of the arc furnace for several heats with and without the SVC.

The average voltage is increased from 44.804 kV (97.4%) to 45.248kV (98.4%) with the addition of the SVC. Without the SVC the average trend varies between 43.502kV (94.6%) and 45.867kV (99.7%). With the SVC, the average trend varies between 44.443kV (96.6%) and 45.824kV (99.6%). Although both modes of operation satisfy the voltage regulation requirement, the SVC increases the low end of the average trend voltage by 2% which is quite an improvement.

Another significant improvement with the SVC can be seen in the instantaneous minimums. The instantaneous minimum is increased from 40.231kV (87.5%) to 42.321kV (92%). This is significant because without the SVC the instantaneous minimum is 4.5% below the acceptable range for voltage regulation. With the SVC, the instantaneous minimum is equal to the lower limit of the acceptable range. In other words, the SVC injects reactive power to counter the instantaneous voltage excursions and hold them to the lower limit which is based on average voltage regulation.

Fig. 15 graphically compares the voltage regulation with and without SVC. With the SVC, the trends show a very tight range in voltage excursions, about equal distance above and below the average. While without the SVC, the minimum excursions are extreme due to the instantaneous short circuits produced in the scrap during arcing. The trends also show with the SVC the average trend is increased approximately 0.5kV.

TABLE V. COMPARISON OF VOLTAGE REGULATION WITH AND WITHOUT SVC

| Quantity | Level | Jan. 20-21 without SVC | | Jan. 27-28 with SVC | |
|---|---|---|---|---|---|
| Volts | inst max | 46,151 | 100.3% | 47,311 | 102.9% |
| | ave max | 45,867 | 99.7% | 45,824 | 99.6% |
| | ave | 44,804 | 97.4% | 45,248 | 98.4% |
| | ave min | 43,502 | 94.6% | 44,443 | 96.6% |
| | inst min | 40,231 | 87.5% | 42,321 | 92.0% |

Notes:
1. PCC is 230kV utility sub. All values reported at 46kV mill bus.
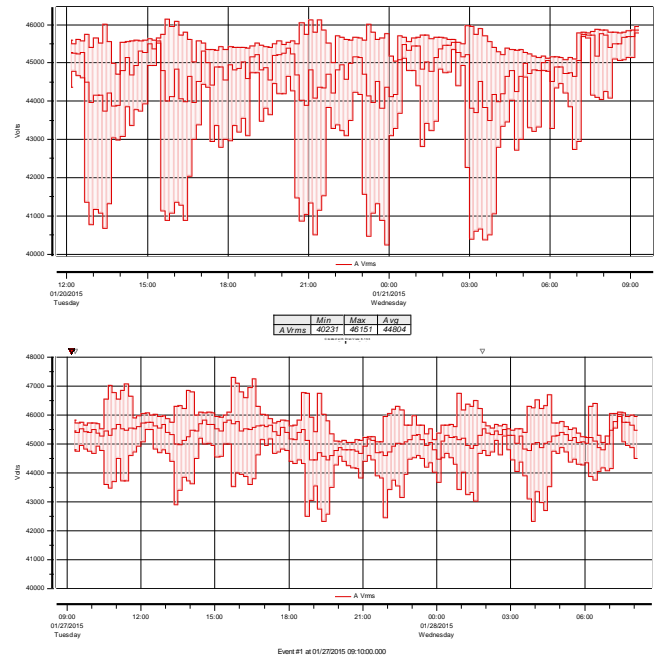


Figure 15. Comparison of Voltage Regulation with and without SVC

## B. Flicker Evaluation

Short-term perceptibility ($P_{ST}$) as defined by the International Electrotechnical Commission (IEC) and recently adopted by IEEE Std. 1453-2011 [2] is used to measure flicker. As explained in [3], the IEC flicker analysis considers the shape of the statistical distribution of the measured flicker values typically over a 10 minute period attempting to measure the buildup of annoyance to the human eye. The formula for calculating $P_{ST}$ per [2] is given in the equation below:

$$P_{ST} = \sqrt{0.0314\, P_{0.1} + 0.0525\, P_1 + 0.0657\, P_3 + 0.28\, P_{10} + 0.08\, P_{50}} \qquad (1)$$

$P_{0.1}$, $P_1$, $P_3$, $P_{10}$ and $P_{50}$ represent the flicker levels in units of perceptibility as calculated by an IEC flicker meter exceeded by 0.1%, 1%, 3%, 10% and 50% of the observation period. As explained in [3], the coefficients were developed from cumulative probability functions from arc furnaces and motor starting. A second quantity called the long-term perceptibility ($P_{LT}$) can be calculated from a series of $P_{ST}$ values.

Table VI summarizes the flicker during operation of the arc furnace for several heats with and without the SVC. Short-term perceptibility $P_{ST}$ and long-term perceptibility $P_{LT}$ are given at the utility 46 kV bus. Although the actual PCC is the utility 230 kV bus, at the time of the measurements it was not possible to access the 230 kV bus. Instead, 46 kV flicker was measured and reported here and projected to the 230 kV PCC. It was explained in [1] the $P_{ST}$ at the 230 kV PCC will be about 25% of the $P_{ST}$ at the 46 kV bus which was based on measurements of flicker for the old EAF and the system studies. The flicker at the 230 kV PCC is then compared to the utility flicker limits for $P_{ST}$ and $P_{LT}$.

As stated in detail in [1] and summarized in Sec. III, the utility requires $P_{ST}$ does not exceed 0.8 and $P_{LT}$ does not exceed 0.6 for more than 1% of the time (99% probability level) using a minimum assessment period of one week. As with voltage regulation, these flicker limits must be met under normal and single transmission element outage conditions including a generating unit outage. Without the SVC, Table VI the $P_{ST}$ at the 46 kV averages 2.01 with maximum of 8.58. With the SVC active, the $P_{ST}$ averages 1.24 with maximum of 2.81. The projected $P_{ST}$ at the 230 kV PCC averages 0.31 with maximum of 0.7. Both $P_{ST}$ and $P_{LT}$ comply with the utility flicker limits.

Fig. 16 compares short term flicker with and without the SVC during operation of the arc furnace for several heats. The $P_{ST}$ maximums of 5 to 8.58 during each heat are reduced to 2.81 to 1.87 at 46 kV bus with and without the SVC respectively. Fig. 17 compares long term flicker with and without the SVC during operation of the arc furnace for several heats. The $P_{LT}$ maximums of 4 to 5 during the heats are reduced to 1.58 to 1.86 at 46 kV bus with and without the SVC respectively. The SVC produces a significant reduction in flicker during operation of the arc furnace as shown in both of these figures.

TABLE VI.　COMPARISON OF FLICKER WITH AND WITHOUT SVC

| Quantity | Level | Jan. 20-21 without SVC[2] | Jan. 27-28 with SVC[2] | Jan. 27-28 with SVC[3] | 230kV Utility Limit[4] |
|---|---|---|---|---|---|
| PLT[1] | max | 5.03 | 1.87 | 0.47 | 0.6 |
| | ave | 3.09 | 1.58 | 0.40 | 0.6 |
| | min | 0.79 | 1.17 | 0.29 | 0.6 |
| PST[1] | max | 8.58 | 2.81 | 0.70 | 0.8 |
| | ave | 2.01 | 1.24 | 0.31 | 0.8 |
| | min | 0.05 | 0.07 | 0.02 | 0.8 |

Notes:
1. PST and PLT are given in per unit.
2. PCC is 230kV utility sub. All values reported at 46kV mill bus.
3. Flicker projected from 46kV to 230kV based on measured flicker for old EAF and system studies.
4. Utility limits may not be exceed for more than 1% of the time (99% probability level).
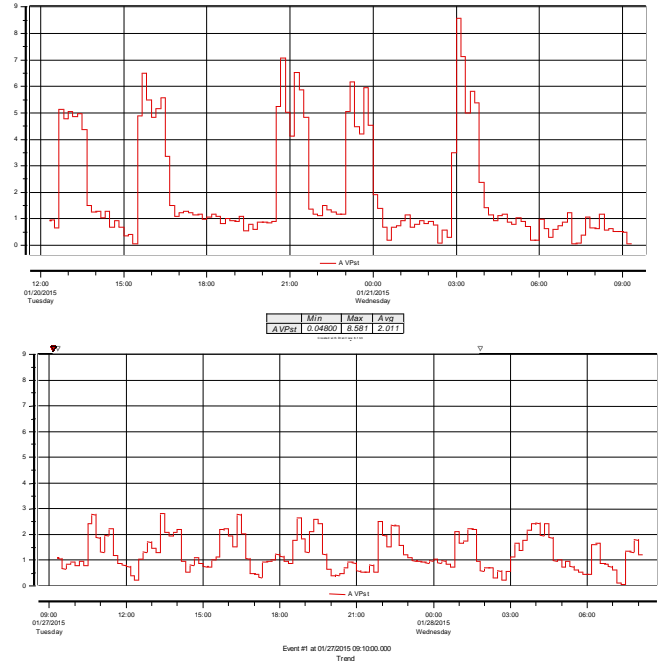5. Minimum assessment period of 1 week.



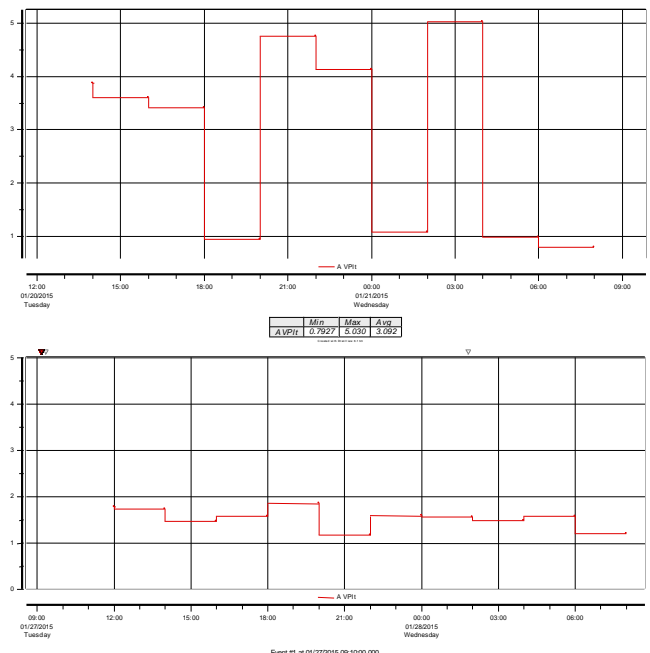Figure 16. Comparison of Short Term Flicker $P_{ST}$ with and without SVC



Figure 17. Comparison of Long Term Flicker $P_{LT}$ with and without SVC

## C. Harmonic Distortion

IEEE Std. 519-1992 defines the maximum distortion limits recommended for industrial, commercial, institutional, and utility electrical distribution systems [4]. At the time the utility interconnect agreement was formalized, IEEE Std 519-1992 was in effect but during installation of the SVC, IEEE Std. 519-2014 was adopted. The harmonic distortion requirements were grandfathered to IEEE Std 519-1992 limits. As explained in [3], the voltage distortion gives a clear representation of the impact of harmonics on the electrical distribution system. The harmonic voltage distortion from an individual customer is evaluated at the PCC where the utility can supply other customers. In this case, the PCC is the 230 kV utility bus. Harmonic voltage distortion per [4] is defined as:

$$\%THD_V = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots}}{V_1} \times 100\% \quad (2)$$

where $V_n$ is the magnitude (rms Volts) of the $n^{th}$ harmonic

Table VII gives the measured VTHD and individual harmonic voltages as measured at 46 kV with and without the SVC during arc furnace operation, and are compared to the IEEE Std. 519-1992 limits. The IEEE Std. 519-1992 limits are determined from the system rated voltage of 230 kV and Table 11.1 of [4]. The limits are 1.5% for VTHD and 1.0 % for individual harmonic voltages.

Without the SVC, the average VTHD of 0.78% is below the IEEE Std. 519-1992 limit of 1.5%. Checking further, the largest average individual harmonic voltage is the $5^{th}$ with a magnitude of 0.4% and the largest instantaneous magnitude is the $3^{rd}$ with magnitude of 3.21%. With the SVC operating, the average VTHD of 1.32% is below the IEEE Std. 519-1992 limit of 1.5%. Checking further, the largest average individual harmonic voltage is the $7^{th}$ with a magnitude of 0.67% and the largest instantaneous maximum is the $7^{th}$ with magnitude of 0.84%.

Fig. 18 compares trends of the VTHD with and without the SVC, and the benefits of the SVC are can be seen. Without the SVC, the average VTHD is 0.77% and varies between 0.34% and 2.52%. The instantaneous maximums reach 4.67% at times. With the SVC, the average is 1.32% and varies between 1.19% and 1.46% and the instantaneous maximums reach only 2.14% at times. The SVC is effective at reducing the instantaneous maximums which generally occur during bore-in when the arcing is most violent. Because the VTHD at 46 kV is within limits, therefore the VTHD at 230 kV PCC will be less and also within limits. This is because of the impedance of the 230/46 kV substation transformers.

TABLE VII.   COMPARISON OF VOLTAGE DISTORTION WITH AND WITHOUT SVC

| Quantity | Level | Jan. 20-21 without SVC | | Jan. 27-28 with SVC | | Std 519 Limit |
|---|---|---|---|---|---|---|
| V1 | max | 45934 | 102.54% | 46010 | 101.71% | N/A |
|    | ave | 44794 | 100.00% | 45237 | 100.00% | N/A |
| V2 | max | 1019 | 2.27% | 252 | 0.56% | 1.00% |
|    | ave | 68 | 0.15% | 77 | 0.17% | 1.00% |
| V3 | max | 1436 | 3.21% | 173 | 0.38% | 1.00% |
|    | ave | 159 | 0.36% | 68 | 0.15% | 1.00% |
| V4 | max | 1026 | 2.29% | 54 | 0.12% | 1.00% |
|    | ave | 66 | 0.15% | 19 | 0.04% | 1.00% |
| V5 | max | 1114 | 2.49% | 369 | 0.82% | 1.00% |
|    | ave | 179 | 0.40% | 270 | 0.60% | 1.00% |
| V6 | max | 808 | 1.80% | 176 | 0.39% | 1.00% |
|    | ave | 66 | 0.15% | 42 | 0.09% | 1.00% |
| V7 | max | 539 | 1.20% | 378 | 0.84% | 1.00% |
|    | ave | 122 | 0.27% | 301 | 0.67% | 1.00% |
| V8 | max | 297 | 0.66% | 90 | 0.20% | 1.00% |
|    | ave | 38 | 0.09% | 28 | 0.06% | 1.00% |
|    |     |    |    |    | 0.00% |    |
| V9 | max | 409 | 0.91% | 204 | 0.45% | 1.00% |
|    | ave | 47 | 0.11% | 58 | 0.13% | 1.00% |
| VTHD | max |  | 4.67% |  | 2.14% | N/A |
|      | ave |  | 0.78% |  | 1.32% | 1.50% |

<u>Notes:</u>
1. Individual harmonic voltage given in volts.
2. PCC is 230kV utility sub. All values reported at 46kV mill bus.
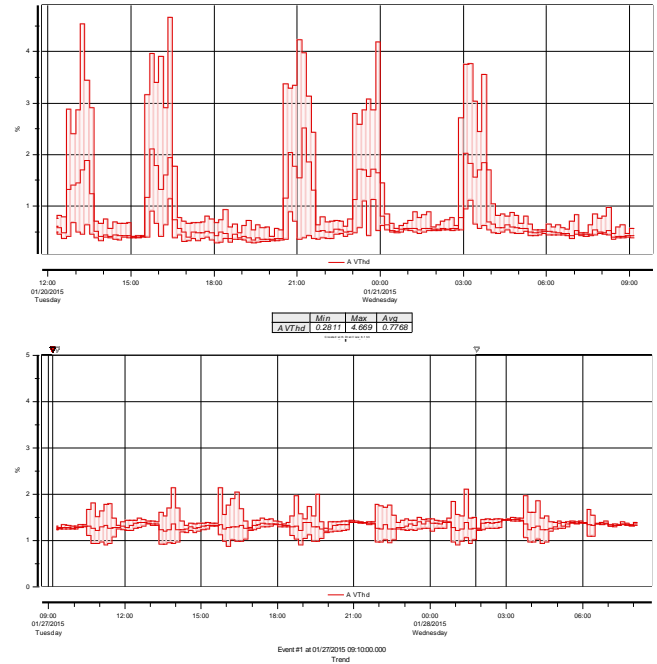3. Max is instantaneous maximum. Average is over 5 minutes.



Figure 18. Comparison of Voltage Distortion with and without SVC

## VII. CONCLUSIONS

This paper described the installation, startup and performance of an SVC for an EAF upgrade to modernize a steel maker's melt shop. Power quality measurements showed the SVC performed as specified meeting the utility electrical requirements for voltage regulation, flicker, harmonic distortion and power factor. Not only complying with the utility requirements, the SVC provided significant improvements to these indicators of electrical power quality and afforded the EAF to operate at increased power resulting in immediate productivity changes, with an average decreased tap to tap time of approximately 5 minutes over a typical 90 minute production cycle. Additionally, several events encountered during commissioning initially contributed to the higher voltage regulation of the SVC, were later determined the result of other causes and considered notable lessons learned.

## REFERENCES

[1] Dionise, T.J., Morello, S. "Comprehensive Analysis to Specify a Static Var Compensator for an Electric Arc Furnace Upgrade", IEEE IAS Annual Meeting Conference Record, October 2014.

[2] IEEE Std 1453-2011, IEEE Recommended Practice - Adoption of IEC 61000-4-15:2010, Electromagnetic compatibility (EMC) - Testing and Measurement Techniques – Flickermeter - Functional and Design Specifications, IEEE SA Standards Board, 2011.

[3] Dionise, T. J., Assessing the Performance of a Static Var Compensator for an Electric Arc Furnace", IEEE Industry Applications Society Annual Meeting, Las Vegas, NV, October 2012.

[4] IEEE Std 519-1992, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, IEEE, 1992, tables 10.2 and 10.3, pp. 77-78.

[5] Robert, M. Couvreur, "Arc Furnace Flicker Assessment and Prediction", in Proc. 12th Int. Conf. Elec. Distrib., CIRED, 1993, vol. 2, pp. 17-21.

[6] Y.J. Hsu, K.H. Chen, P.Y. Huang and C.N. Lu, "Electric Arc Furnace Voltage Flicker Analysis and Prediction", IEEE Transactions on Instrumentation and Measurement, Vol. 60, No. 10, October 2011.