Real-Time Measurement Approach for Tracking the $\Delta V_{10}$ Estimate Value of DC EAF

Jin-Lung Guan, Jyh-Cherng Gu, Chun-Wei Huang, Hsin-Hung Chang

Abstract—This investigation develops a revisable method for estimating the estimate value of equivalent 10 Hz voltage flicker ($DV_{10}$) of a DC Electric Arc Furnace (EAF). This study also discusses three 161kV DC EAFs by field measurement, with those results indicating that the estimated $DV_{10}$ value is significantly smaller than the survey value. The key point is that the conventional means of estimating $DV_{10}$ is inappropriate. There is a main cause as the assumed $Q_{\text{max}}$ is too small.

Although DC EAF is regularly operated in a constant MVA mode, the reactive power variation in the Main Transformer (MT) is more significant than that in the Furnace Transformer (FT). A substantial difference exists between estimated maximum reactive power fluctuation ($DQ_{\text{max}}$) and the survey value from actual DC EAF operations. However, this study proposes a revisable method that can obtain a more accurate $DV_{10}$ estimate than the conventional method.

Keywords—Voltage Flicker, dc EAF, Estimate Value, $DV_{10}$

I. INTRODUCTION

VOLTAGE flicker is one of major types of pollution that influences power supply quality, and is currently being targeted by the aggressive power supply quality improvement efforts of the Taiwan Power Company (TPC). Presently, the major source of flicker is the EAF used in steel making plants. During the operation of EAF, the electric poles short circuit and produce a very unstable current disrupting current flow, and in turn causing serious voltage flickers that influence neighboring power consumers.

Voltage flicker problems have long existed in several of the distribution areas served by TPC, namely those areas that contain steel plants operating arc furnaces [1], [2]. Voltage flicker causes sudden flashes of luminosity in fluorescent lamps and electric lights, and consequent eye discomfort, while noticeable, persistent and long-term flicker causes eye tiredness and vision problems [3]. Unstable lighting is thus the most frequent voltage flicker related complaint of power consumers. In the case of TV sets, the size of the screen image changes with the intensity of the flicker, while other instances of precision electronic equipment also suffer a certain degrees of negative influence from voltage flickers. The Central Research Institute of the Electric Power Industry (CRIEPI) of Japan suggested using $\Delta F_{10}$ as the standard for assessing voltage flicker [4]. This approach effectively explains the severity of voltage flicker survey values and control bases. Furthermore, $\Delta V_{10}$ is the method currently used by TPC, and thus is used herein.

DC EAFs have recently become widespread owing to the development of the large capacity thyristor technique, and the consequent decline in levels of active power, electrode bat, and firebrick loss. Mendis [5] confirmed the relationship between DC EAF operation and voltage flicker in transmission power systems. DC EAF theoretically has a more stable current than AC EAF, and thus has a lower voltage fluctuation [6]. Nevertheless, the rating of DC EAF could be up to 100MVA. Steel factories still experience serious voltage flicker problems, particularly if the short circuit capacity ($MVA_{\text{sc}}$) of the power supply system is insufficient or an EAF irregularity occurs during the steel-making process. This investigation discusses the load characteristics of 161kV DC EAF as determined by field measurement. Although DC EAF is operated using constant MVA mode, the MT still exhibits obvious reactive power variation. The survey results demonstrate that significant reactive power variation of MT is the primary cause of serious voltage flicker.

The DC EAF has relatively shorter application time and lesser correlation research than AC EAF. Presently, the criteria using to estimate the severity of DC EAF voltage flicker is utilizing the maximum reactive power fluctuation method (MRPFM) [4], [7]. However, the method suffers a severe shortcoming in that the estimated $\Delta V_{10}$ is smaller than the survey value [2], [8]. That restated, MRPFM couldn’t react to actual voltage fluctuation during the operation of DC EAF. To overcome the shortcomings of the traditional method, this investigation examines the differences between the estimate of voltage flicker and the survey value of actual DC EAF operation. Furthermore, this study proposes a revised method for calculating the $\Delta V_{10}$ of DC EAF voltage flicker. Survey results reveal that the revised method can obtain a more accurate $\Delta V_{10}$ estimate.
II. MAXIMUM REACTIVE POWER FLUCTUATION METHOD

This section describes the traditional method of obtaining the $\Delta V_{10}$ value of dc EAF. Generally, the maximum reactive power ($Q_{\text{max}}$) of point of common coupling (PCC) of factory equal to the rated apparent power capacity ($S_{\text{FT}}$) of FT is assumed. Meanwhile, the assumed minimum firing angle ($\alpha_{\text{min}}$) of the rectifier thyristor is the power factor angle of a full dc EAF load ($PF = 0.8$). Fig. 1 displays the load curves of dc EAF. The dotted line indicates that the probable maximum overload appears to be a power of actual dc EAF operation. Furthermore, $\Delta V_{10}$ and $\Delta Q_{\text{max}}$ can be seen to be related with their relationship being formulated as follow [9]:

$$\Delta Q_{\text{max}} = S_{\text{FT}} (K \times \sin \theta - \sin \alpha_{\text{min}}) \quad \text{MVAR} \quad (1)$$

$$\Delta V_{\text{max}} = X_s (\Delta Q_{\text{max}} / MVA_{\text{max}}) \quad \text{P.U.} \quad (2)$$

$$\Delta V_{10} = \Delta V_{\text{max}} / 3.6 \quad \text{P.U.} \quad (3)$$

where $K$: Over load factor caused by time delay of firing gate (around 1.0–1.15)
$
\theta$: Phase angle of electrode short circuit
$X_s$: Short circuit reactance of power supply system
$MVA_{\text{max}}$: Base of apparent power

III. ANALYSIS OF ACTUAL POWER DATA SURVEY

This investigation discusses and analyses the dc EAF load characteristics, such as V, I, P, Q and S, of three 161kV dc EAFs (namely A, B and C) by using a field survey. Table I lists their basic data, while Fig. 2 displays the survey points.

### TABLE I

<table>
<thead>
<tr>
<th>Factory</th>
<th>$S_{\text{FT}}$ (MVA)</th>
<th>$\Delta Q_{\text{max}}$ (MVA)</th>
<th>$\alpha_{\text{min}}$ (Deg)</th>
<th>$\Delta V_{10}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>82</td>
<td>32.8</td>
<td>36.87</td>
<td>0.398</td>
</tr>
<tr>
<td>B</td>
<td>100</td>
<td>38.7</td>
<td>37.86</td>
<td>0.350</td>
</tr>
<tr>
<td>C</td>
<td>82</td>
<td>41.8</td>
<td>28</td>
<td>0.302</td>
</tr>
</tbody>
</table>

Using the continuous model, data are obtained at a rate of one sample per power cycle (60Hz), and total 3600 samples for each second in Fig. 3. Data are sampled during the initial stage of meltdown period because voltage flicker is particularly evident at this time. Factory A is selected as example, while Figs. 3 and 4 show the survey results on the secondary side of MT and the primary side of FT. Meanwhile, the Ladle Furnace is not operating.

![Figure 1: The load curves of the dc EAF](image1)

![Figure 2: Single-line diagram of steel factory A](image2)

![Figure 3: Field V, I, P, Q and S measurement results based on a rate of 1 sample/cycle on the secondary side of the MT of factory A](image3)
The design and is I.2.768 kV and is 2 cycles. Table II lists the survey results. However, from the survey results, displayed in Figs. 3 and 4, the power system (P) and filters remain constant and the reactive power variation (∆Q) of MT approximated to FT (∆QFT) in theory.

Fig. 5 Field QMT + QC - QFT measurement results of 33kV bus of factory A

\[ Q_{MT} + Q_C = Q_{FT} \]
\[ \Delta Q_{MT} + \Delta Q_C = \Delta Q_{FT} \]
\[ \frac{\Delta Q_{MT}}{\Delta Q_{FT}} = 1 - \frac{\Delta Q_C}{\Delta Q_{FT}} \] (4)
\[ \therefore V_{new} = V_{old} + \Delta V \] And \[ \Delta V = -X_{BUS} \times \Delta Q_{FT} \]
\[ \therefore \Delta Q_C = \frac{V_{new}^2 - V_{old}^2}{X_C} = \frac{\Delta V \times (2V_{old} + \Delta V)}{X_C} \] (5)

where \( X_{BUS} \): Short circuit reactance on the primary side of FT.

The sign of \( \Delta Q_{FT} \) is positive while the de EAF increases the demand. If \( \Delta Q_{FT} \) is positive, \( \Delta V \) and \( \Delta Q_C \) will be negative. Consequently, the value of \( \Delta Q_{MT} / \Delta Q_{FT} \) is bigger than one. For example, \( \Delta Q_{MT} \) is 54.31 MVAR while \( \Delta Q_{FT} \) is 45.97 MVAR. Meanwhile, \( \Delta V \) is -2.768kV and \( \Delta Q_c \) is -8.94 MVAR when \( \Delta t \) is 2 cycles. Table II lists the survey results. However, the \( \Delta Q_{max} \) value of PCC is assumed to be the same as the rated capacity of FT and can be used to calculate the \( \Delta V_{10} \) value during the design stage. The scale of actual \( \Delta Q \) to the design value is 1.18 (54.31/45.97).

### Table II

<table>
<thead>
<tr>
<th>Field Q Measurement Results of Different Voltage at 33kV Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>33kV bus of Steel Factory A</td>
</tr>
<tr>
<td>Qmt (MVAr)</td>
</tr>
<tr>
<td>Qmt (MVAr)</td>
</tr>
<tr>
<td>Qmt (MVAr)</td>
</tr>
<tr>
<td>ΔQmt /ΔQFT</td>
</tr>
</tbody>
</table>

### IV. ANALYSIS OF ESTIMATED ΔV10

When EAF is operated after installation, the power company and steel factories must assess the influence of EAF on power systems. Before installing the EAF, the capacities of facilities to reduce voltage flicker must be estimated. Owing to considerable EAF load variation in steel factories, the non-linear phenomenon clearly follows the degree of melting of scrap iron. Regarding the estimation of the severity of voltage flicker, part circuits and load parameters were often ignored or assumed
owing to an inability to obtain their true parameters. However, in accordance with tradition, MRPFM is generally used to estimate the $\Delta V_{10}$ value of the dc EAF.

To understand the severity of voltage flicker at PCC of factory A, the sampling rate is one sample per minute. Fig. 6 shows the survey result of $\Delta V_{10}$ value during off-peak hours. The $\Delta V_{10_{\text{max}}}$ value is 1.215%, and the 95% cumulative probability of $\Delta V_{10}$ is 0.882%. Meanwhile, the limitation of $\Delta V_{10}$ and permitted by the TPC is 0.45%, and thus is used herein. Besides, the $\Delta V_{10_{\text{max}}}$ design data of steel factory A applies for power supply as follows:

$$Q_{\text{max}} = S_{\text{FT}} = 82 \text{ MVA}$$

$$\Delta Q_{\text{max}} = 82 \times (1 - \sin (\cos^{-1} 0.8)) = 32.8 \text{ MVAR}$$

$$\Delta V_{10_{\text{max}}} = \Delta V_{\text{max}} / 3.6 = 0.437 \times (32.8/10) / 3.6 = 0.398 \%$$

An estimate related problem exists. Before installing the EAF, factory A using the uses the traditional method to ensure that the estimated value of $\Delta V_{10_{\text{max}}}$ is below the permitted value. Nevertheless, the survey value clearly exceeds the design value, thus showing that further investigation of this case is required.

The question arises of why the $\Delta V_{10_{\text{max}}}$ survey value ($\Delta V_{10_{\text{40-49\%}}} = 0.882\%$) is significantly greater than the estimated value ($0.398\%$). Briefly, the key to answering this question lies in how the $\Delta Q_{\text{max}}$ value of the dc EAF is calculated. Generally, the $\Delta Q_{\text{max}}$ value is obtained using (1). From the design data of factory A, the assumed minimum firing angle $\theta_{\text{a min}}$ equals 36.87$^\circ$ ($\cos \theta_{\text{a min}} \approx 0.8$) when the dc EAF operates as intended. The $\sin \theta_{i}$ value and $K$ both equal 1 when a short circuit occurs. Meanwhile, supposing $\Delta Q_{\text{max}}$ equals FT capacity $S_{\text{FT}}$ then $\Delta Q_{\text{max}}$ equals 32.8MVAr.

Obviously, the $\Delta Q_{\text{max}}$ value of the original design is too small to respond the actual variation of reactive power. Meanwhile, the difference of $\Delta Q_{\text{max}}$ between design value and actual value is quite big and is the main reason for the $\Delta V_{10_{\text{max}}}$ value of the original design being smaller than the survey value.

V. DISCUSSIONS

The load of the dc EAF generally uses constant current control, and thus the currents of FT are kept almost constant. However, the current of MT varies enormously owing to the significant change in the power factor angle of FT. Consequently, the actual $\Delta Q_{\text{max}}$ value exceeds the original estimate and the design value of $\Delta V_{10_{\text{max}}}$ is lower than actual value. Obviously, those assumptions are too conservative to obtain a correct $\Delta V_{10}$ estimation in design stage.

However, this investigation suggests that the $\Delta V_{10}$ estimate calculation must adopt a stricter standard when utilizing the MRPFM. Therefore, we refer to the standards and experience of manufacturers, namely the actual $\Delta Q_{\text{max}}$ value equals the design value multiplied by 1.2. Finally, the formula for calculation $\Delta Q_{\text{max}}$ is modified, as represented by (6). Meanwhile, the $\Delta V_{10_{\text{max}}}$ is evaluated by the $\Delta V_{\text{max}} / 1.8$ equation [10].

$$\Delta Q_{\text{max}} = 1.2 \times S_{\text{FT}} (K \times \sin \theta_{i} - \sin 36.87^\circ)$$

(6)

Factory A is chosen as an example; the $\Delta V_{10_{\text{max}}}$ values are calculated again and listed as follows:

$$\Delta Q_{\text{max}} = 1.2 \times 82 \times (1 \times \sin 36.87^\circ) = 39.36 \text{ MVAR}$$

$$\Delta V_{10_{\text{max}}} = \Delta V_{\text{max}} / 1.8 = 0.437 \times (39.36/10)/1.8 = 0.96 \%$$

Similarly, the $\Delta V_{10_{\text{max}}}$ values of factories B and C are also calculated. Meanwhile, the modified values of $\Delta V_{10_{\text{max}}}$ are 0.88% and 0.57% respectively. Table III lists the comparisons of original design, modification and field survey of the dc EAF factories A, B and C. Significantly, the original estimated $\Delta V_{10_{\text{max}}}$ values (column 4th) are far less than the modification results (column 6th), and the modification results are close to the actual field survey (column 7th). However, a minor discrepancy exists between the modification results and the field survey, likely because of an abnormality in the operation of circuit elements or an irregularity of the EAF during the steel-making process.

<table>
<thead>
<tr>
<th>Factory</th>
<th>Original Design (Calculate)</th>
<th>Modification (Calculate)</th>
<th>Actual Field Survey</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$S_{\text{FT}}$ (MVA) (%)</td>
<td>$\Delta V_{10_{\text{max}}}$ (MVAR) (%)</td>
<td>$\Delta Q_{\text{max}}$ (MVAR) (%)</td>
</tr>
<tr>
<td>A</td>
<td>82 0.437 0.398</td>
<td>39.36 0.96 0.882</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>100 0.326 0.350</td>
<td>48.01 0.88 0.998</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>82 0.259 0.302</td>
<td>39.37 0.57 0.667</td>
<td></td>
</tr>
</tbody>
</table>

The $Q_{\text{max}}$ assumed at PCC is too small. The survey results indicate that the $\Delta Q$ value of MT is exceeds that of FT, and thus we suggest that the $Q_{\text{max}}$ assumed at PCC must use 1.2 multiples of the rated capacity of FT.
VI. CONCLUSIONS

The dc EAF loads of more than three steel factories have been extensively surveyed during the past several years. Meanwhile, these investigations found that the estimated $\Delta V_{10}$ is lower if the conventional means of estimating criteria is applied. Because the severity of the dc EAF caused voltage flicker problem was under-estimated, some factories did not install any compensation equipment, and others failed to install sufficient compensation equipments. Both the utilities and factories are confused by this mismatch between theoretical estimation and actual measurement of $\Delta V_{10}$.

The ultimate cause of the mismatch was that the $\Delta Q_{\text{max}}$ estimates of the dc EAF is insufficient, but we suggest that (6), developed here, should be adopted to replace the traditional formula (1) when utilizing the Maximum Reactive Power Fluctuation Method to calculate $\Delta Q_{\text{max}}$ and $\Delta V_{10}$. Then, the accurate capacity of compensation equipment can be estimated and installed in advance. Thereafter, the voltage flicker problems will be effectively improved.

REFERENCES


