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Real-Time Measurement Approach for Tracking the ΔV_{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_{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_{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 complain 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 precision electronic equipment also suffers a certain degrees of negative influence from voltage flickers. The Central Research Institute of the Electric Power Industry (CRIEPI) of Japan suggested using ΔV_{10} as the standard for assessing voltage flicker [4]. This approach effectively explains the severity of voltage flicker survey values and control bases. Furthermore, ΔV_{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_{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 ΔV_{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 ΔV_{10} of DC EAF voltage flicker. Survey results reveal that the revised method can obtain a more accurate ΔV_{10} estimate.

Jin-Lung Guan, and Hsin-Hung Chang are with the Department of Electrical Engineering, Hwa Hsia Institute of Technology, Taipei, Taiwan, R.O.C. (e-mail: gjl4127@cc.hwh.edu.tw)

Jyh-Cherng Gu, and Hsin-Hung Chang are with the National Taiwan University of Science and Technology, Taipei, Taiwan, R.O.C. (e-mail: jcgu@ mouse.ee.ntust.edu. tw)

II. Maximum Reactive Power Fluctuation Method

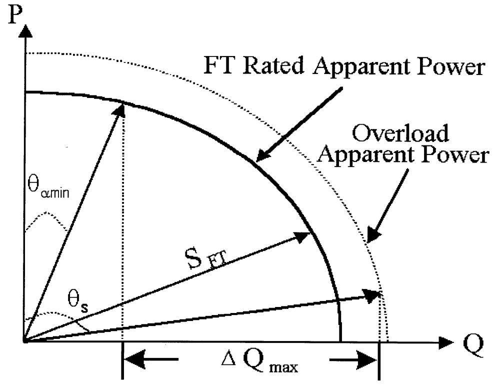

Fig. 1 The load curves of the dc EAF

This section describes the traditional method of obtaining the ΔV_{10} value of dc EAF. Generally, the maximum reactive power ($Q_{\max}$) of point of common coupling (PCC) of factory equal to the rated apparent power capacity (S_{FT}) of FT is assumed. Meanwhile, the assumed minimum firing angle ($\theta_{\alpha\min}$) 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, $\Delta V_{10\max}$ and $\Delta Q_{\max}$ can be seen to be related with their relationship being formulated as follow [9]:

$$\Delta Q_{\max} = S_{FT}(K \times Sin\theta_s - Sin\theta_{\alpha\min}) \quad \text{MVAR} \tag{1}$$

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

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

where K : Over load factor caused by time delay of firing gate (around 1.0~1.15)

θ_s : Phase angle of electrode short circuit

X_s : Short circuit reactance of power supply system

MVA_{base} : 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
Basic Information on the Surveyed DC EAF Factories

Factory	S_{FT} (MVA)	$\Delta Q_{\max}$ (MVA)	$\theta_{\alpha\min}$ (Deg)	ΔV_{10} (%) Design Value
A	82	32.8	36.87	0.398
B	100	38.7	37.86	0.350
C	82	41.8	28	0.302

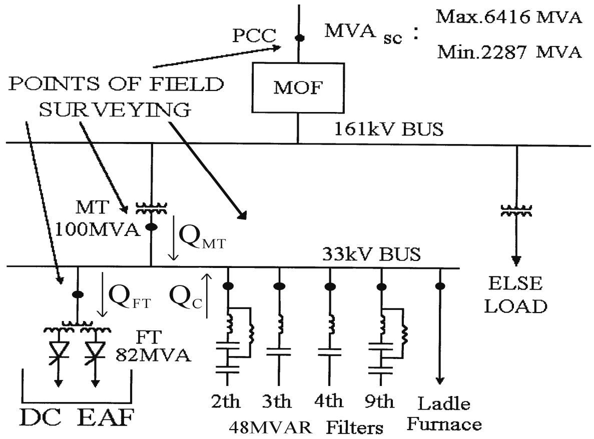

Fig. 2 Single-line diagram of steel factory A

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.

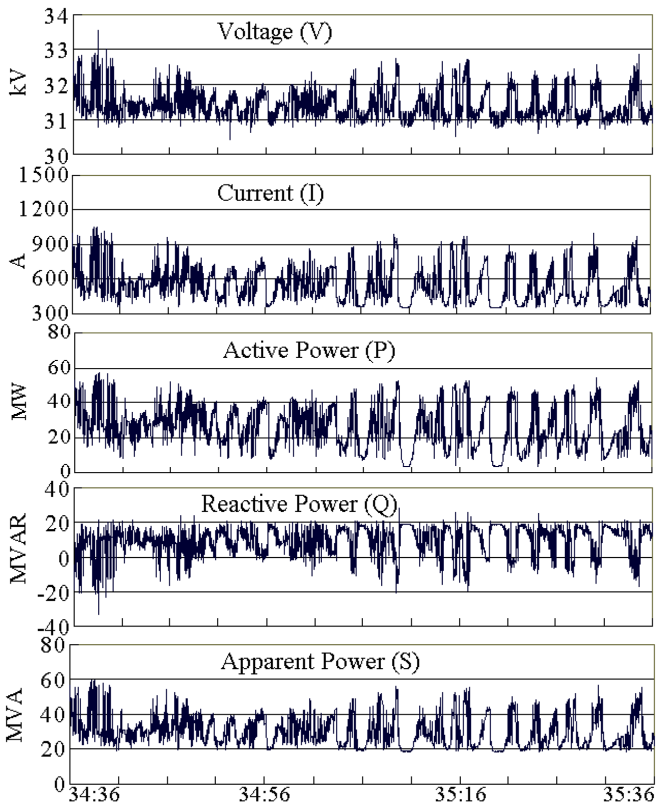

Fig. 3 Field V, I, P, Q and S measurement results based on a rate of 1 sample/cycle on the secondary side of the MT of factory A

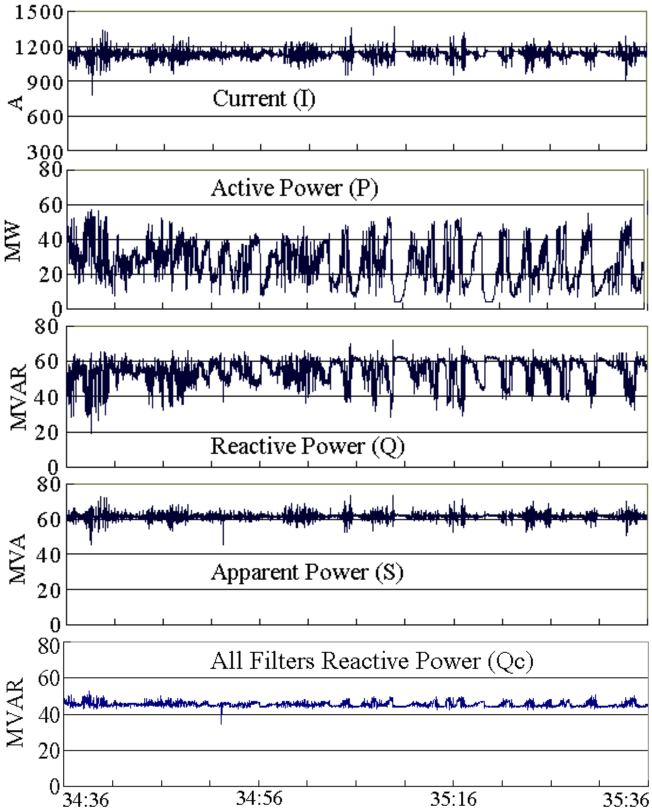

Fig. 4 Field I, P, Q and S measurement results based on a rate of 1sample/ cycle on the primary side of the FT of factory A and Qc on the filters

Fig. 3 presents the survey results of MT, and clearly shows extreme variations in the dc EAF load. The voltage is between 33.6kV~30.4kV while the reactive power is between –33MVAR~28MVAR, and the reactive power supply sometimes exceed the demand and thus cause Q to become negative. Meanwhile, the reactive power flows to the PCC. Fig. 4 presents the survey result of FT, and reveals that the reactive power is between 18.8MVAR~ 71.5MVAR. The variation of P and Q on the primary side of FT are generally followed by the variation of P and Q on the secondary side of MT. The FT survey results also reveal that load control is achieved via a constant current. Apparent power is kept almost constant, while active and reactive powers remain complementary.

Besides, the survey reactive power of MT is noted to be more severe than FT, in turn causing more serious voltage flickers. This difference in reactive power is also one of the reasons for the ΔV_{10} survey value exceeding the estimated value.

The Q_{MT} , Q_{FT} and Q_C of reactive power flows are displayed in Fig. 2. The power system (Q_{MT}) and filters (Q_C) supply the reactive power to the dc EAF(Q_{FT}). Fig. 5 shows the curve of $Q_{MT}+Q_C-Q_{FT}$ on the 33kV bus. The reactive power of filters remains constant and the reactive power variation (ΔQ_{MT}) of MT approximated to FT (ΔQ_{FT}) in theory. Nevertheless, from the survey results, displayed in Figs. 3 and 4, the variations in survey reactive power is more severe for MT than FT. Briefly, the key to answering this question lies in that the Q_C value cannot be consider as constant. Finally, ΔQ_C can be represented as follows:

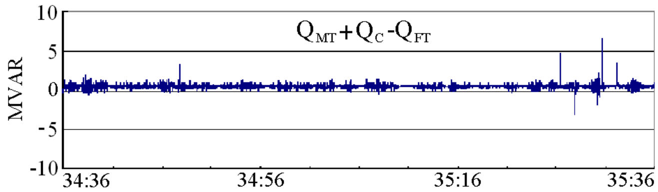

Fig. 5 Field $Q_{MT}+Q_C-Q_{FT}$ measurement results of 33kV bus of factory A

$$\begin{aligned} Q_{MT}+Q_C &= Q_{FT} \\ \Delta Q_{MT}+\Delta Q_C &= \Delta Q_{FT} \\ \frac{\Delta Q_{MT}}{\Delta Q_{FT}} &= 1-\frac{\Delta Q_C}{\Delta Q_{FT}} \end{aligned} \tag{4}$$

$$\because V_{new}=V_{old}+\Delta V \text{ And } \Delta V=-X_{BUS}\times\Delta Q_{FT}$$

$$\therefore \Delta Q_c=\frac{V_{new}^2-V_{old}^2}{X_C}=\frac{\Delta V\times(2V_{old}+\Delta V)}{X_C} \tag{5}$$

where X_{BUS} : Short circuit reactance on the primary side of FT

The sign of ΔQ_{FT} is positive while the dc EAF increases the demand. If ΔQ_{FT} is positive, ΔV and ΔQ_C will be negative. Consequently, the value of $\Delta Q_{MT}/\Delta Q_{FT}$ is bigger than one. For example, ΔQ_{MT} is 54.31MVAR while ΔQ_{FT} is 45.97 MVAR. Meanwhile, ΔV is -2.768kV and ΔQ_C is -8.94 MVAR when Δt 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 ΔV_{10} value during the design stage. The scale of actual ΔQ to the design value is 1.18 (54.31/45.97).

TABLE II
FIELD Q MEASUREMENT RESULTS OF DIFFERENT VOLTAGE AT 33KV BUS

33kV bus of Steel Factory A	V_{OLD} (33.554kV)	V_{NEW} (30.786kV)	$V_{NEW}-V_{OLD}$ (-2.768kV)
Q_C (MVAR)	53.03	44.09	-8.94 (ΔQ_C)
Q_{MT} (MVAR)	-32.95	21.37	54.31 (ΔQ_{MT})
Q_{FT} (MVAR)	18.83	64.80	45.97 (ΔQ_{FT})
$\Delta Q_{MT}/\Delta Q_{FT}$		1.18	

IV. Analysis of Estimated ΔV_{10}

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 ΔV_{10} value of the dc EAF.

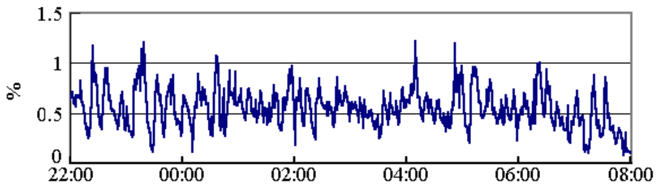

Fig. 6 Field ΔV_{10} measurement results of the PCC of factory A during off-peak hours

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 ΔV_{10} value during off-peak hours. The $\Delta V_{10\max}$ value is 1.215%, and the 95% cumulative probability of ΔV_{10} is 0.882%. Meanwhile, the limitation of ΔV_{10} and permitted by the TPC is 0.45%, and thus is used herein. Besides, the $\Delta V_{10\max}$ design data of steel factory A applies for power supply as follows:

$$Q_{\max} = S_{FT} = 82 \quad MVA$$
$$\Delta Q_{\max} = 82 \times (1 - Sin \ (Cos^{-1} 0.8)) = 32.8 \quad MVAR$$
$$\Delta V_{10\max} = \Delta V_{\max} / 3.6 = 0.437 \times (32.8/10)/3.6 = 0.398 \ \%$$

An estimate related problem exists. Before installing the EAF, factory A using the uses the traditional method to ensure that the estimated value of $\Delta V_{10\max}$ 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 $\Delta V_{10\max}$ survey value ($\Delta V_{10-95\%}$ =0.882%) is significantly greater than the estimate value (=0.398%). Briefly, the key to answering this question lies in how the $\Delta Q_{\max}$ value of the dc EAF is calculated. Generally, the $\Delta Q_{\max}$ value is obtained using (1). From the design data of factory A, the assumed minimum firing angle $\theta_{\alpha\min}$, equals 36.87° ($Cos\theta_{\alpha\min} \approx 0.8$) when the dc EAF operates as intended. The $Sin\theta_s$ value and K both equal 1 when a short circuit occurs. Meanwhile, supposing $\Delta Q_{\max}$ equals FT capacity S_{FT} then $\Delta Q_{\max}$ equals 32.8MVAR.

Obviously, the $\Delta Q_{\max}$ value of the original design is too small to respond the actual variation of reactive power. Meanwhile, the difference of $\Delta Q_{\max}$ between design value and actual value is quite big and is the main reason for the $\Delta V_{10\max}$ 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 $\Delta Q_{\max}$ value exceeds the original estimate and the design value of $\Delta V_{10\max}$ is lower than actual value. Obviously, those assumptions are too conservative to obtain a correct ΔV_{10} estimation in design stage.

However, this investigation suggests that the ΔV_{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 ΔQ value equals the design value multiplied by 1.2. Finally, the formula for calculation $\Delta Q_{\max}$ is modified, as represented by (6). Meanwhile, the $\Delta V_{10\max}$ is evaluated by the $\Delta V_{\max}/1.8$ equation [10].

$$\Delta Q_{\max} = 1.2 \times S_{FT} (K \times Sin\theta_s - Sin36.87°) \quad (6)$$

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

$$\Delta Q_{\max} = 1.2 \times 82 \times (1\text{-Sin}36.87°) = 39.36 \text{ MVAR}$$
$$\Delta V_{10\max} = \Delta V_{\max} / 1.8 = 0.437 \times (39.36/10)/1.8 = 0.96 \ \%$$

Similarly, the $\Delta V_{10\max}$ values of factories B and C are also calculated. Meanwhile, the modified values of $\Delta V_{10\max}$ 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 $\Delta V_{10\max}$ 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 III
THE COMPARISON OF ORIGINAL DESIGN, MODIFICATION AND FIELD SURVEY OF THE DC EAF FACTORIES

Factory	Original Design (Calculate)			Modification (Calculate)		Actual Field Survey
	S_{FT} (MVA)	X_s (%)	$\Delta V_{10\max}$ (%)	$\Delta Q_{\max}$ (MVA)	$\Delta V_{10\max}$ (%)	$\Delta V_{10-95\%}$ (%)
A	82	0.437	0.398	39.36	0.96	0.882
B	100	0.326	0.350	48.01	0.88	0.998
C	82	0.259	0.302	39.37	0.57	0.667

The $Q_{\max}$ assumed at PCC is too small. The survey results indicate that the ΔQ value of MT is exceeds that of FT, and thus we suggest that the $Q_{\max}$ 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 ΔV_{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 ΔV_{10}.

The ultimate cause of the mismatch was that the $\Delta Q_{\max}$ 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 $\Delta Q_{\max}$ and ΔV_{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

[1] Gu, J.C., Wu, C.J., and Chiang, J.C.: 'Effects of High Voltage Side Voltage Flicker Sources on Low Voltage Side Customers'. Research Report, Power Research Institute, Taiwan Power Company, 1994

[2] Wu, C.J., and Lee, L.H.: 'Electric Power Quality Evaluation of 161kV Large Size Steel Plants'. Research Report, Power Research Institute, Taiwan Power Company, 1995

[3] Manchur, G., and Erven, C.C.: 'Development of A Model for Estimating Flicker from Electric Arc Furnaces', IEEE Trans. on Power Delivery, 1992, 7 (1), pp. 416-426

[4] 'New trend in supply problems of arc furnace for steel plants'. Technology Report, Electrical Engineering Society, Japanese, 1978, 2 (72)

[5] Mendis, S.R., Do, A.V., and Boyd, D.M.: 'Investigation of Transmission System Voltage Flicker due to Multiple AC and DC Furnace Operations'. IEEE Trans. on Power Delivery, 1995, 10 (1), pp.483-496

[6] Chiang, J.C.: 'Electric Power Quality Actual Illustration' (Chwa Book Co., Taiwan, 2000 1st edn.)

[7] 'The Survey of DC Arc Furnace'. Technology Report, Nihon Kou-Kan Co., Japanese, 1989

[8] Wu, C.J.: 'Measurement and Analysis of Voltage Flicker'. Research Report, Power Research Institute, Energy Commission, Ministry of Economic Affairs, Taiwan, 2000.

[9] J. L. Guan, J. C. Gu, and C. J. Wu, "A Novel Method for Estimating Voltage Flicker," *IEEE Trans. on Power Delivery*, vol. 20, no. 1, pp. 242-247, Jan. 2005.

[10] J. L. Guan, J. C. Gu, and C. J. Wu, " Real-time Measurement Approach for Tracking the Actual Coefficient of ΔV / ΔV_{10} of Electric Arc Furnaces," *IEEE Trans. on Power Delivery,* vol. 19, no. 1, pp. 309-315, Jan. 2004.