Power Factor Definitions and Effect on Revenue of Electric Arc Furnace Load

Chi-Jui Wu , Member, Cheng-Ping Huang, Tsu-Hsun Fu, Tzu-Chih Zhao, and Hung-Shian Kuo

***Abstract*--The value of power factor generally is an important penalty factor in the revenue of electricity customers. However, the traditional power factor definition always assumes that the load condition is sinusoidal. The effects of load unbalance and harmonic distortion are neglected. It is suggested that a suitable power factor definition should be required for reflecting the fluctuant load characteristics. Therefore, the customers would be forced to improve the power quality disturbances. The transmission lines loss can be reduced and the system available rating is increased. In this paper, a 15-minute measurement data at the MOF of a 69-kV electric arc furnace user is used for analysis. Five definitions of power factor are investigated by considering the essence of power quantities. The effect on the billing of an electric arc furnace user is also studied.**

***Index Terms*—power quality, power factor, electric arc furnace, revenue, IEEE Std. 1459**

I. INTRODUCTION

Steel production gives important contribution to the economics of Taiwan. Many electric arc furnaces (EAFs) are installed to use electricity in the off-peak period. The capacity of an EAF in Taiwan could be up to 100 MVA. It is quite important to study their effects on the power quality because the Taiwan power system is isolated [1-2]. Generally, the operating process of an EAF to make steel by melting scrap is a batch type operation. The scrap melting can be divided into three periods, which are boring-down, melting-down, and refining. The arc current changes dramatically during boring-down and melting-down because the scrap is continuously melted and irregularly collapses among the graphite electrodes. Therefore, the status of an EAF randomly varies among short circuit, open circuit, and nonlinear arc model. The scrap is usually recharged two or three times before the refining period [3].

The major disturbances from an EAF are voltage flicker, load unbalance, and harmonics [1-7], and these problems exist in several areas of Taiwan Power Company for a long time [1-2]. It is a doubt whether the traditional metering method could really reflect the load characteristics of an EAF. The power metering method for industrial customers in Taiwan is also traditional. The power quantities essentially only consider the fundamental components. The power factor uses the average value over a monthly period. And the largest MW demand is the largest one among all average values of every 15-minute period in a month. The results of power metering can not really reveal the problems of voltage flicker, load unbalance, and harmonics. It has been reported that if traditional electro-mechanical meters are used in circumstances of non-sinusoidal and three-phase unbalanced voltages or currents, the error can reach 20%~30% [8]. In recent years, there are many discussions regarding the power definitions and calculations [8-13]. Several definitions are given in the IEEE Std. 1459, such as effective apparent power, arithmetic apparent power, and vector apparent power [11]. Good definitions of power quantities and power factor may well reflect the practical situations of three-phase unbalanced and non-sinusoidal circuits.

To reveal revenue reasonably, a suitable power factor definition should be required for reflecting the EAF characteristics. In this paper, a 15-minute measurement data at the MOF of a 69-kV electric arc furnace user are used for analysis. Five definitions of power factor are investigated and the corresponding monthly billings are estimated. From the calculation results, the highest power factor value is 0.97 and the lowest value is 0.90, which will cause 1% difference in the monthly electricity billing.

II. POWER FACTOR DEFINITION

For a single-phase load under non-sinusoidal condition, the instantaneous voltage and current are [11], respectively,

$$v(t)=V_0+\sqrt{2}\sum_{h\neq 0}^{\infty}V_h\sin(h\omega t+\alpha_h) \tag{1}$$

$$i(t)=I_0+\sqrt{2}\sum_{h\neq 0}^{\infty}I_h\sin(h\omega t+\beta_h) \tag{2}$$

The RMS values are

$$V=\sqrt{\sum_{h=0}^{\infty}V_h^2} \tag{3}$$

$$I=\sqrt{\sum_{h=0}^{\infty}I_h^2} \tag{4}$$

Hence the apparent power, active power, and Budeanu's reactive power, are

$$S=VI \tag{5}$$

$$P=\sum_{h=0}^{\infty}V_hI_h\cos(\alpha_h-\beta_h) \tag{6}$$

$$Q=\sum_{h=0}^{\infty}V_hI_h\sin(\alpha_h-\beta_h) \tag{7}$$

And the power factor is

$$PF=\frac{P}{S} \tag{8}$$

For a three-phase load under non-sinusoidal and

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unbalanced conditions, there are arithmetic apparent power, S_A, and vector apparent power, S_V [11],

$$S_A = V_R I_R + V_S I_S + V_T I_T \quad (9)$$

$$S_V = \sqrt{(P_R + P_S + P_T)^2 + (Q_R + Q_S + Q_T)^2 + (D_R + D_S + D_T)^2} \quad (10)$$

It is always $S_A \geqq S_V$. Then the arithmetic power factor, PF_A, and vector power factor, PF_V, are

$$PF_A = \frac{P}{S_A}, \quad P = P_R + P_S + P_T \quad (11)$$

$$PF_V = \frac{P}{S_V} \quad (12)$$

Another definition is based on the effective consideration. Hence

$$V_e = \sqrt{\frac{V_R^2 + V_S^2 + V_T^2}{3}} \quad (13)$$

$$I_e = \sqrt{\frac{I_R^2 + I_S^2 + I_T^2}{3}} \quad (14)$$

The effective apparent power, S_e [11], is

$$S_e = 3 V_e I_e \quad (15)$$

And the effective power factor, PF_e, is

$$PF_e = \frac{P}{S_e} \quad (16)$$

If the traditional electro-mechanical (rotating disc type) power meters are used, only the fundamental component could be obtained, considering the frequency responses of meters. Then the fundamental (displacement) power factor is

$$PF_1 = \cos\left(\tan^{-1}\frac{Q_1}{P_1}\right) \quad (17)$$

where

$$P_1 = P_{R1} + P_{S1} + P_{T1}, \quad Q_1 = Q_{R1} + Q_{S1} + Q_{T1} \quad (18)$$

And the corresponding apparent power is

$$S_1 = \sqrt{(P_1)^2 + (Q_1)^2} \quad (19)$$

In the revenue practice, the average power factor values should be used for a fixed period, such as a month. The power factor values are calculated by the values from kVAh, kWh, and kvarh meters. Therefore, there are five definitions for the average power factor.

$$PF_A = \frac{\int_T P(t)dt}{\int_T S_A(t)dt} \quad (20)$$

$$PF_V = \frac{\int_T P(t)dt}{\int_T S_V(t)dt} \quad (21)$$

$$PF_e = \frac{\int_T P(t)dt}{\int_T S_e(t)dt} \quad (22)$$

$$PF_1 = \cos\tan^{-1}\frac{\int_T Q_1(t)dt}{\int_T P_1(t)dt} \quad (23)$$

And the modified fundamental power factor

$$PF_{1m} = \cos\tan^{-1}\frac{\int_T Q_{1m}(t)dt}{\int_T P_1(t)dt} \quad (24)$$

with

$$Q_{1m}(t) = \begin{cases} Q_1(t), & Q_1(t) \geq 0 \\ 0, & Q_1(t) < 0 \end{cases}$$

And

$$S_{1m} = \sqrt{(P_1)^2 + (Q_{1m})^2} \quad (25)$$

III. CALCULATING OF BILL

Regarding the tariff of the Taiwan Power Company [14], the electricity charge of a large customer includes demand charge and energy charge. The demand charge of the high voltage customer excluding summer time is (unconsidered interruptible power rates)

Demand charge = (usually contractual fare) x (usually contractual demand) + (contractual fare) x (contractual demand) + (off-peak contractual fare) x {(off-peak contractual demand) – [(usually contractual demand) + (contractual demand)] x 0.5}

All fares and demands are values except summer. If the last term is less than zero between the brackets "{" and "}", it is viewed as zero.

For calculation simplification, some assumptions are as follows.

(1) The monthly average power factor is substituted by the average power factor of a 15-minute field measurement data.
(2) There is no load during daytime because the EAF operates during off-peak period.
(3) The accumulative electric energy of a 15-minute field measurement data is used to estimate the energy charge during a month.

Therefore, the energy charge is

Energy charge = (off-peak energy charge fare per kWh excluding summer time) x (accumulative electric energy during 15 minutes) x 4 x (9 hours) x (30 days)

In addition to demand charge and energy charge, the load power factor is also an important penalty factor. At present, the criterion of load power factor of the Taiwan Power Company is 0.8. The promotion penalty rules are

(1) If load power factor is large than 0.8, the revenue is decreased by (PF-0.8) x 100 x 0.15%
(2) If load power factor is less than 0.8, the revenue is increased by (0.8-PF) x 100 x 0.3%

IV. FIELD MEASUREMENT ANALYSIS

Fig. 1 shows the one-line diagram of a 69-kV ac electric arc furnace (EAF) steel plant. The size of furnace is 50 tons. The static var compensator (SVC) consists of a thyristor-controlled reactor (TCR) and the 2nd and the 3rd order harmonic filters. The SVC can provide instantaneous reactive power compensation to improve voltage fluctuation. In this paper, a 15-minute measurement data at the MOF are used for analysis.

Fig. 2 shows the active power during the interval of 15 minutes. The ratio of the fundamental active power and active power is shown in Fig. 3. The ratio is generally larger than one. It means that the harmonic active power is negative. This result is also in evidence from the accumulative values in Table 1. The accumulative active power is 7938 kWh and the accumulative fundamental active power is 7940 kWh. Therefore, the accumulative harmonic active power is negative. The fundamental reactive power during the interval of 15 minutes is shown in Fig. 4 and the accumulative value up to 1955 kvarh as listed in Table 1. The results of the modified fundamental reactive power are similar to those in Fig. 4, but the negative parts are viewed as zero. Therefore, the largest revenue is obtained by using the effective power factor and the smallest revenue is by the fundamental power factor.

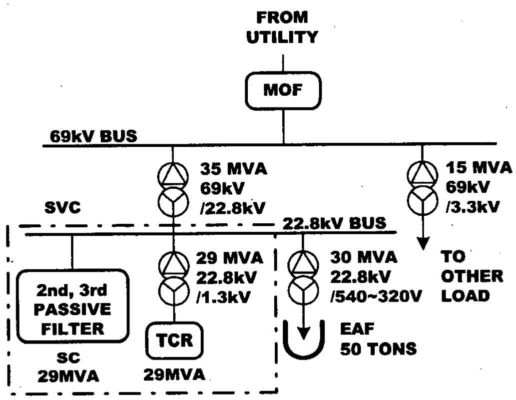

Fig. 1. One-line diagram of ac electric arc furnace steel plant.

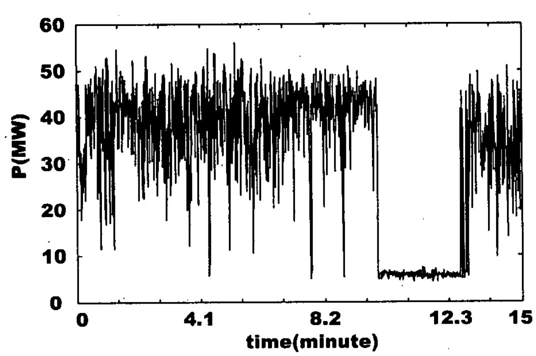

Fig. 2. The active power, P, during the interval of 15 minutes.

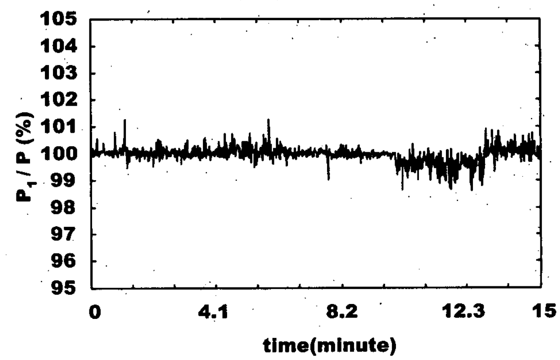

Fig. 3. The ratio of fundamental active power and active power, P_1/P, during the interval of 15 minutes.

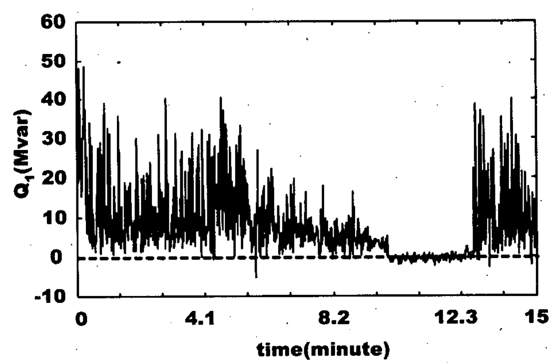

Fig. 4. The fundamental reactive power, Q_1, during the interval of 15 minutes.

The accumulative value is 1981 kvarh. The effective apparent power is shown in Fig. 5. The ratios of arithmetic apparent power, vector apparent power, fundamental apparent power, and modified fundamental apparent power to effective apparent power are shown in Fig. 6-9, respectively. The accumulative values of various apparent powers are given in Table 1. It reveals that the largest accumulative value is the effective apparent power, and the smallest value is the fundamental apparent power.

The calculation results of five average power factor and the corresponding bills are given in Table 2. It is found that

fundamental power factor > modified fundamental power > vector power factor > arithmetic power factor > effective power factor

Therefore, the largest revenue is obtained by using the effective power factor and the smallest revenue is by the fundamental power factor. The difference of monthly bill is NT$ 95,721 dollars (about 1 %).

Table 1. Accumulative values of apparent power, active power, and reactive power in the 15-minute period

apparent power definition	accumulative values		
	kVAh	kWh	kvarh
arithmetic	8717	7938	
vector	8625	7938	
effective	8784	7938	
fundamental	8178	7940	1955
modified fundamental	8184	7940	1981

Table 2. Average power factor values and monthly bills

Power factor definition	Average power factor value	monthly bill (NT dollars)
arithmetic	0.9106	9,494,730
vector	0.9203	9,480,658
effective	0.9038	9,504,668
fundamental	0.9710	9,408,947
modified fundamental	0.9702	9,410,036

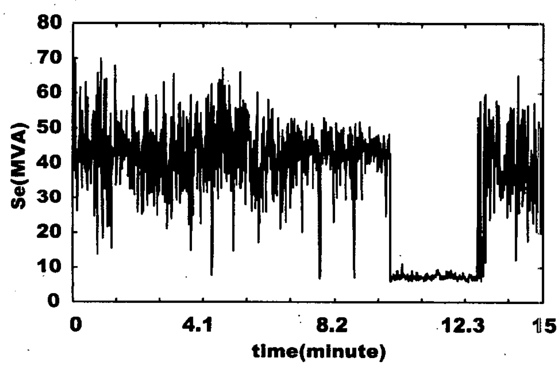

Fig. 5. The effective apparent power, S_e, during the interval of 15 minutes.

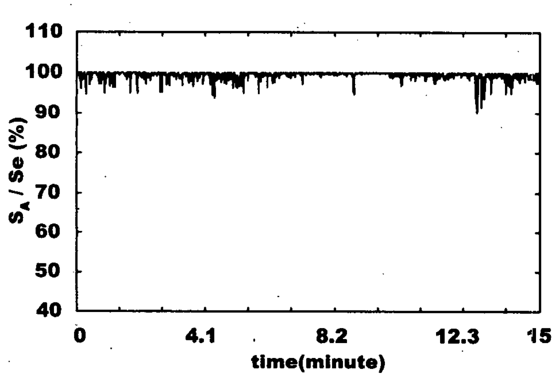

Fig. 6. The ratio of arithmetic apparent power and effective apparent power, S_A/S_e, during the interval of 15 minutes

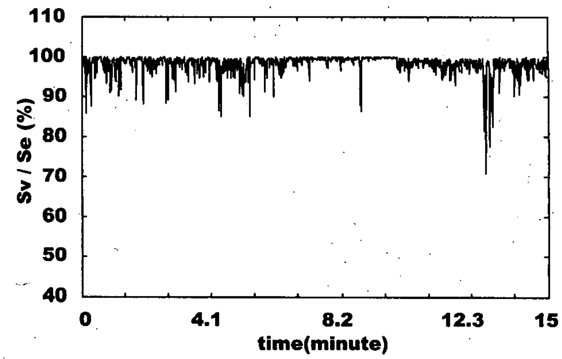

Fig. 7. The ratio of vector apparent power and effective apparent power, S_V/S_e, during the interval of 15 minutes.

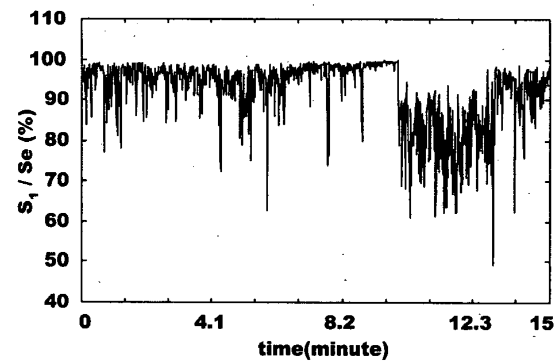

Fig. 8. The ratio of fundamental apparent power and effective apparent power, S_1/S_e, during the interval of 15 minutes.

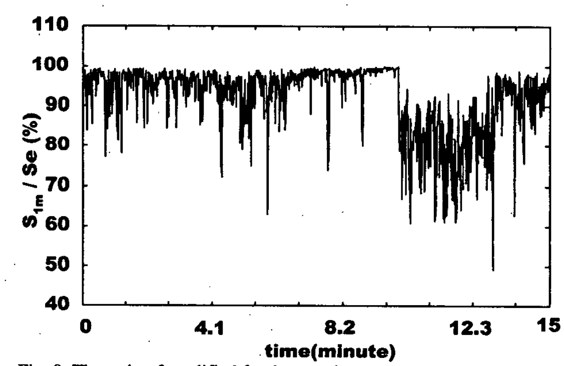

Fig. 9. The ratio of modified fundamental apparent power and effective apparent power, S_{1m}/S_e, during the interval of 15 minutes.

V. CONCLUTION

This paper compares the power factor definitions in the revenues of an electric arc furnace plant. Although the differences of the calculated bills are less than 1%, it still makes a huge difference for those large-scale bills with monthly revenue closed to 10-million NT dollars. Today many utilities adopt the fundamental components to calculate the power factor and ignore unbalanced conditions. This revenue evaluation may be unreasonable. A more suitable and complete consideration must be applied to the calculation of power factor in order for the customers to pay more attention on power quality and to encourage them to improve it.

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