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Voltage Flicker Mitigation Using STATCOM and BESS

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***Summary*: The Voltage flicker, a phenomenon of annoying light intensity fluctuation, caused by rapid change in industrial and domestic load such as Electric Arc Furnaces (EAF), rolling mills, welding equipments and pumps operating periodically has been a major concern for supply utilities, electricity regulatory agencies and customers. Static Voltage Compensators (SVC's) and Static Synchronous Compensators (STATCOM) have been able to solve the voltage flicker problem by rapidly controlling the reactive power. But, the control of active power along with reactive power control helps to mitigate the voltage flicker problem more effectively. In this paper, voltage flicker mitigation of EAF with STATCOM along with Battery Energy Storage System (BESS) is presented and performance results of the system using PSCAD/EMTDC software are analyzed.**

Keywords:
Battery Energy Storage System,
Power Quality,
Voltage Flicker,
SVC,
STATCOM

1. INTRODUCTION

Power quality in distribution system has been attracting an increasing interest during recent years. Research studies include the quality of voltage supply with respect to temporary interruptions, voltage dips, harmonics, and voltage flicker. Erratic variation in reactive power demands lead to a fluctuating voltage drops across the impedance of a distribution system which result in voltage fluctuation at the point of common coupling (PCC). These fluctuations result from the presence of non-linear loads (cyclic loads), including electric arc furnace, rolling mills in the steel works, large mine hoists, and resistance welders. Other load categories such as motor starting and sudden load switching produce random flicker. These voltage fluctuations drastically affect the quality of energy distributed by supply utilities [1]. The voltage fluctuation causes an annoying variation in the output illumination from incandescent or fluorescent lamps. The severity of the annoyance is generally dependent on the frequency and amplitude of the voltage variation and the short circuit capacity of the PCC. It is reported that a small voltage fluctuation of less than 0.5% in the frequency range of 5-10 Hz can cause a visible and uncomfortable incandescent flicker [2].

In addition to the perceptible and sometimes irritating lighting flicker to humans, voltage flicker can also cause electrical equipment efficiency drop, torque and power oscillations, and interference in protection systems. Now a day, consumers require high quality power supply for their sensitive loads. The voltage flicker has therefore been an important power quality concern for supply utilities, regulatory agencies and customers. To quantify the degree of voltage flicker and its mitigating solutions various definitions and standards have been proposed [3, 4]. The IEEE Standard 1453-2004 [5], which is referred widely, defines maximum permissible voltage flicker levels with respect to frequency as shown in Figure 1.

Several non-linear loads such as Electrical Arc Furnaces (EAF), Resistance Welding Equipment do not only generate harmonics, but also voltage dips. The voltage across an arc varies because the length of the arcs varies with a degree of randomness, causing the phenomenon of voltage flicker. Instantaneous fluctuation with large amplitude of active and reactive power in the non-linear load as mentioned above are the source of voltage flicker in an electric power system. Traditionally, for a mainly inductive supply system, power quality can be improved by using reactive power control methods. But for the loads as mentioned above, only adjusting reactive power is not enough. Power Electronics capable of switching at high power have led to the application of Static Voltage Compensators (SVC's) and Static Synchronous Compensators (STATCOM).

These devices have been able to solve the power quality problems in distribution and transmission systems by rapidly controlling reactive power [6]. But for the power quality problems caused by the loads as mentioned above, things are quite different. For effective mitigation, the mitigating device needs to provide the control and support of real power in addition to the reactive power control.

Advances in both battery energy storage technologies and the necessary power electronic interface have made Battery Energy Storage Systems (BESS) a viable technology for high power utility. The power industry's demands for more flexible, reliable and fast active power compensation devices make the ideal opportunity for ESS application [7].

In this paper, an EAF model with actual data is used. Using this model, the problems caused by the EAF in a distribution

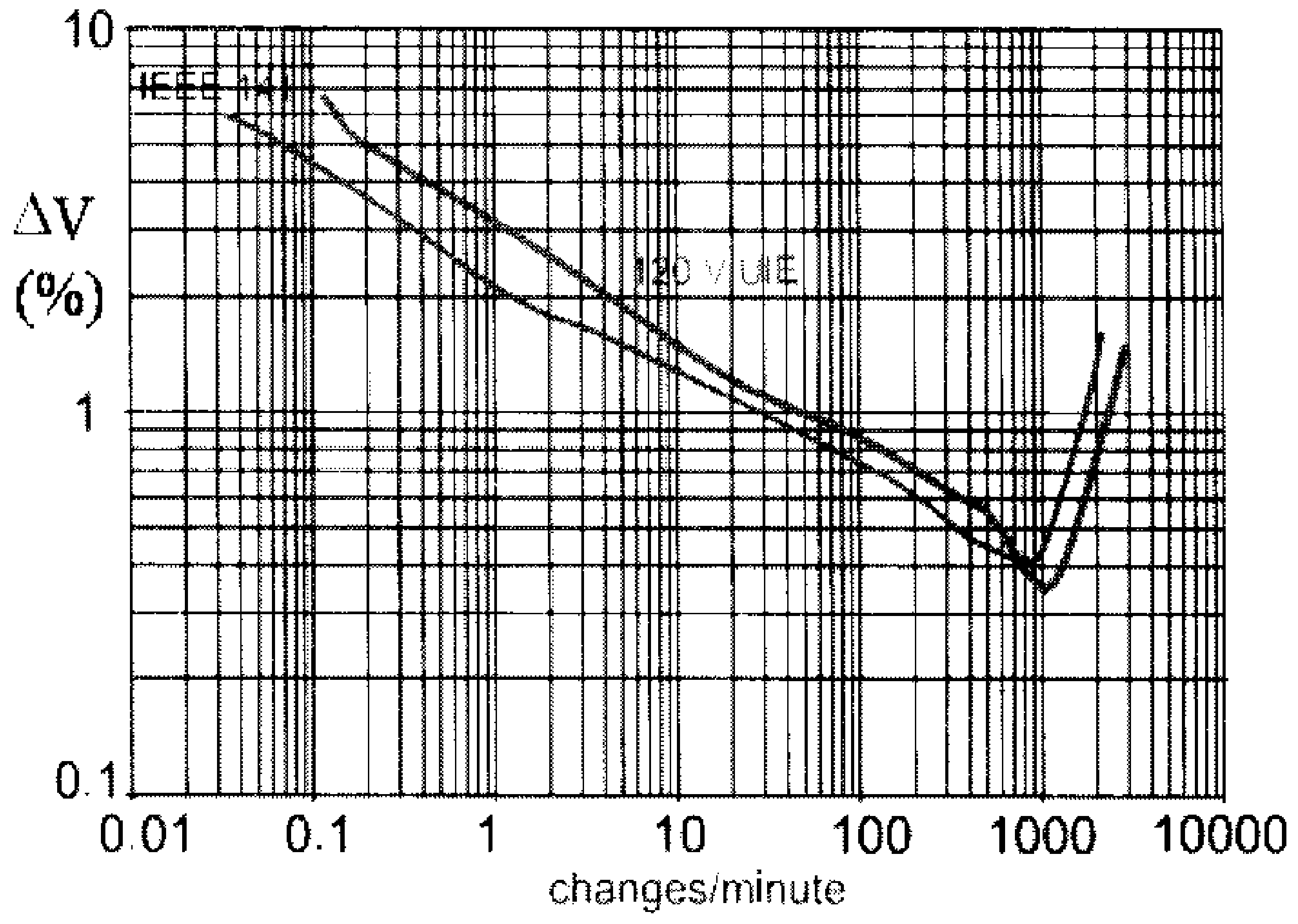


Fig. 1. Maximum permissible voltage fluctuations

power system have been presented. The paper presents the solutions for the EAF induced problems by STATCOM/ BESS, especially the compensation of active power to solve the voltage oscillation and power fluctuation problem. The study results show that the STATCOM/ESS system holds an advantage over more conventional methods because of its real power control capability.

2. EAF FLICKER MODEL

The Arc furnace operation is a complicated dynamic arcing process. Historically, there are various methods to model arc furnace, such as arcing resistance model, harmonics accumulation model and frequency domain method [8, 9]. These methods can match the non-linear v-i curve, stochastic and even chaotic characteristics of EAF, therefore, they are satisfactory for the purpose of power quality analysis. By examining the actual V-I characteristic of arc furnace, in general the arc melting process can be divided into three periods. For convenience of study, some approximations are made according to these three periods, which are explained below:

1) In the first period the arc begins to reignite from extinctions. When the arc voltage increases to zero, the arc current also reaches its zero crossing point. As the arc voltage increases to the reignition voltage V_{ig}, the equivalent circuit acts as an open circuit. However, a small leakage current exists, which flows through the foamy slag parallel to the arc. The foamy slag is assumed to be a constant resistance R_g, and the reignition voltage is assumed to be proportional to the arc length.
2) In the second period, the arc is established. A transient process appears in the voltage waveform at the beginning of arc melting process. The arc voltage drops suddenly from V_{ig} to a constant value V_d. This process is assumed to be expressed as an exponential function with time constant τ_1.

During the third period, the arc begins to extinguish. The arc voltage continues to drop smoothly, except a sharp change after the arc extinction. This process is also assumed to be represented by an exponential function with a time constant τ_2.

Following the above approximation, the arc model can be expressed in the form of current controlled nonlinear resistance as represented by (1):

$$R_a = \begin{cases} R_g \, 0 \le |i| \prec i_{ig} \\ and \dfrac{d|i(t)|}{dt} \succ 0 \\ \left(V_d + \left(V_{ig} - V_d\right) e^{-\left(|i| - i_g\right)/\tau_1} \right) / |i| ; |i| \ge i_{ig} \\ and \dfrac{d|i(t)|}{dt} \succ 0 \\ \left(V_t + \left(V_{ig} - V_t\right) e^{-|i|/\tau_2}\right) / \left(|i| + i_{ig}\right); \dfrac{d|i(t)|}{dt} \prec 0 \end{cases} \tag{1}$$

c

With the continuous condition of the arc resistance at the maximum current value I_{max} and the experimental formulas, some parameters in (1) can be calculated as (2):

$$\begin{cases} V \approx 1.15 * V_d \\ i_{ig} = \dfrac{V_{ig}}{R_g} \\ V_t = \dfrac{I_{max} + i_{ig}}{I_{max}} V_d \end{cases} \tag{2}$$

Normally, the average arc voltage V_d has a linear relationship with the average arc length l, that is:

$$V_d = A + Bl \tag{3}$$

Where A and B are constant. Thus the nonlinear resistance is controlled by arc length.

As shown in Figure 2, a flicker model consisting of switching passive loads is proposed to model EAF flicker under worst case condition. This behavior model can represent similar impedance as real-world EAF and therefore produces similar flicker at PCC.

From the real-time recorded waveform of EAF, the flicker can be summarized as below: (1) the flicker frequency: around 5Hz; (2) the flicker magnitude (ΔV/V): around 1%; (3) Source Xs/Rs; around 3 [10].

Since the 1% flicker is beyond the IEEE irritability threshold curve of IEEE standard [4], the mitigation device has to be applied to mitigate the flicker to an acceptable range.

3. FLICKER MEASUREMENTS

A flicker meter is an instrument used to measure illumination fluctuations. Mostly, for simplicity, the illumination fluctuations are not directly measured, but indirectly with the supplying voltage as input to the meter. There are number of commercial flicker meters which are being used for measurement of flicker. The IEC flicker meter [5] evaluates the voltage and gives an output value describing the flicker obtained with standardized 60W/230 V bulb. The flicker meter in total thus emulates the transfer function of voltage-bulb-eye-brain and gives an output that corresponds to the disturbance level. From the statistical part, one of the outputs is presented each 10 minutes, the short time flicker severity. This output is called Pst, P stands for papillotment (French for Flicker) or perception and st for short time. The

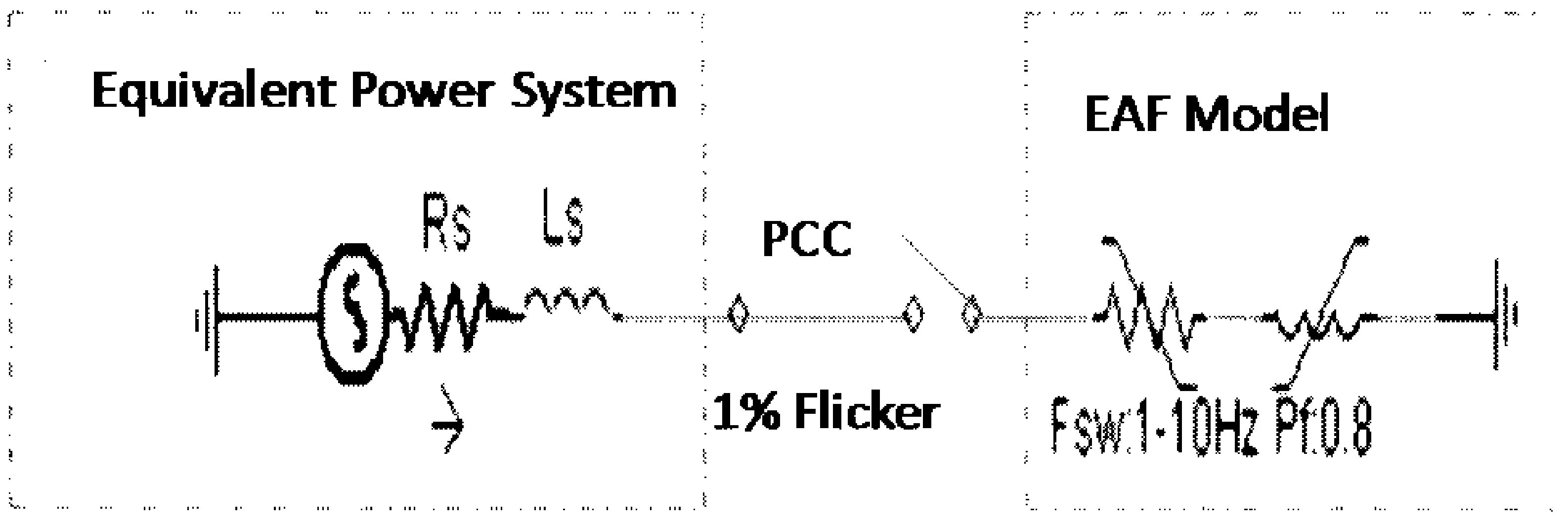


Fig. 2. Worst-case Flicker Model of Electric Arc Furnace

other flicker measurement, Plt, is calculated from Pst values every second hour with a cubic squaring law as:

$$Plt = \sqrt[3]{\frac{\sum_{i=1}^{N} Pst_i^3}{N}} \qquad (4)$$

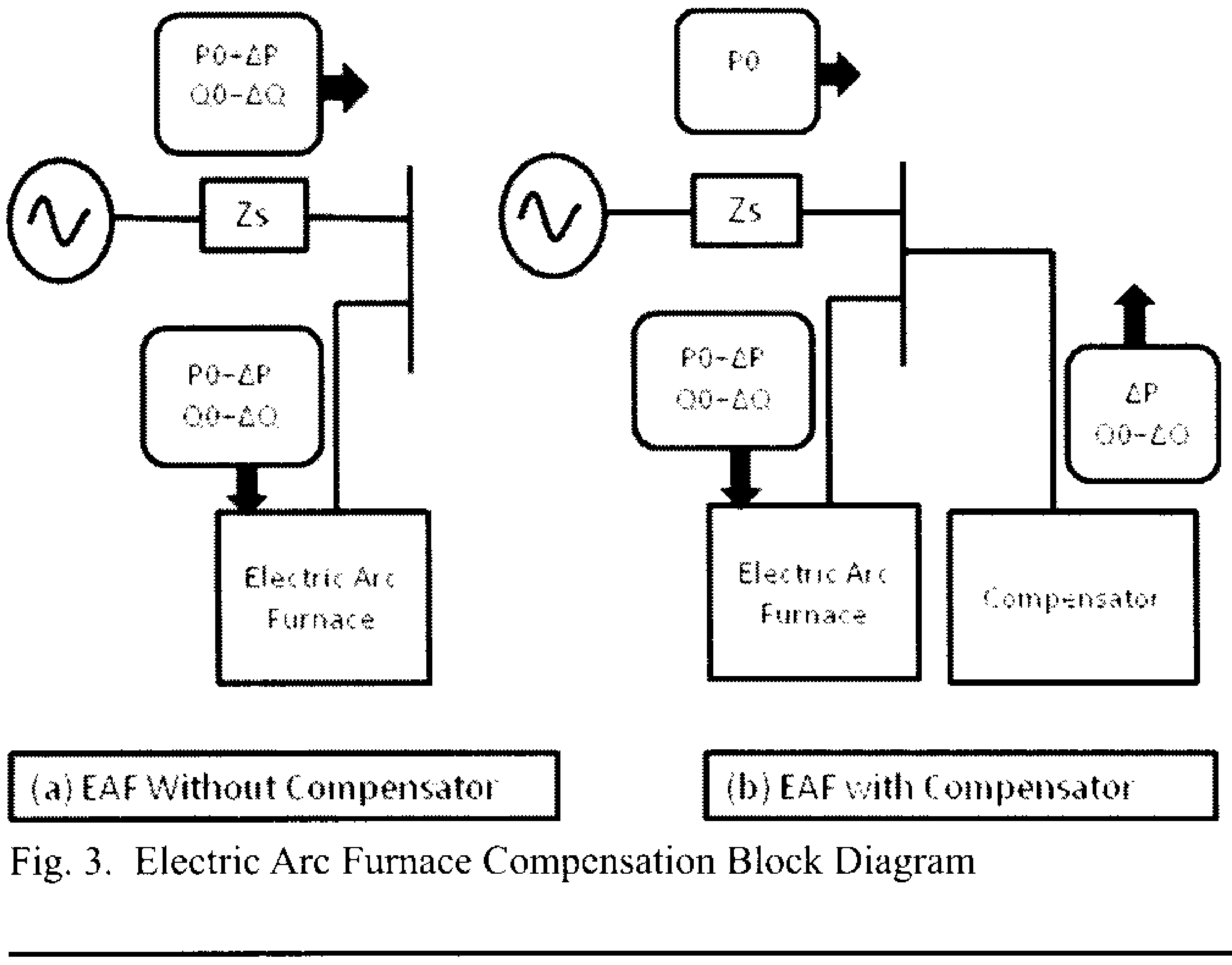
Since the Pst is calculated every 10 minute, N in the summation above will be equal to 12. To ascertain the effectiveness of flicker mitigation strategy the flicker meter is simulated in PSCAD/EMTDC, which gives the instantaneous flicker level (IFL). The IFL is processed using the MATLAB code to give the Pst(2s).

4. FLICKER MITIGATION SOLUTIONS

From power flow point of view, the basic principle of flicker mitigation solution can be simply explained as shown in Figure 3.

The power consumed by EAF can be regarded as a constant power (P_0, Q_0) plus a fluctuating power (ΔP, ΔQ). Generally, P_0 affects the angle stability, load power factor and ΔP is mainly related to the fluctuations of bus voltage magnitude. To solve the EAF power quality issues, ideally, it is obvious to compensate Q_0, ΔP and ΔQ so that the supply only provides the constant P_0 with unity power factor, and, thereby, the bus voltage magnitude and angle is kept constant. However, because of cost-effectiveness and other factors, Q_0, ΔP and ΔQ cannot be fully compensated, but only mitigated to an acceptable level in the real world. Particularly, ΔP mainly affects the voltage angle other than flicker and requires energy storage source for compensation. Flicker Mitigation techniques can be classified into three types: (1) Passive filters, which can be either series or shunt [11]. The passive filters are simple, reliable, low-cost and highly efficient, it is difficult to design for a stiff system, time consuming for tuning, easy to induce resonance, and not, susceptible to system impedance variations. (2) Series active compensators, such as series impedance regulation [12].

Moreover, it is also expensive and cumbersome to control the upstream transformer reactance in today's deregulated power system. (3) Shunt active compensator, such as SVC and STATCOM. SVC can improve the power quality and increase the EAF productivity leading to additional economic benefits. However, it cannot react to the fast varying flicker (1Hz-20Hz) very well within the inherent limit of relatively low bandwidth and its dynamic performance for flicker mitigation is limited. The state-of-art solution is the STATCOM based on high frequency switching voltage source converter (VSC). While SVC performs as controlled reactance admittance, STATCOM functions as synchronous voltage source. The STATCOM response time is less than one cycle and follows the fast changing flicker well. Moreover, STATCOM can also provide real power compensation if interfaced with energy storage unit [6].



(a) EAF Without Compensator (b) EAF with Compensator

Fig. 3. Electric Arc Furnace Compensation Block Diagram

5. MATHEMATICAL MODEL STATCOM WITH BESS

In a transmission/distribution line voltage support applications, the STATCOM provides a controlled source of reactive power by drawing balanced positive sequence currents from the line at fundamental frequency. However, if the voltage source inverter in the STATCOM is appropriately designed with high bandwidth control capability, then it can be used to force three phase current of arbitrary wave-shape through the tie-inductance into the power line. This unique capability makes the STATCOM an ideal candidate for flicker mitigation.

The ac supply bus for a non-linear load prone to flicker, the STATCOM can thus be made to supply those components of the load comprising non-sinusoidal, unbalanced, randomly fluctuating currents, in addition to the fundamental reactive power. These are precisely the components which are associated with flicker production when they must be supplied through the utility power network. When these components are supplied by the STATCOM they no longer flow through the power network and the voltage flicker is drastically reduced.

5.1. Battery Energy Storage System

The STATCOM will not normally have a source of real power connected to its dc terminals. It is therefore unable to supply sustained real power or real power fluctuation below a certain frequency. It can only affect the active power flow in the power system indirectly by regulating the voltage at the point of connection with the transmission line. If a bulk energy storage device like a battery is connected across the dc capacitor, the power regulation ability of a common STATCOM can be expanded to both reactive and active power compensation [12, 13].

A battery energy storage (BES) system acts as a quasi-voltage source. It maintains a relatively constant terminal voltage while supplying or absorbing variable current on demand up to a maximum safe limit. The state of charge, however, will define the "constant" operating voltage. Close to depletion, the voltage level can drop to 85% of its initial value. During discharge, the power interface, drawing constant power, will have to conduct increasing current as the terminal voltage of the BES decreases. Since BES is a constant voltage source, the output current flow from it can be interrupted, and it can be disconnected from the power interface.

A STATCOM, no matter whether connected to a battery or usually uses a high power voltage inverter to accomplish the dc to ac voltage conversion. There are different switching methods that can trigger the inverter and modulate the output voltage of the inverter. For a STATCOM with an energy storage battery, the switching method must provide control of the output voltage magnitude and phase angle.

In order to derive the monitoring level control of a battery, a dynamic model of the STATCOM and battery need to be set up.

In Figures 4, V_a, V_b, V_c represent the three phase line-to-neutral system voltage at the connection point. The voltages e_a, e_b, e_c represent the fundamental harmonic of three phase line-to-neutral output voltage of the STATCOM's inverter. The L and R represent the impedance of the transformer. The battery is represented by an ideal dc voltage source V, and a resistor R. This resistance also accounts for any losses in the inverter.

If, we assume the STATCOM is working in a balanced condition, then, we can define a reference frame transformation and make the attained dynamic model of the STATCOM and battery simple. The reference frame coordinate is defined where the d-axis is always coincident with the instantaneous system vector and q-axis is in quadrature with it. The transformation of variable is defined in equation (1) [14]:

$$[c]=\frac{2}{3}\begin{pmatrix} \cos\varphi & \cos\left(\varphi-\frac{2\pi}{3}\right) & \cos\left(\varphi+\frac{2\pi}{3}\right) \\ -\sin\varphi & -\sin\left(\varphi-\frac{2\pi}{3}\right) & -\sin\left(\varphi+\frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \tag{5}$$

Where ϕ is the angle between instantaneous system voltage vector and the A-phase axis of the abc coordinate. In the reference frame coordinate, the equation of the AC side circuit in Figure 4 can be written as:

$$p\begin{bmatrix} i_d \\ i_q \end{bmatrix}=\begin{bmatrix} -\frac{R}{L} & \omega_0 \\ \omega_0 & -\frac{R}{L} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix}+\begin{bmatrix} \frac{\left(e_d-|v|\right)}{L} \\ \frac{e_q}{L} \end{bmatrix} \tag{6}$$

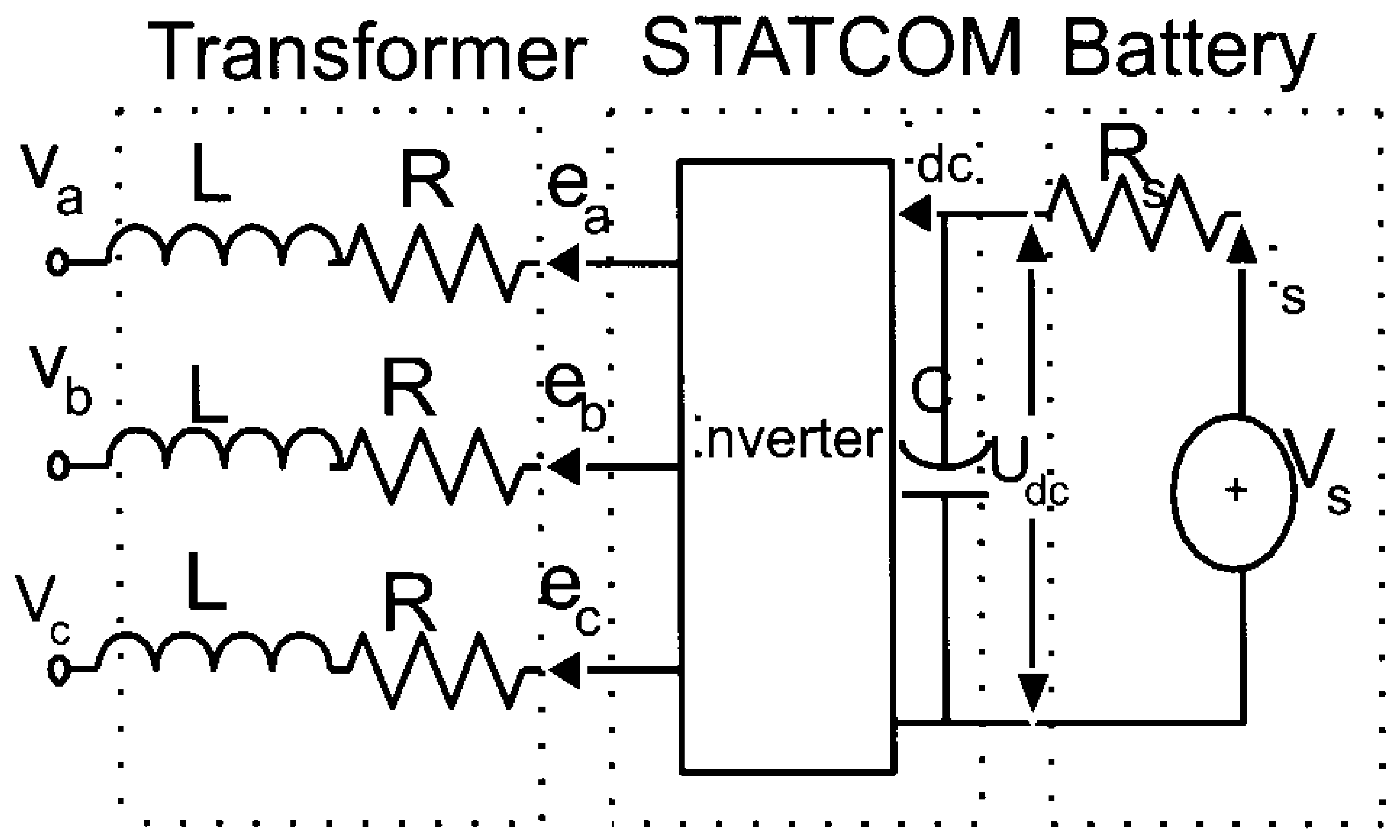


Fig. 4. Scheme of STATCOM with Battery

Where $p = d/dt$, $\omega_0 = 2\pi f_0$, $f_0 = 50$ Hz. The DC side equation can be written as:

$$\begin{aligned} &=\frac{1}{R_s C}\left(V_s-U_{dc}\right)-\frac{1}{C}i_{dc} \\ pV_{dc}&=\frac{1}{C}\left(i_s-i_{dc}\right) \end{aligned} \tag{7}$$

The instantaneous active power on the ac side of the inverter is calculated by:

$$P_{ac}=e_a i_a+e_b i_b+e_c i_a=\frac{3}{2}\left(e_d i_d+e_q i_q\right) \tag{8}$$

And the power on the dc side of the inverter can be expressed by:

$$P_{dc}=U_{dc}I_{dc} \tag{9}$$

Considering that the instantaneous active power exchanged between the ac and dc side of the inverter should be same, equation (10) must hold:

$$\begin{aligned} P_{ac}&=P_{dc} \\ U_{dc}I_{dc}&=\frac{3}{2}\left(e_d i_d+e_q i_q\right) \end{aligned} \tag{10}$$

So,

$$I_{dc}=\frac{3}{2}\left(\frac{e_d i_d+e_q i_q}{U_{dc}}\right) \tag{11}$$

When an inverter of a STATCOM operates in SPWM mode, its output voltage must satisfy the following equations:

$$\begin{aligned} e_d&=\frac{1}{2}U_{dc}M\cos\alpha \\ e_q&=\frac{1}{2}U_{dc}M\sin\alpha \end{aligned} \tag{12}$$

Where M is the duty cycle ratio of the sinusoidal reference wave and α is the firing angle of the sinusoidal reference wave referring to the system voltage vector.

Combining equation (7) with equation (6) and substituting equation (12) and equation (11) into them, we can set up a dynamic model for a STATCOM with battery.

$$p\begin{bmatrix} i_d \\ i_q \\ U_{dc} \end{bmatrix}=[A]\begin{bmatrix} i_d \\ i_q \\ U_{dc} \end{bmatrix}+\begin{bmatrix} \frac{U_{dc}}{2L}M\cos\alpha \\ \frac{U_{dc}}{2L}M\sin\alpha \\ -\frac{3I_d}{4C}M\cos\alpha-\frac{3I_q}{4C}M\sin\alpha \end{bmatrix}+\begin{bmatrix} -\frac{|v|}{L} \\ 0 \\ \frac{v_s}{R_s C} \end{bmatrix} \tag{13}$$

$$[A]=\begin{bmatrix} -\frac{R}{L} & \omega_0 & 0 \\ -\omega_0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{1}{R_sC} \end{bmatrix} \tag{13}$$

Equation (13) describes the dynamics of an affine nonlinear system. After linearization in the neighborhood of equilibrium point, the control system shown in equation (13) can be transformed into linear system as shown in equation (14):

$$p\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta U_{dc} \end{bmatrix}=[A_0]\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta U_{dc} \end{bmatrix}+[B_0]\begin{bmatrix} \Delta M \\ \Delta\alpha \end{bmatrix}$$

$$\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta U_{dc} \end{bmatrix}=\begin{bmatrix} i_d-i_{d0} \\ i_q-i_{q0} \\ U_{dc}-U_{dc0} \end{bmatrix},\ \begin{bmatrix} \Delta M \\ \Delta\alpha \end{bmatrix}=\begin{bmatrix} M-M_0 \\ \alpha-\alpha_0 \end{bmatrix}$$

$$[A_0]=\begin{bmatrix} -\frac{R}{L} & \omega_0 & \frac{M_0\cos\alpha_0}{2L} \\ -\omega_0 & -\frac{R}{L} & \frac{M_0\sin\alpha_0}{2L} \\ -\frac{3M_0\cos\alpha_0}{4C} & -\frac{3M_0\sin\alpha_0}{4C} & -\frac{1}{R_sC} \end{bmatrix}$$

$$[B_0]=\begin{bmatrix} \frac{U_{dc0}\cos\alpha_0}{2L} & -\frac{U_{dc0}M_0\sin\alpha_0}{2L} \\ \frac{U_{dc0}\sin\alpha_0}{2L} & \frac{U_{dc0}M_0\cos\alpha_0}{2L} \\ -\frac{3\left(i_{d0}\cos\alpha_0+i_{q0}\sin\alpha_0\right)}{4C} & \frac{3M_0\left(i_{d0}\sin\alpha_0-i_{q0}\cos\alpha_0\right)}{4C} \end{bmatrix}$$

Where the state variable is vector, and are the control variable vector. All the symbols with a subscription 0 in equation (14) represent the values at the equilibrium point. We will use the linear model to derive the monitoring level control of STATCOM with a battery.

5.2. P-Q Decoupled PI Control

In Figure 4, the active power P and reactive power Q on the power system side can be calculated in the reference frame coordinate by equation (15):

$$P=\frac{3}{2}|v|i_d,\quad Q=\frac{3}{2}|v|i_q \tag{15}$$

Thus, realizing PQ decoupled control means realizing i_d, i_q decoupled control.

We assume that there is no active power exchange when the STATCOM and battery are working at the equilibrium point. Thus, $i_d0=0$ and $\alpha_0=0$. Therefore, we can simplify the matrix A_0 and B_0 in equation (10) into the form:

$$[A_0]=\begin{bmatrix} -\frac{R}{L} & \omega_0 & \frac{M_0}{2L} \\ -\omega_0 & -\frac{R}{L} & 0 \\ -\frac{3M_0}{4C} & 0 & -\frac{1}{R_sC} \end{bmatrix}$$

$$[B_0]=\begin{bmatrix} \frac{V_{dc0}}{2L} & 0 \\ 0 & \frac{V_{dc0}}{2L} \\ 0 & -\frac{3M_0 i_{q0}}{4C} \end{bmatrix} \tag{16}$$

By substituting equation (16) into equation (14) and rewriting first two rows of equation (14) yields:

$$p\begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix}=\begin{bmatrix} -\frac{R}{L} & 0 \\ 0 & -\frac{R}{L} \end{bmatrix}\begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix}+\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{17}$$

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}=\begin{bmatrix} \frac{U_{dc0}}{2L}\Delta M_0+\omega_0.\Delta i_q+\frac{M_0}{2L}\Delta U_{dc} \\ \frac{U_{dc0}M_0}{2L}\Delta\alpha_0-\Delta\omega_0.\Delta i_d \end{bmatrix}$$

Where is an introduced new control variable vector. Therefore, the i_d, i_q decoupled control has already been realized.

If we set:

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}=\begin{bmatrix} \left(k_1+\frac{k_2}{p}\right).\left(i_{d\_ref}-i_d\right) \\ \left(k_1+\frac{k_2}{p}\right).\left(i_{q\_ref}-i_q\right) \end{bmatrix} \tag{18}$$

Where:

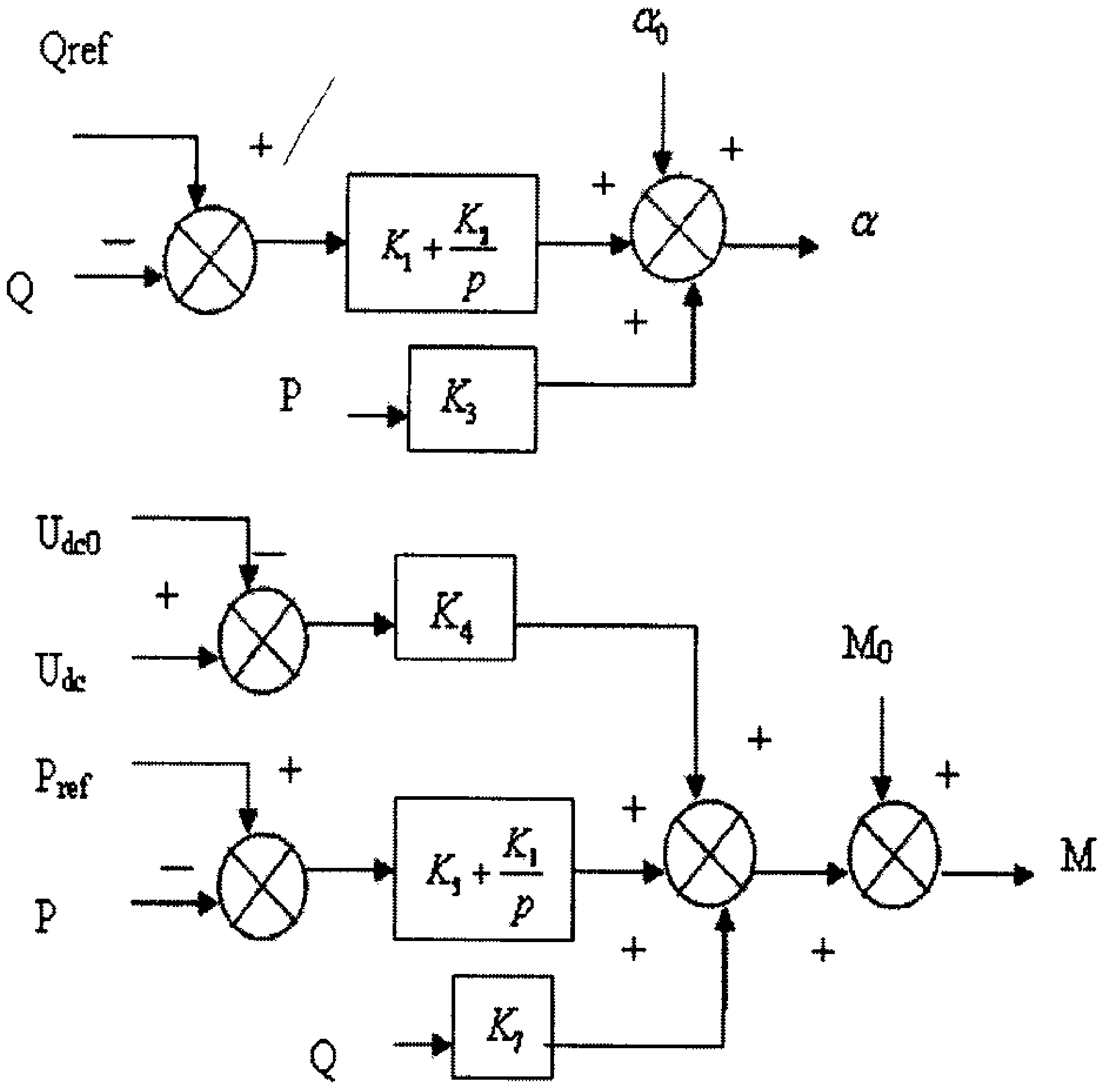


Fig. 5. Control scheme for the mitigating system

$$\left[i_{d\_ref}\quad i_{q\_ref}\right]^T = \left[\frac{2P_{ref}}{3|v|}\quad \frac{2Q_{ref}}{3|v|}\right]^T, P_{ref}, Q_{ref}$$

are the PQ reference, and k_1 k_2 are integration and proportion gain, a PQ decoupled PI control strategy is finally obtained as shown figure 5.

5.3. The PV decoupled PI Control

If it is assumed that the firing angle α mainly affects the variation of the active power P exchanged between the power system and the STATCOM, and the duty cycle ratio M mainly regulates the magnitude of the STATCOM's output voltage and therefore the system voltage magnitude, then, we can derive an approximate PV decoupled PI control as shown in equation (19):

$$\Delta\alpha = \left(k_1 + \frac{k_2}{p}\right).\left(P_{ref} - P\right)$$
$$\Delta M = \left(k_1 + \frac{k_2}{p}\right).\left(V_{ref} - V\right) \tag{19}$$

Where V_{ref} and V represent the system voltage reference and system voltage magnitude respectively.

6. CONTROL STRATEGY

Conventionally, mainly fluctuations in reactive power of a load have been considered to cause flicker since a fluctuation voltage drop occurs across the reactance of the grid. This is basically true, but the flicker generation is more complicated [10].

For control studies, the system was transferred into dq frame rotating synchronously with the alternating voltage. The more general concepts for real and reactive power proposed by Akagi et al. [15] were used to study the instantaneous electrical properties. Through this theory, the arc furnace current was split up in one real component, i_d, in phase with the instantaneous voltage and one imaginary component, i_q, in quadrature with voltage. With a dynamic calculation, it was found that the voltage fluctuations in the PCC were caused by three different components; the imaginary current, the real current and the derivative of the real current. By using a flicker mitigating unit without energy storage, it is however not possible to directly compensate for the fluctuations in active load power. If the compensator current i_c instead is set up as:

$$\bar{i}_c = j\left(i_q + i_d \frac{R}{X} f(\theta) + \frac{1}{\omega}\frac{di_d}{dt} f(\theta) + K\right) \tag{20}$$

The voltage fluctuations in the PCC would ideally be nullified. R and X are the resistance and reactance of the grid respectively. ω is the synchronous line frequency and $f(\theta)$ is correction factor due to phase shift across the transformer.

7. DIGITAL SIMULATIONS

Digital Simulation employing the control strategy given above is carried out for the system shown in Figure 6. The STATCOM is represented in two ways: first as an ideal current source without any energy storage and then with energy storage.

The first investigation was performed with the ideal current source as a model of the STATCOM. With the arc furnace represented as a constant resistance added to the sinusoidal varied resistance per phase, the flicker mitigation performance was investigated. The voltages at the point of common coupling are shown in Figures 7, 8 and 9 for the EAF without STATCOM, with STATCOM and with STATCOM along with BESS respectively.

Table 1. System Components and its ratings.

System Components	Rating
Utility Source Voltage	31.5 kV
Furnace Transformer	31.5/0.9 kV, 100 MVA
Arc Furnace	100 MVA, 0.8 p.f.
STATCOM	-30 to +90 MVAr
BESS Storage Capacity	21.33 MWh

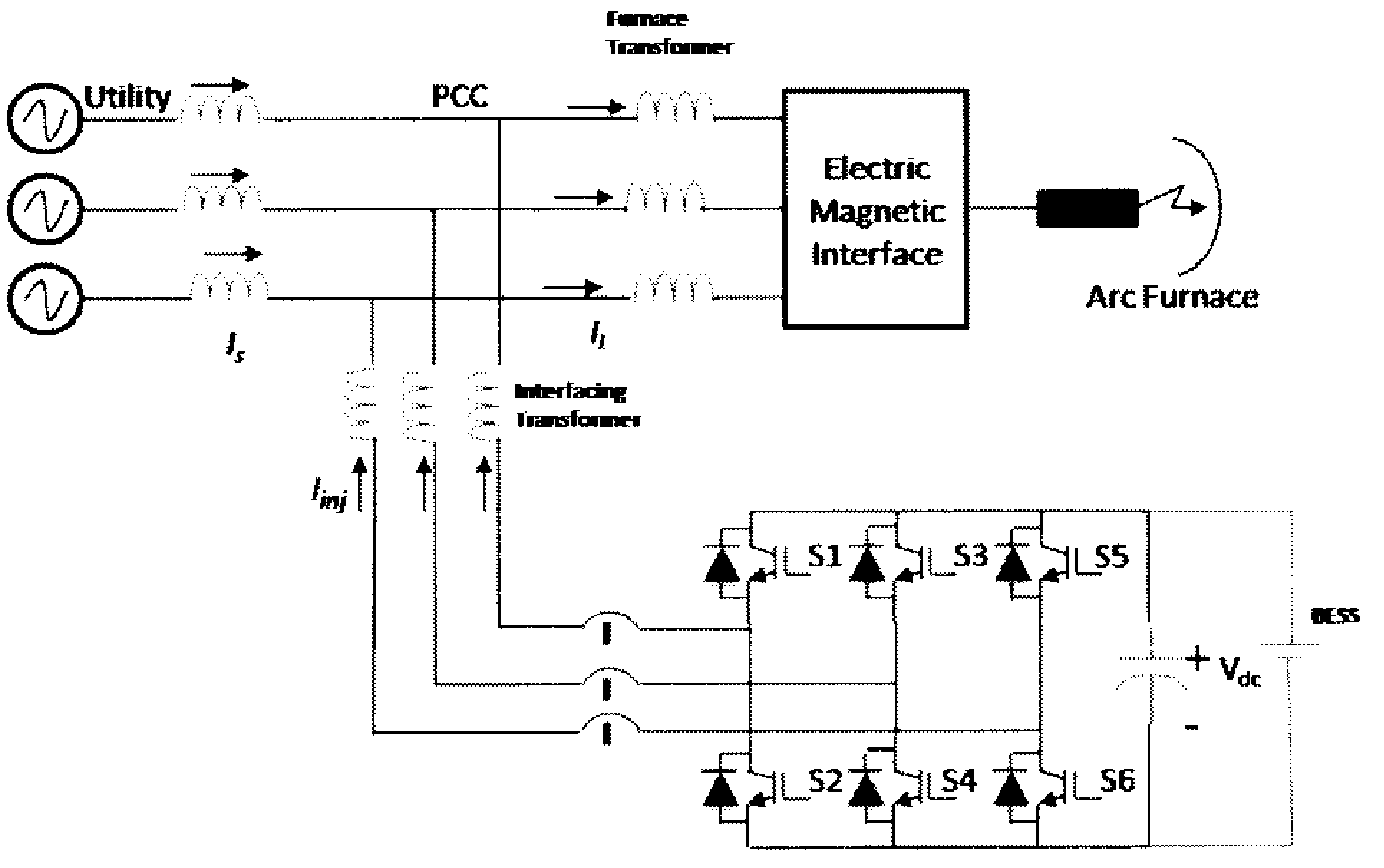


Fig. 6. The power circuit of the three-phase STATCOM with time varying arc furnace

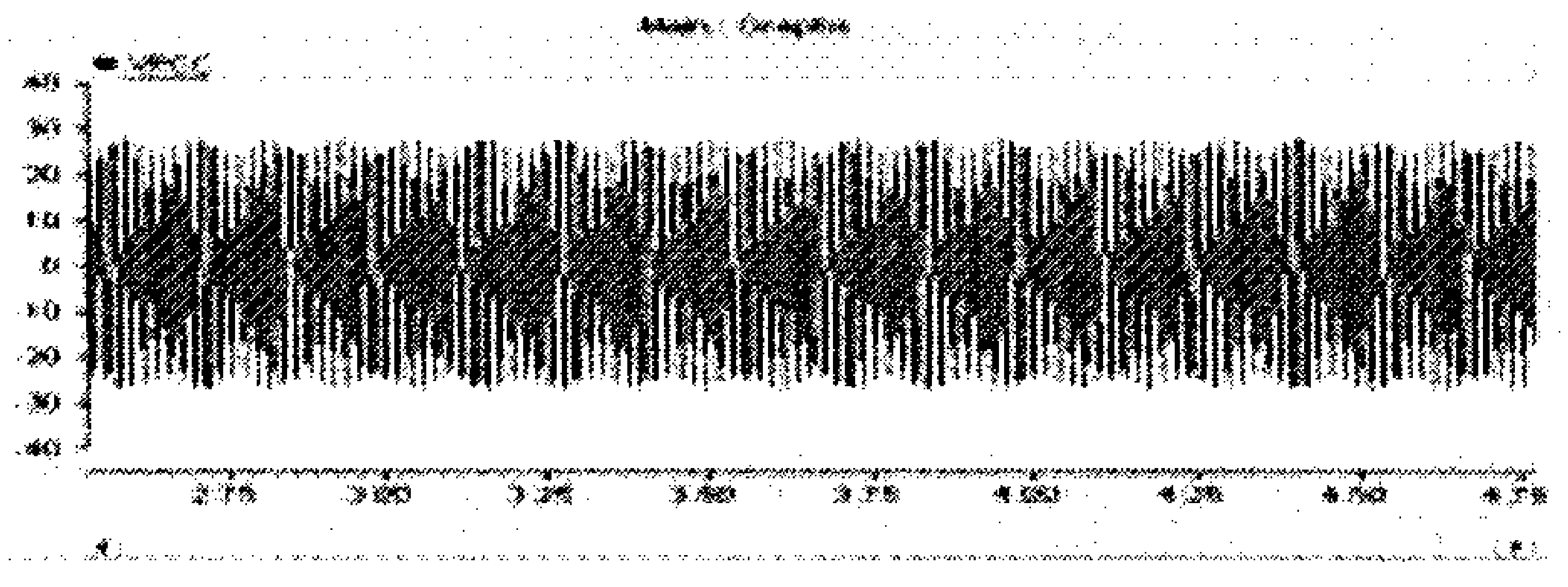


Fig. 7. Voltage at PCC without compensation

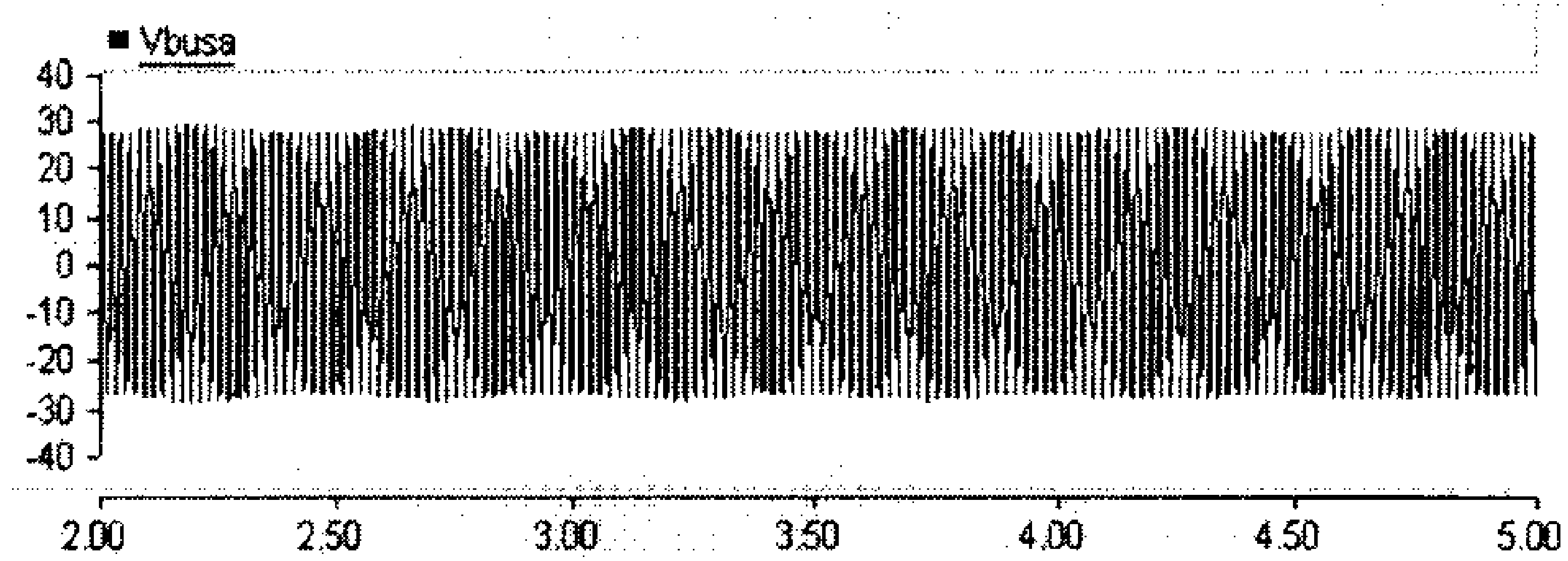


Fig. 8. Voltage at PCC with compensation of STATCOM

Table 2. Flicker severity index.

Compensation strategy	PST
No compensation means	3.5
Compensation with STATCOM without ESS	1.58
Compensation with STATCOM with ESS	0. 32

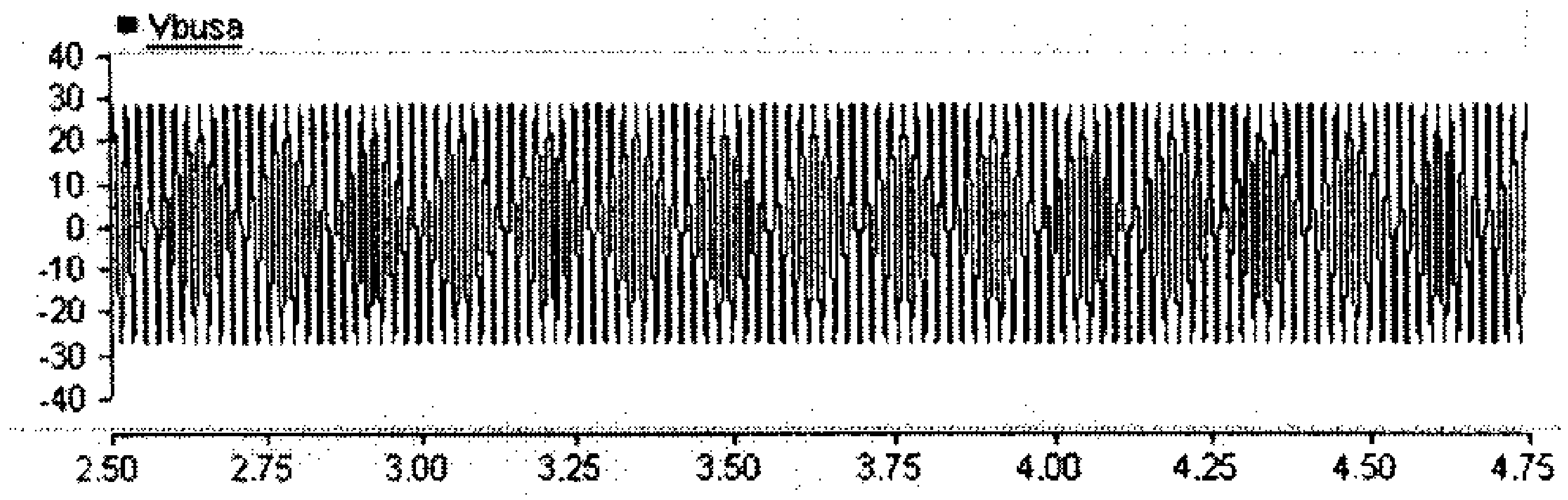


Fig. 9. Voltage at PCC with compensation of STATCOM and BESS

The Short Time flicker severity index (PST) for three different cases are s shown in Table 2.

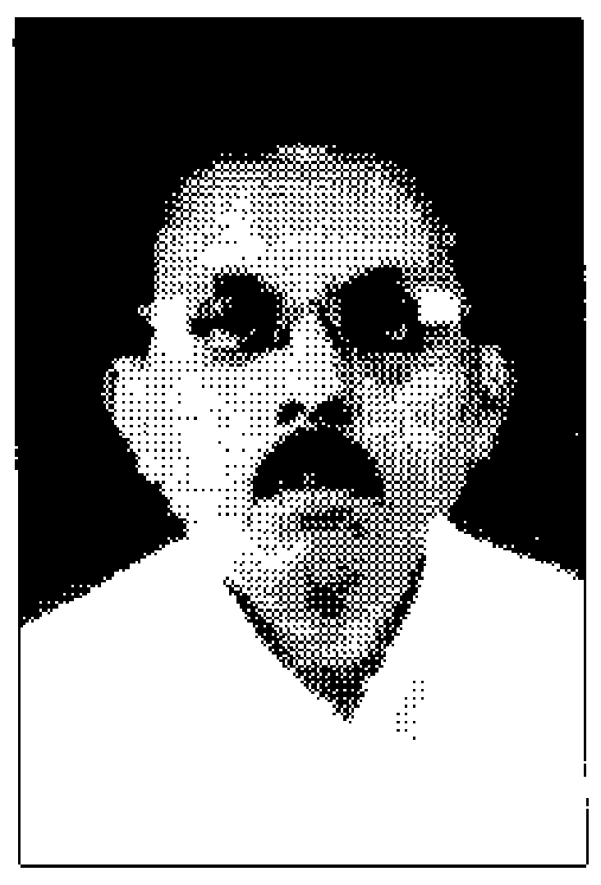
The result in Table 2 verifies the theory for flicker mitigation.

8. CONCLUSION

The paper describes mitigation of flicker due to electric arc furnace by means of STATCOM with Energy Storage System (ESS). In the investigations performed here, the flicker, as indicated by the PST (flicker) value of the PCC voltage, was initially 3.5 without any compensating devices. With STATCOM (without ESS) PST equals to 1.58 and with STATCOM and ESS it is 0.32. Incorporating the real power support in compensation improves the flicker mitigation to a significant level. It indicates that reactive power support along with real power support of compensator is more effective than reactive power alone.

REFERENCES

1. Montanari G.C., Logging M., Cavallin A., Pitti L.: *Flicker and distortion in electrical plants supplying arc-furnaces, in: Proceedings of the 1994.* IAS Annual Meeting, Colorado, October 1994, pp.2249–2255.
2. Ashole P. and Amante P.: *System Flicker disturbances from Industrial Loads and their compensation.* Power engineering Journal, Oct. 1997, pp.213–218.
3. *IEEE Recommended Practices for Electric Power Distribution for Industrial Plants.* 1994, IEEE Standard 141–1993.
4. *IEEE Recommended Practices for Harmonic Control in Electric Power Systems.* IEEE Standard 519-1992, 1993, pp. 80–82.
5. *IEEE Recommended Practices for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems.* 2004, IEEE Standard 1453.
6. Garcia-Gerrada A., Garcia-Gonzalez P., Collantes R.: *Comparison of Thyristor-Controlled Reactor and Voltage Source Inverters for Compensation of Flicker Caused by Arc furnaces.* IEEE Trans power Delivery, vol. 15, 2000, pp. 1225–1231.
7. Yang Z., Shen C., Zhang L., Crow M. L. and Arcitty S.: *Integration of a STATCOM and Battery Energy Storage.* IEEE Trans Power System, Vol. 16, May 2001 ,pp.. 254–260.
8. Toxin Zheng, Makaram E.B.: *An Adaptive arc furnace model.* IEEE Trans on Power Delivery, vol. 15, July 2000, no. 3, pp.931–939.
9. Vardan S., Makaram E. B., Girgis A. A.: *A new time domain voltage source model for an arc furnace using EMTP.* IEEE trans on Power Delivery, vol. 11, July 1996 , no. 3, pp. 1685–1691.
10. Li Zhang, Yilu Liu, Ingram M.R., Bradshaw D.T., Eckroad S. and Crow M.L.: *EAF Voltage Flicker Mitigation By FACTS/ESS.* Power System Conference & Exposition, vol. 1, Oct. 2004, pp. 372–378.
11. Das J.C.: *Passive Filterss- potentialities and limitations.* IEEE Trans on IAS, vol. 40, no. 1, Jan. 2004 , pp-232-241.
12. Chong Han, Zhanoning Yang, Bin Chen, Alex Q. Haung, Bin Zhang, Michael Ingram, Abdel-Atey: *valuation of Cascade-Multilevel-Converter-Based STATCOM for Arc Furnace Flicker Mitigation.* IEEE Trans. On Industry Application, vol. 43, March-April 2007, No.2.
13. Chen Shen, Zhipping Yang, Mariesa L. Crow, Stan Atcitty: *Control of STATCOM with Energy Storage Device.* Proceedings of Power Engineering Society Winter Meeting (2000).
14. Schauder C.et al.: *Vector analysis and control of advanced Static VAR compensators.* IEE Proceeding-C Vol. 140, July 1993, No. 4.
15. Akagi H., Kanazawa Y., Nabae A.: *Instantaneous reactive power compensators comprising switching devices without energy storage components.* IEEE Trans. On Industry Application, vol. 1A-20, no. 3, May/June 1984, pp. 625–630.



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