7-1-2008

A Comparison of Linear and Nonlinear STATCOM Control for Power Quality Enhancement

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Abstract—**This paper introduces a multilevel STATCOM for electric arc furnace power quality enhancement. An eleven level cascaded multilevel converter is used to alleviate the impacts of an unbalanced arc furnace load. The STATCOM provides a power electronic-based means of embedded control for reactive power support.**

Index Terms—**Cascaded Multilevel Inverter, Arc Furnace, STATCOM, Power Quality**

I. INTRODUCTION

SOME industrial loads such as electric arc furnaces cause rapid and large swings in active and reactive power with harmonic distortion and phase imbalances. This fluctuation in load leads to fast nonperiodic voltage variations with appreciable voltage distortion. Customers who share the distribution feeder with these nonlinear loads frequently experience significant voltage variations that produce disturbances in their equipment operation.

The use of fast acting power electronics converters such as the static synchronous compensator (STATCOM) with fast and efficient controllers can provide precise and flexible control to alleviate disturbances and improve power quality.

In this paper, an eleven level cascaded multilevel STATCOM with PWM control is introduced to compensate for a nonlinear unbalanced load that emulates an electric arc furnace. There are many papers in the literature that utilize a STATCOM to enhance power quality [1-10], but few of them address how to *quantify* the improvement in power quality. Additionally, most STATCOM control is based on a linear approach; in this paper we introduce a nonlinear control for power quality improvement and compare it to traditional PI control.

II. SYSTEM MODELING

A. Electrical network

The single line diagram of the electrical distribution system feeding an arc furnace is shown in Fig. 1. The electrical network consists of a 115 kV generator and impedance that is equivalent of a large network at the point of common coupling (PCC). The STATCOM is connected to the system through a 115/25 kV Y-Delta transformer. The electrical arc furnace load is non-sinusoidal, unbalanced, and randomly fluctuating [11]. Also to improve the harmonic levels before the transformer, a $100\eta F$ parallel capacitor bank filter is used.

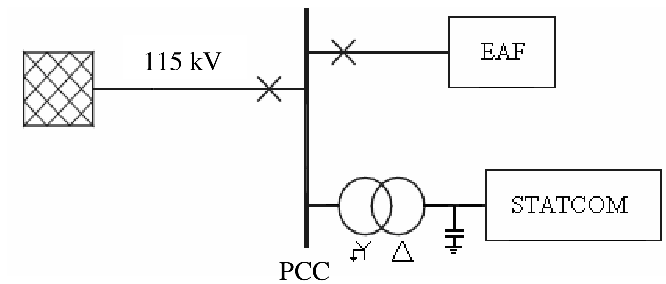


Figure 1. Case Study Network

B. Arc Furnace

Electric arc furnaces are typically used to melt steel and will produce current harmonics that are random. In addition to integer harmonics, arc furnace currents are rich in inter-harmonics. To synthesize the variations to the RMS waveform, an aperiodic waveform is generated by

$$\phi(t) = a_L \cos(\omega_L t + \theta_L) + a_H \cos(\omega_H t + \theta_H) + h \quad (1)$$

where ω_L and ω_H are randomly generated frequencies in the range of interest and a_L and a_H are randomly generated positive scalars such that $a_L + a_H \leq 1$. At each zero crossing, a new set of parameters $[a_L, \omega_L, a_H, \omega_H]$ are generated. The phase angles θ_L and θ_H are then calculated such that the waveform is continuous across the zero crossing.

For arc furnace applications, the low frequency component ω_L should be centered about a frequency in the 5-35 Hz range. The high frequency component ω_H should be centered about an odd integer multiple of ω_L. The human eye is particularly sensitive to variations around 10 Hz [11]. A non-sinusoidal randomly fluctuating flicker waveform can be produced from

$$\omega_L = 2\pi(1+\rho 8)$$

where $\rho \in [0, 1]$ is a randomly generated number. Similarly,

$$\omega_H = 2\pi(10+\rho 30)$$
$$a_L = 50\rho \text{ and } a_H = 10\rho$$

Figure 2 shows the unbalanced nonlinear resistances that have been modeled to produce the EAF load. The load imbalance is modeled by using a base resistance of 135 Ω for phases a and b, and a base resistance of 80 Ω for phase c.

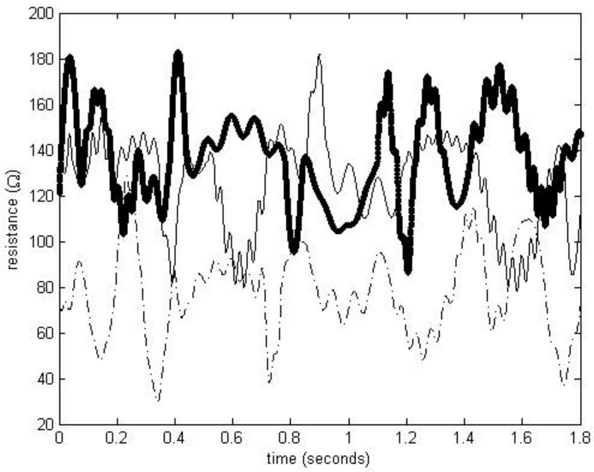


Figure 2. EAF flicker waveform

Figure 3 shows the frequency spectrum of the load signal. Note the clustering about 30 Hz and again around 8 Hz with a much wider frequency spread at low frequencies.

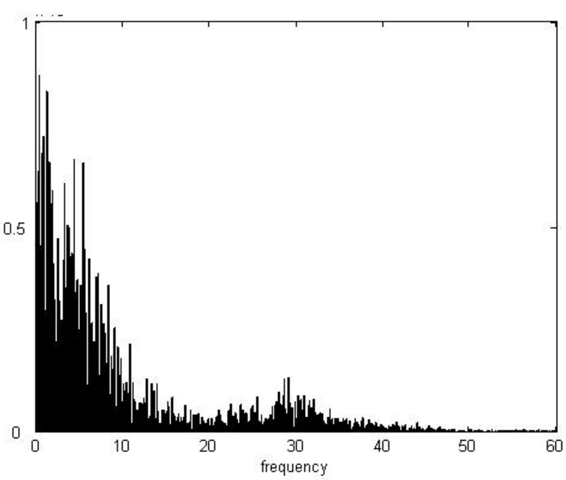


Figure 3. EAF flicker frequency spectrum

C. STATCOM

In this paper, the model of STATCOM (cascaded multilevel inverter) is implemented in PSCAD. The configuration of the STATCOM can be seen in Fig. 4 [3]. The power electronic switches are controlled to balance the internal DC capacitor voltages, a look up table has been used to select the redundant states (RSS) such that in each voltage level the lookup table will decide which capacitors should provide the desired voltage. The primary objective of this paper is to compare and contract two methods, one linear and one nonlinear to calculate the control parameters: the modulation index k and the modulation phase angle α.

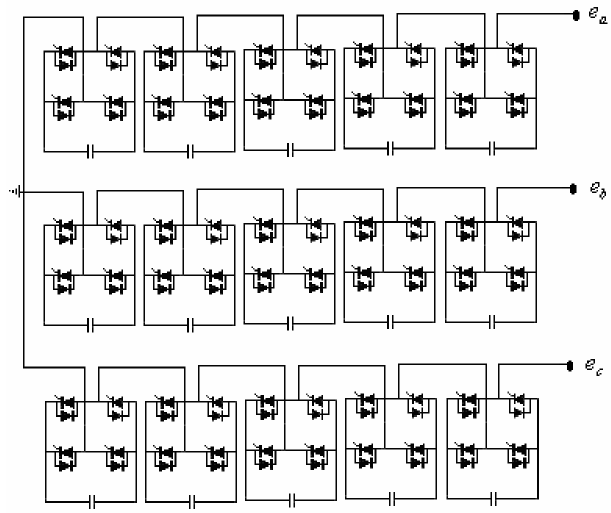


Figure 4. Eleven Level Cascaded Multilevel Inverter (STATCOM)

A cascaded multilevel STATCOM contains several H-bridges in series to synthesize a staircase waveform. The inverter legs are identical and are therefore modular. For our case study, each leg has five H-bridges. Since each full bridge generates three different level voltages (*V, 0, -V*) under different switching states, the number of output voltage levels will be eleven. This configuration is chosen because it has the following advantages comparing to other converter types:

1. It is more suitable to high-voltage, high-power applications than the conventional inverters since the currents and voltages across the individual switching devices are less,
2. It generates a multistep staircase voltage waveform approaching a pure sinusoidal output voltage by increasing the number of levels [3], and
3. It is far better than other types of multilevel converters in DC voltage balancing, because each bridge has its own DC source.

III. System Control

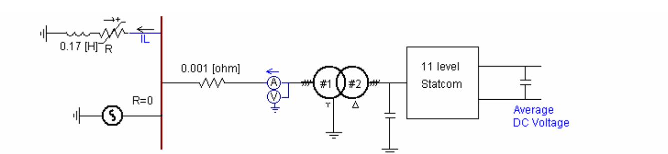
A. Pulse Width Modulation

Sinusoidal Pulse Width Modulation (SPWM) is utilized to control the power electronic switches. This strategy is used to synthesize a sinusoidal waveform proportional in magnitude to the modulation gain k and shifted by the phase angle α. The advantage of pulse width modulation is that both parameters k and α can be independently controlled. As the phase angle of the voltage on the converter side is changed with respect to the phase angle of the AC system voltage, the STATCOM will attempt to generate or absorb active power from the AC system. The exchanged active power will charge or discharge the internal DC capacitors.

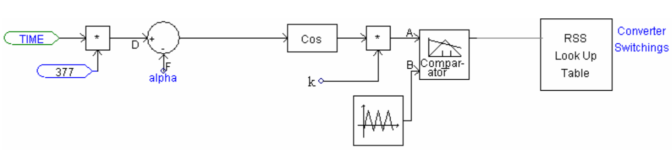
B. *Capacitor Voltage Balancing using Redundant State Selection (RSS)*

To achieve a high quality output voltage waveform, the voltages across all DC capacitors should maintain a constant value. However, the power system operation and modulation scheme together have different effects on each capacitor so that they are not charged and discharged evenly leading to different voltages in each leg of each phase. However, because of redundancy, there is always more than one switching state that can form any given voltage level. Therefore, there exists a "best" state among all the possible states that produces the most balanced voltages [2]. For example, if a DC capacitor is scheduled to charge, then the capacitor with the current lowest voltage is chosen to be charged. Thus, to balance the capacitor voltages, redundant state selection (RSS) is an effective tool in balancing the DC capacitor voltages.

In this method the capacitor balancing is going to be achieved by using the proper capacitor in each level in order to get the desired level dictated by SPWM. In each level if the current direction of the phase is tending to charge the capacitors the least charged ones should be used to maintain the desired level and if the current direction tends to discharge the capacitors the most charged capacitors come into play. Figure 5 shows the outline of the SPWM control system.



(a) System one-line diagram



(b) SPWM control

Figure 5. Control System

IV. Obtaining the Control Parameters

A. *Linear Control*

The primary control targets of a STATCOM are to control the AC line voltage (V_{stat}) and the DC capacitor voltage (V_{dc}). The AC voltage control is achieved by filtering out the second harmonic and the low frequencies of the AC voltage and then a lead-lag and a PI controller are applied to the voltage error in order to obtain the modulation phase shift α. The DC capacitor voltage error is put through a PI controller to provide the modulation index gain k. Figure 6 shows the linear control system.

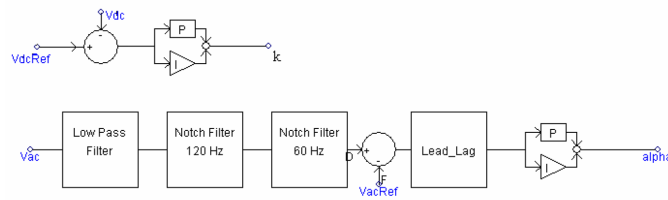


Figure 6. Linear Control Block Diagram

B. *Nonlinear Control Based on Energy Function*

Linear control has the advantages of simplicity, ease of implementation, and computational efficiency. However, the disadvantages include the requirement that it be tuned about a particular operating point. For this reason, nonlinear control sometimes provides improved performance. In this section, a nonlinear control is developed and applied to the 11-level cascaded STATCOM.

The STATCOM state equations are given by [7]:

$$p\begin{bmatrix} i_d' \\ i_q' \\ V_{dc}' \end{bmatrix} = [A]\begin{bmatrix} i_d' \\ i_q' \\ V_{dc}' \end{bmatrix} - \frac{\omega_b}{L'}\begin{bmatrix} |V'| \\ 0 \\ 0 \end{bmatrix}$$

where

$$[A] = \begin{bmatrix} \frac{-R_s'\omega_b}{L'} & \omega & \frac{k\omega_b}{L'}\cos(\alpha) \\ -\omega & \frac{-R_s'\omega_b}{L'} & \frac{k\omega_b}{L'}\sin(\alpha) \\ \frac{-3}{2}kC'\omega_b\cos(\alpha) & \frac{-3}{2}kC'\omega_b\sin(\alpha) & \frac{-\omega_b C'}{R_p'} \end{bmatrix} \quad (2)$$

The target values for the dq currents are given by

$$i_d^{'*} = (V_{dc}^{'*} - V_{dc}')(K_{pdc} + \frac{K_{Idc}}{s}) \quad (3)$$

$$i_q^{'*} = (V_{REF}' - |V'|)(K_{pac} + \frac{K_{Iac}}{s}) \quad (4)$$

where $i_d'^*$ and $i_q'^*$ are the per unit values of the desired active and reactive currents respectively and $V_{dc}'^*$ is the average value of the desired DC voltage.

The errors are defined as:

$$e_d = i_d'^* - i_d' \tag{5}$$

$$e_q = i_q'^* - i_q' \tag{6}$$

The control approach is developed based on minimizing the system energy. Recall that a positive definite Lyapunov function can be defined as:

$$W = \frac{c}{2}e_d^2 + \frac{c}{2}e_q^2, (c > 0) \tag{7}$$

where the derivative of (7) is given by:

$$\dot{W} = p_1 u_1 + p_2 u_2 + p_3 - c\frac{R_s \omega_s}{L_s}(e_d^2 + e_q^2) \tag{8}$$

where:

$$u_1 = k\cos(\alpha) \tag{9}$$

$$u_2 = k\sin(\alpha) \tag{10}$$

and

$$p_1 = -c\frac{\omega_s}{L_s}V_{dc}' e_d$$

$$p_2 = -c\frac{\omega_s}{L_s}V_{dc}' e_q$$

$$p_3 = c(e_d \frac{d}{dt} i_d'^* + e_q \frac{d}{dt} i_q'^*) + c\frac{R_s \omega_s}{L_s}(e_d i_d^* + e_q i_q^*)$$

$$-c\omega(e_d i_q^* - e_q i_d^*) + c\frac{\omega_s}{L_s}V' e_d$$

The derivative of the Lypunov function is guaranteed to be negative if

$$\dot{e}_d = -c_1 e_d \tag{11}$$

$$\dot{e}_q = -c_2 e_q \tag{12}$$

for positive constants c_1 and c_2. Using equations (2), (11) and (12) yields:

$$e_d = -c_1 \frac{L_s'}{\omega_s}(i_d'^* - i_d') - R_s' i_d' - L_s' i_q' - \left|V'\right| - \frac{L_s}{\omega_s}\dot{i}_d'^* \tag{13}$$

$$e_q = -c_2 \frac{L_s'}{\omega_s}(i_q'^* - i_q') - R_s' i_q' + L_s' i_d' - \frac{L_s'}{\omega_s}\dot{i}_q'^* \tag{14}$$

Considering (9), (10), (13) and (14), results in the following control parameters [13]:

$$k = \sqrt{e_d^2 + e_q^2} \tag{15}$$

$$\alpha = \tan^{-1}(\frac{e_q}{e_d}) \tag{16}$$

V. Power Quality Assessment

To assess the effectiveness of the STATCOM, the impact of the control performance on following factors is studied:

- RMS value
- Voltage Balancing
- Total Harmonic Distortion (THD)
- Flicker Mitigation

A. *RMS Value*

The effectiveness of STATCOM for power quality enhancement and the comparison between linear and nonlinear control is illustrated in this part through the simulation results. Figure 7 shows the voltage RMS value of V_{pcc}. The STATCOM control is engaged at 1.3 seconds. The uncontrolled voltage varies randomly and often with greater than 5% variation. Note that both the linear and nonlinear controllers improve the RMS voltage considerably, but the nonlinear controller shows better performance over the linear controller. With the linear control there are fluctuations that are in a tolerable range, but with the nonlinear control a nearly constant V_{pcc} is obtained.

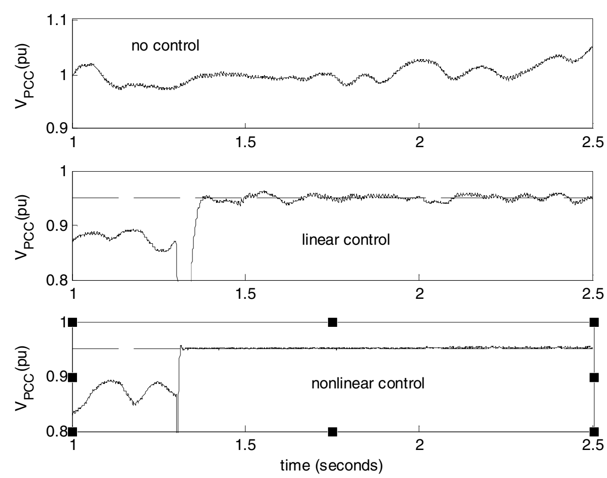


Figure 7. RMS Value of Voltage at the PCC with no control (top), linear control (middle), and nonlinear control (bottom)

B. *Voltage Balancing*

Fig. 8 shows the impact of STATCOM on individual voltage phase balancing. In Fig. 8(a), the individual phases voltages show significant imbalance in peak magnitude as well as variation in magnitude over time (due to the random fluctuations in load). The STATCOM with linear control shows correction of the phase imbalance and improves the peak magnitude consistency as well. The nonlinear control provides the best phase voltage correction.

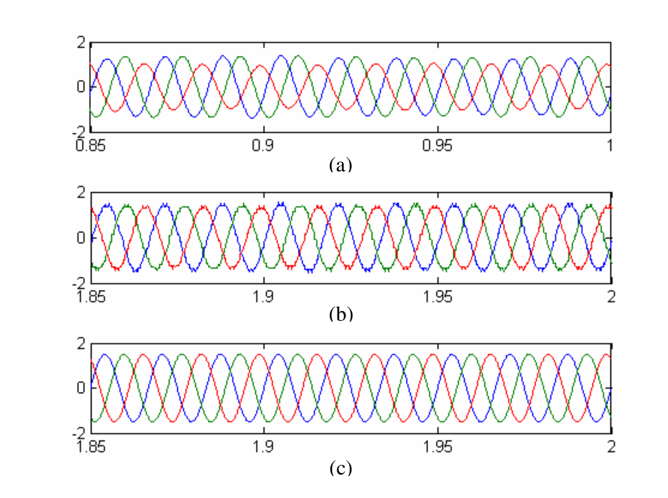


Figure 8. Three phase voltages at PCC (a) without control, (b) linear control, and (c) nonlinear control.

Fig. 9 shows the simulation results of the average value of the DC capacitor voltages. In all cases, the capacitor voltage balancing scheme is used, so only the average DC voltage variation is of interest. With no control, the DC voltage varies significantly, but it does not show any long term decrease or increase since the STATCOM is essentially idle without control. With control, the DC voltage is better maintained at the target value (0.98 pu), with the nonlinear control providing the best performance.

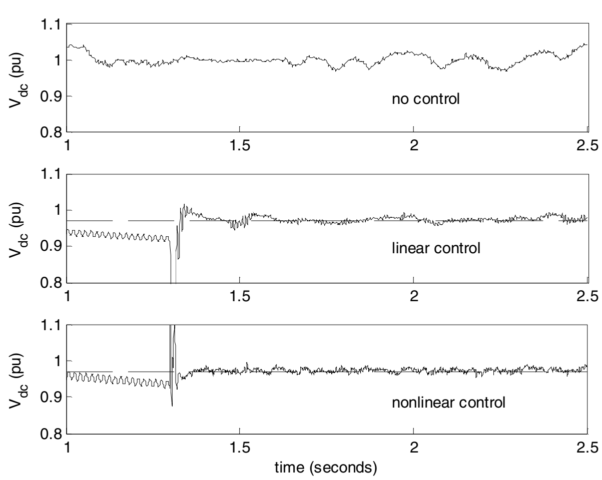


Figure 9: Average of the Internal DC Voltages Applying linear control (top) and nonlinear control (bottom)

C. Total Harmonic Distortion

PSCAD modules have been used to get the RMS and THD of PCC voltage. For flicker analysis, the IEC flicker meter given in [1] has been implemented in PSCAD.

Figs. 10 and 11 show the THD level of the three phase voltages at PCC using the linear and nonlinear control respectively. Recall the STATCOM control is engaged at 1.3 seconds. Prior to engaging the control, the THD is quite large, at times reaching nearly 5%. However, once the control is engaged, the THD drops dramatically. The THD for the linear controller is consistently less than 2%. The THD for the nonlinear controller is consistently less than 1%. These results again validate the performance of both controllers, with the nonlinear control providing slightly better performance.

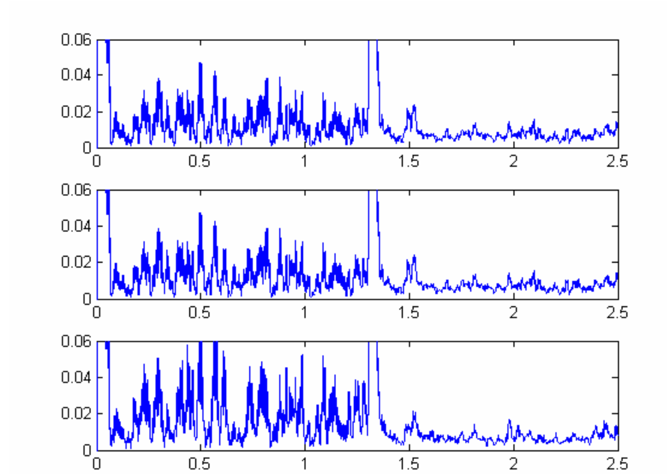


Figure 10: The THD of the Three Phase Voltages at PCC Applying the Linear Controller

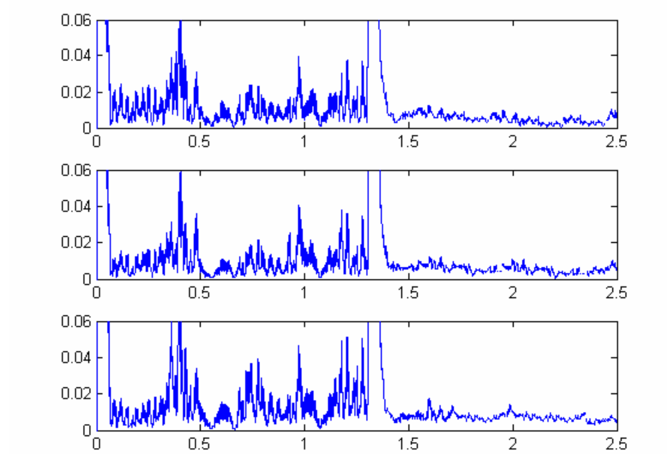


Fig. 11 THD of the Three Phase Voltages at PCC Applying the nonlinear control

D. Flicker Mitigation

Figs. 12 and 13 show the flicker meter signals at the PCC. Recall again that the control is not engaged until 1.3 seconds. After the initial transients from engaging the control die out, the flicker content of the waveform is nearly entirely mitigated for both the linear and nonlinear controllers.

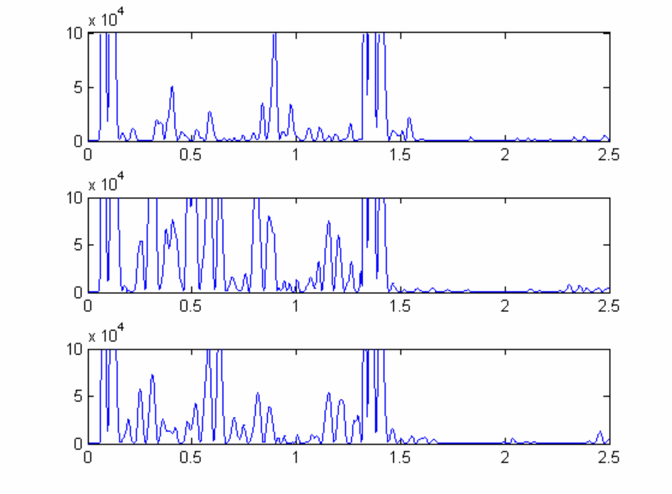


Figure 12. Flicker meter signal at PCC with Linear Control

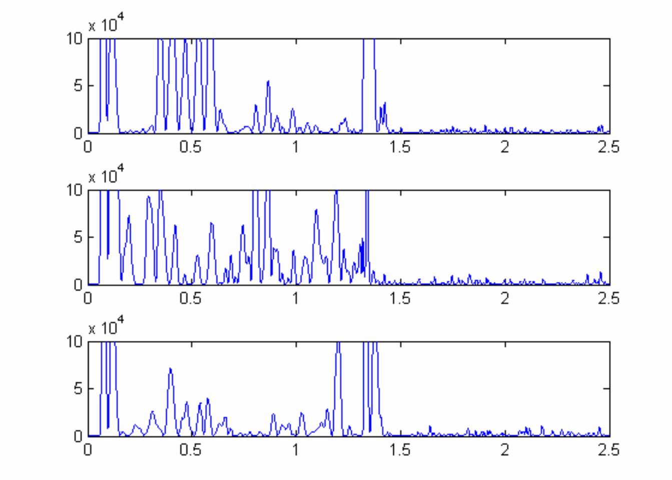


Figure 13. Flicker meter signal at PCC with Nonlinear Control

VI. CONCLUSIONS

In this paper, two different methods for controlling the STATCOM have been introduced. Comparing the results of the controllers, the nonlinear control is more robust in compensating unbalanced and random loads such as arc furnaces. Also one of the primary advantages of the nonlinear control is that it is not dependent on any of the system or load parameters.

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