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An Improved Nonlinear STATCOM Control for Electric Arc Furnace Voltage Flicker Mitigation

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***Abstract*—Electric arc furnaces (EAFs) are prevalent in the steel industry to melt iron and scrap steel. EAFs frequently cause large amplitude fluctuations of active and reactive power and are the source of significant power-quality (PQ) disturbances. Static synchronous compensators (STATCOMs) provide a power-electronic-based means of embedded control for reactive power support and PQ improvement. This paper introduces a new nonlinear control for the STATCOM that provides significant reduction in EAF-induced aperiodic oscillations on the power system. This method is compared with traditional PI controls and has shown to have improved performance.**

***Index Terms*—Arc furnace flicker, nonlinear control, static synchronous compensator (STATCOM).**

I. Introduction

ELECTRIC arc furnaces (EAFs) comprise a major portion of industrial loading on the bulk power system. EAF flicker is induced by low-frequency modulation (generally between 5–35 Hz) of the voltage at the point of common coupling (PCC) with the system. 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. Typically, a static VAr compensator (SVC) or static synchronous compensator (STATCOM) is added to compensate for the reactive power fluctuation [1]–[3]. Analyses of EAF loads indicated that a variation in active power is nearly as great as the variation in reactive power and is a significant contributor to voltage flicker [4]. Therefore, it is necessary to develop controls that can impact active and reactive power flows to mitigate electric arc furnace disturbances. The SVC cannot react rapidly enough to counteract the rapidly varying flicker; therefore, the STATCOM is an attractive solution [5].

Recent work has investigated the use of multilevel-converter-based STATCOMs for arc furnace flicker mitigation [6], [7]. Multilevel converters are attractive due to the reduction in harmonics and smaller-sized components. In this paper, an 11-level cascaded multilevel STATCOM with PWM control is introduced to compensate for a nonlinear load that emulates an EAF. Most STATCOM control proposed for EAF flicker mitigation has focused on the use of PI or PID linear control to provide the reactive and active power compensation through current control [3]–[7]. Linear control often provides adequate control, but can suffer from degradation in performance if the operating conditions change or if multiple modes of oscillation are present.

One recent STATCOM control development was reported in [8]. In this approach, an energy-based control law is designed to provide stability whereas an adaptive mechanism is used to improve the robustness to parametric uncertainties. In this paper, the authors coordinated the generator excitation and the STATCOM for improved performance. Although the authors used a simplified model of the STATCOM, they were able to acheive an effective control law that provided significant oscillation damping. The primary drawback with the proposed approach is that in some applications, such as EAFs, the STATCOM may be located significantly distant from the generator so that coordinated generator/STATCOM control may not be realistic.

Another similar nonlinear STATCOM control developed specifically for fast load regulation, such as electric arc furnace applications, is presented in [9]. In this paper, the authors propose a nonlinear controller that is robust in the face of system variations. The authors design a nonlinear control strategy that achieves asymptotic regulation of the voltage magnitude while compensating for uncertainties in the load conductance. While the goal of this control is different than that of the STATCOM for EAF flicker mitigation, this paper provides several salient approaches that will be exploited. In particular, the authors proposed a coordinate transformation that allows for the development of a stable control strategy utilizing a novel Lyapunov function. While the proposed control is significantly different, there are still several conceptual similarities between these two approaches. For this reason, we propose a new nonlinear controller that provides improved performance for flicker mitigation and power-quality (PQ) improvement for EAF applications. Specifically, the contributions of this paper are:

1) the development of a new nonlinear control for the STATCOM;
2) the introduction of a new method to model EAF voltage flicker;
3) the application of the proposed control to mitigate EAF flicker;
4) a comparison with a traditional PI control method.

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II. New Nonlinear Control for STATCOM

The STATCOM state equations are given by [10]

$$\frac{L_s}{\omega_s}\dot{i}_d = -R_s i_d + L_s i_q + k\cos(\alpha+\theta_i)V_{\rm dc} - V_i\cos\theta_i \quad (1)$$

$$\frac{L_s}{\omega_s}\dot{i}_q = -R_s i_q - L_s i_d + k\sin(\alpha+\theta_i)V_{\rm dc} - V_i\sin\theta_i \quad (2)$$

$$\frac{C_{\rm dc}}{\omega_s}\dot{V}_{\rm dc} = -k\cos(\alpha+\theta_i)i_d - k\sin(\alpha+\theta_i)i_q - \frac{1}{R_{\rm dc}}V_{\rm dc} \quad (3)$$

where i_d and i_q are the dq-axis currents, ω_s is the synchronous angular frequency, $V_{\rm dc}$ is the voltage across the dc-link capacitor $C_{\rm dc}$, $R_{\rm dc}L_s$ is the leakage reactance of the transformer, R_s and $R_{\rm dc}$ are resistances that represent the losses in the converter and dc-link capacitor, and $V_i\angle\theta_i$ is the PCC voltage. The two STATCOM control inputs are the voltage phase angle α and the modulation index k. These control inputs are fed to the VSC to synthesize the appropriate injected current waveform with variable magnitude and angle.

The STATCOM injected power is

$$P_{\rm inj} = V_i(i_d\cos\theta_i + i_q\sin\theta_i)$$

and the injected reactive power is

$$Q_{\rm inj} = V_i(i_d\sin\theta_i - i_q\cos\theta_i).$$

The control objective for the STATCOM is to track a desired injected active power $P^\star_{\rm inj}$ and desired reactive power $Q^\star_{\rm inj}$ so that the variations in load are localized behind the PCC and do not propagate into the system. The active power injection $P^\star_{\rm inj}$ is specified to keep the line active power constant and to account for the STATCOM losses

$$P^\star_{\rm inj} = P^\star_{\rm line} - P_{\rm load} + \left(i_d^2 + i_q^2\right)R_s + \frac{1}{R_{\rm dc}}V_{\rm dc}^2$$

The reactive power injection $Q^\star_{\rm inj}$ is chosen so that the voltage magnitude at the control bus is maintained constant. The desired injected powers are converted into desired currents $i_d^\star$ and $i_q^\star$ through

$$\begin{bmatrix} i_d^\star \\ i_q^\star \end{bmatrix} = \begin{bmatrix} \cos\theta_i & \sin\theta_i \\ \sin\theta_i & -\cos\theta_i \end{bmatrix}^{-1} \begin{bmatrix} P^\star_{\rm inj}/V_i \\ Q^\star_{\rm inj}/V_i \end{bmatrix}. \quad (4)$$

To track the target, new state variables e_d and e_q are defined so that

$$e_d = i_d^\star - i_d \quad (5)$$

$$e_q = i_q^\star - i_q \quad (6)$$

leading to new state equations

$$\frac{d}{\rm dt}e_d = \frac{d}{\rm dt}i_d^\star + \frac{R_s\omega_s}{L_s}i_d^\star - \frac{R_s\omega_s}{L_s}e_d - \omega_i i_q^\star + \omega_i e_q - \frac{\omega_s}{L_s}V_{\rm dc}k\cos(\alpha+\theta_i) + \frac{\omega_s}{L_s}V_i\cos\theta_i \quad (7)$$

$$\frac{d}{\rm dt}e_q = \frac{d}{\rm dt}i_q^\star + \frac{R_s\omega_s}{L_s}i_q^\star - \frac{R_s\omega_s}{L_s}e_q + \omega_i i_d^\star - \omega_i e_d - \frac{\omega_s}{L_s}V_{\rm dc}k\sin(\alpha+\theta_i) + \frac{\omega_s}{L_s}V_i\sin\theta_i. \quad (8)$$

Let the control inputs be defined as

$$u_1 = k\cos\alpha \quad (9)$$

$$u_2 = k\sin\alpha. \quad (10)$$

A positive definite Lyapunov function is given by

$$V = \frac{c}{2}e_d^2 + \frac{c}{2}e_q^2, \quad c > 0. \quad (11)$$

The derivative of V is given by

$$\dot{V} = p_1u_1 + p_2u_2 + p_3 - c\frac{R_s\omega_s}{L_s}\left(e_d^2 + e_q^2\right) \quad (12)$$

where

$$p_1 = -c\frac{\omega_s}{L_s}V_{\rm dc}(e_d\cos\theta_i + e_q\sin\theta_i)$$

$$p_2 = c\frac{\omega_s}{L_s}V_{\rm dc}(e_d\sin\theta_i - e_q\cos\theta_i)$$

$$p_3 = c\left(e_d\frac{d}{\rm dt}i_d^\star + e_q\frac{d}{\rm dt}i_q^\star\right) + c\frac{R_s\omega_s}{L_s}\left(e_d i_d^\star + e_q i_q^\star\right) - c\omega_i\left(e_d i_q^\star - e_q i_d^\star\right) + c\frac{\omega_s}{L_s}V_i(e_d\cos\theta_i + e_q\sin\theta_i).$$

The derivative $\dot{V}$ is guaranteed to be negative if

$$p_1u_1 + p_2u_2 + p_3 = -c_1\left(e_d^2 + e_q^2\right), \quad c_1 > 0. \quad (13)$$

Therefore, from Lyapunov's second theorem on stability [11], this system is asymptotically stable in the sense of Lyapunov for bounded inputs u_1 and u_2.

Solving for u_1 and u_2 yields

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = -C^{-1}\left(E + c_1\begin{bmatrix} e_d \\ e_q \end{bmatrix}\right) \quad (14)$$

where

$$C = -\frac{\omega_s V_{\rm dc}}{L_s}\begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix}$$

$$E = \begin{bmatrix} \frac{\omega_s}{L_s}\left(R_s i_d^\star + V_i\cos\theta_i\right) - \omega_i i_q^\star + \frac{d}{\rm dt}i_d^\star \\ \frac{\omega_s}{L_s}\left(R_s i_q^\star + V_i\sin\theta_i\right) + \omega_i i_d^\star + \frac{d}{\rm dt}i_q^\star \end{bmatrix}.$$

Equations (9) and (10) can be solved for k and α from

$$k = \sqrt{u_1^2 + u_2^2} \quad (15)$$

and

$$\alpha = \begin{cases} \tan^{-1}\frac{u_1}{u_2} u_1 > 0 \\ \tan^{-1}\frac{u_1}{u_2} + \pi u_1 < 0 \\ \sin^{-1}\frac{u_2}{k} u_1 = 0 \end{cases}. \quad (16)$$

Both k and α are limited to bound the magnitude of the injected current and, therefore, limit the injected active and reactive powers. In this control, only the parameter c_1 must be tuned.

This control is compared against the traditional PI controller shown in Fig. 1. The primary control targets of a STATCOM are to control the PCC root-mean-square (rms) line voltage (Vstat) and the active power flow on the line. The ac voltage control is

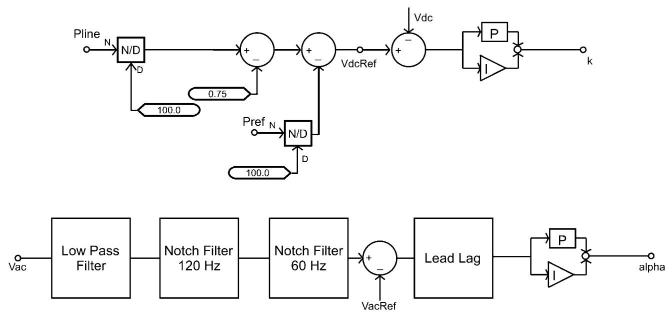


Fig. 1. PI control.

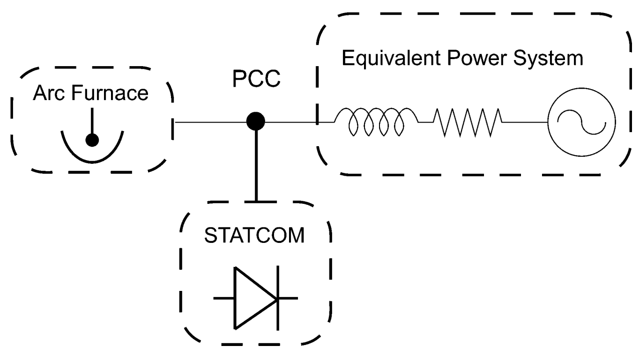


Fig. 2. Test system.

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 dc 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.

One significant difference between the two controllers is the choice of parameters. The proposed control only requires one paramater (c_1) that is simply chosen to be large and positive. The PI controller requires four separate parameters (two proportional gains and two integral gains) that must be tuned at a specific operating point. If the operating point changes significantly, these parameters must be retuned for optimal results.

III. Test System

The single-line diagram of the electrical distribution system feeding an arc furnace is shown in Fig. 2. The electrical network consists of a 115-kV generator and an impedance that is equivalent to that of a large network at the PCC. The STATCOM is connected to the system through a 115/25-kV Y-Delta transformer. The dc-link voltage across each 1-mF capacitor is 4 kV. The electrical arc furnace load is nonsinusoidal and randomly fluctuating.

A. Arc Furnace Flicker Signal Generation

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 interharmonics [12]. The flicker waveform has subsynchronous variations in the 5–35 Hz range [4]. To synthesize the variations to the rms waveform, an aperiodic waveform is generated by

$$R(t) = R_0 + a_L \cos(\omega_L t + \theta_L) + a_H \cos(\omega_H t + \theta_H)\Omega \quad (17)$$

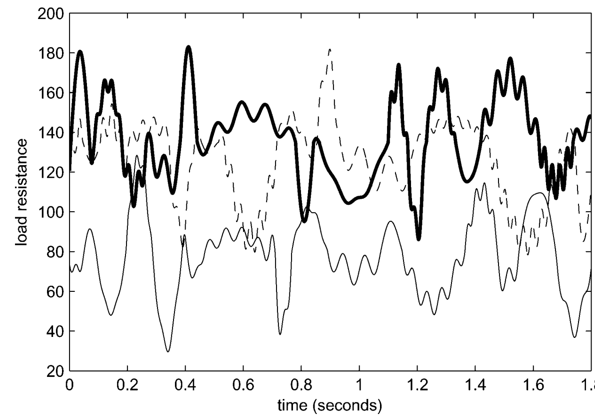


Fig. 3. EAF flicker waveform.

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. At each zero crossing, a new set of parameters $[a_L\ \omega_L\ a_H\ \omega_H]$ is generated. The phase angles θ_L and θ_H are then calculated so that the waveform is continuous across the zero crossings.

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. For example, one of these generated flicker waveforms can be produced from the following parameters:

$$\begin{aligned}
\omega_L &= 2\pi(1 + \rho 8) \text{ where } \rho \in [0,1] \text{ is a random number}\\
\omega_H &= 2\pi(10 + \rho 30)\\
a_L &= 50\rho\\
a_H &= 10\rho\\
R_0 &= 130\ \Omega\ (\text{phase } a, b) R_0 = 80\ \Omega (\text{phase } c)
\end{aligned}$$

A three-phase set of resistive loads generated by (17) is shown in Fig. 3. Note that each phase contains considerable variance and multiple modal content. This is consistent with the analysis of the arc furnace load characteristics given in [13] which indicate that imbalance and randomness exist in each phase independently. The harmonic spectrum of the phases is shown in Fig. 4. The waveform is aperiodic, but as expected, the frequency spectrum shows a primary concentration of around 8 Hz with a high-frequency concentration around 30 Hz with a much wider spread in harmonics.

This generated signal can be compared to actual EAF 230-kV rms flicker shown in Fig. 5. While the signal generator given in (17) incorporates a random component and cannot exactly reproduce actual signals, the qualitative behaviors are very similar between the generated flicker and the actual flicker of Fig. 5. These results are also consistent with other proposed chaos-based models [14]. Therefore, the proposed signal generator will be used to produce the EAF flicker on which to test the new control.

The phase voltages at the PCC are shown in Fig. 6. Note that the voltages are considerably unbalanced as a result of the load imbalance.

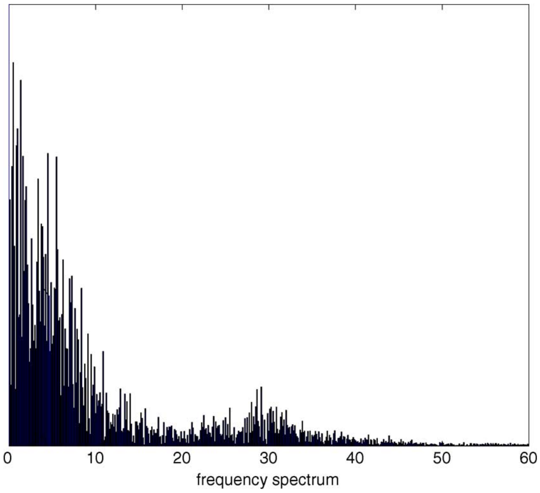


Fig. 4. EAF flicker frequency spectrum.

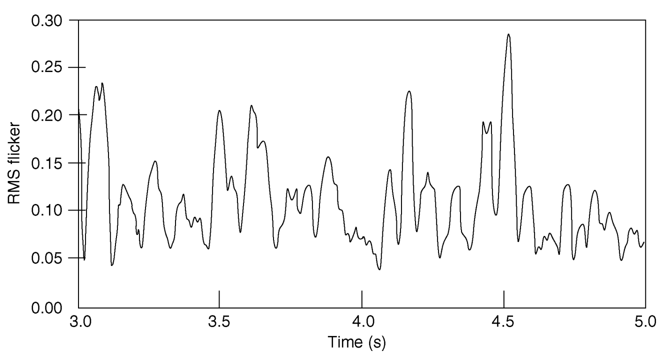


Fig. 5. Actual rms EAF flicker waveform.

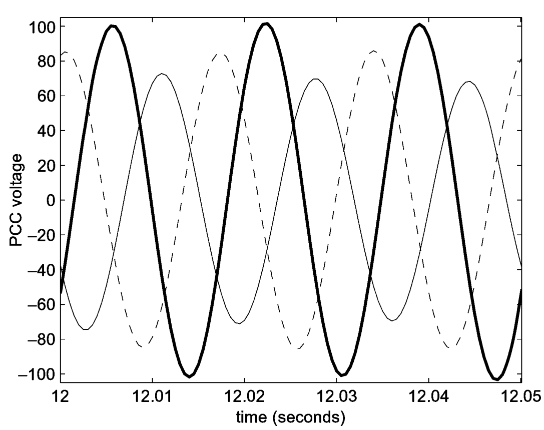


Fig. 6. Phase voltages at the PCC—no control.

B. STATCOM

The configuration of the STATCOM is shown in Fig. 7 [15]. A cascaded multilevel STATCOM contains several H-bridges in series to synthesize a staircase waveform. The inverter legs are identical and are therefore modular. In the 11-level STATCOM, 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 11. A multilevel configuration is used because it offers several advantages over other converter types [15]:

Fig. 7. Eleven-level cascaded multilevel STATCOM.

1) it is better suited for high-voltage and high-power applications than the conventional converters since the currents and voltages across the individual switching devices are smaller;
2) it generates a multistep staircase voltage waveform approaching a more sinusoidal output voltage by increasing the number of levels;
3) it has better dc voltage balancing, since each bridge has its own dc source.

To achieve a high-quality output voltage waveform, the voltages across all of the dc capacitors should maintain a constant value. However, the randomly varying load causes the dc capacitors to charge and discharge unevenly, leading to different voltages in each leg of each phase. However, because of the redundancy in switching states, there is frequently more than one state that can synthesize any given voltage level. Therefore, a "best" state exists among all of the possible states that produce the most balanced voltages [16]. Since there are multiple possible switching states that can be used to synthesize a given voltage level, the particular switching topology is chosen so that the capacitors with the lowest voltages are charged or conversely, the capacitors with the highest voltages are discharged.

The test system is simulated by using the software platform PSCAD. PSCAD provides the ability to fully model all three phases of the system down to the component level of the multievel STATCOM. This level of detail is required to study the affects of the electric arc furnace load on harmonics, load imbalance, and flicker. These effects cannot be fully represented in a system-level simulation package. One drawback of this level of system simulation, however, is that it is difficult to perform large-scale system studies.

IV. Proposed Control Effectiveness

The effectiveness of the controls presented earlier is assessed by using several quantitative assessments. The controllers are compared and contrasted for their performance in:

- maintaining the rms voltage and line active power;
- voltage balancing between phases;
- reduction of total harmonic distortion (THD);
- flicker mitigation.

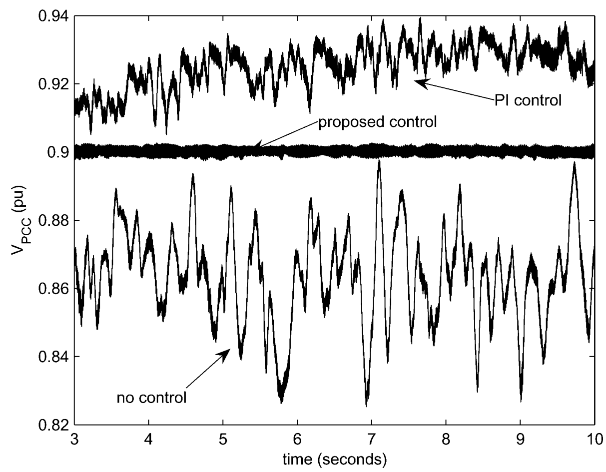
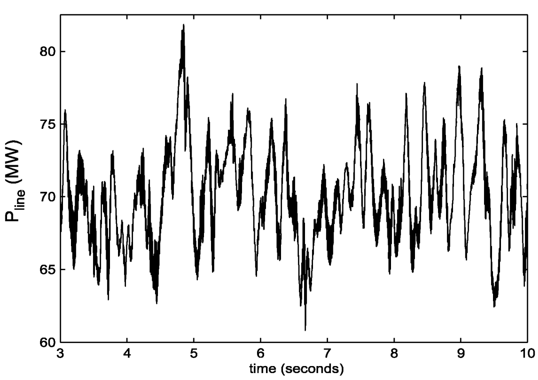
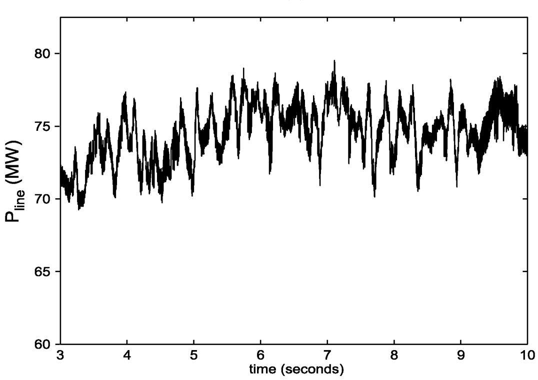


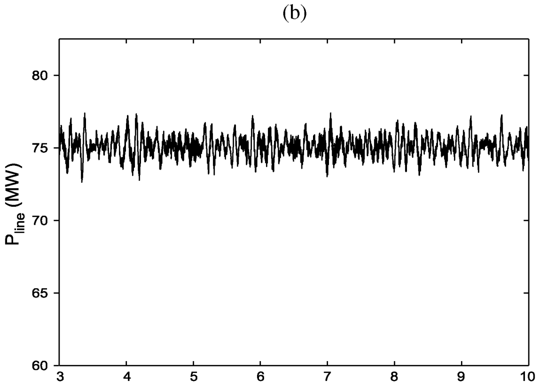
Fig. 8. RMS voltage for the test system.



(a)



(b)



(c)

Fig. 9. Load and line active powers for the test system. (a) Active power drawn by the load. (b) Line active power with STATCOM PI control. (c) Line active power with proposed control.

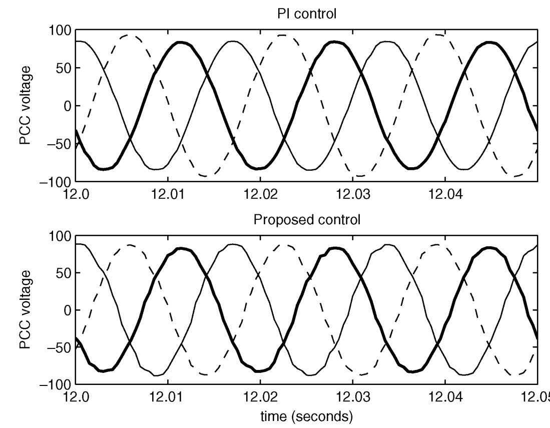


Fig. 10. Phase voltages at the PCC. PI control—top, proposed control—bottom.

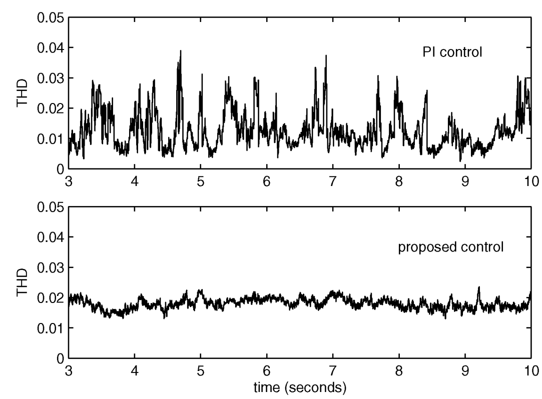


Fig. 11. THD of the PCC voltage (phase a).

A. RMS Voltage and Line Active Power

Fig. 8 shows the rms value of V_{PCC} with the unbalanced varying arc furnace load. The uncontrolled voltage magnitude varies randomly and often with greater than 5% variation. Note that the linear and nonlinear controllers improve the rms voltage considerably, but the nonlinear controller shows better performance than the linear controller and is able to control it better to the specified reference voltage (0.9 p.u.). With the linear control, there are fluctuations that are in a tolerable range, but with the nonlinear control, a nearly constant voltage magnitude is obtained.

Fig. 9 shows the active power load and the line active power for the PI and proposed control. Note that in addition to maintaining the bus voltage magnitude to a constant value, the STATCOM is also required to compensate for the variations in load so that the line active power from the system is constant. Even though the load varies randomly and with large variations, the STATCOM is able to effectively charge and discharge the dc-link capacitors to compensate so that the system sees a nearly constant load.

B. Voltage Balancing

Numerous control approaches have been introduced to mitigate voltage unbalance in STATCOM applications. Voltage imbalance, if not controlled, can significantly affect the STATCOM's ability to provide reactive power compensation and voltage control at the PCC. IEC standards require that the

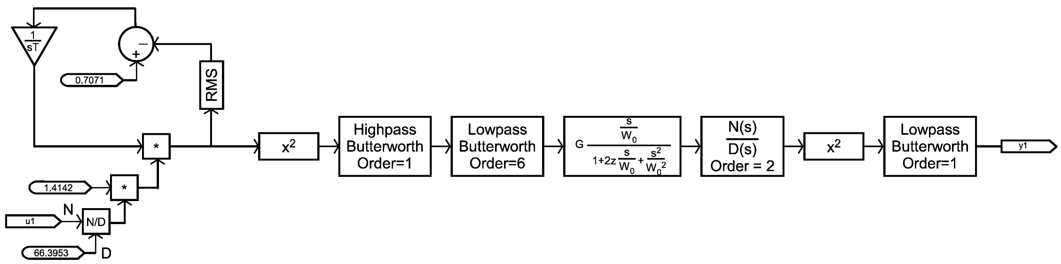


Fig. 12. Flicker measure of the PCC voltage (phase a).

steady-state voltage imbalance must remain below 2% [17]. For unbalanced loads, the main problems that exist are harmonic generation on the dc side and consequent generation of low-frequency harmonics on the ac side [18]. It will be shown that neither of these problems exist in the proposed system and control. The use of a multilevel converter, redundant state selection, and the proposed control can effectively mitigate any reasonable level of voltage imbalance.

Recall from Fig. 6 that the EAF load caused considerable unbalance and harmonic content in the PCC voltage. The uncontrolled voltages exhibit a phase imbalance of more than 20% with a difference in peak–peak voltage between phases of nearly 20 kV. Fig. 10 shows the PCC voltage with both PI control (top) and the proposed nonlinear control (bottom). The imbalance in the PI control phase voltages is reduced to 5%. The phase imbalance in the proposed control case is 2%, which is within the specified standard.

C. Total Harmonic Distortion (THD)

The THD of the system with the STATCOM under both controls is shown in Fig. 11. The THD has been calculated by using the THD module in PSCAD. For generality, only phase a is shown in the figure, but phases b and c are qualitatively similar although quantitatively different. Note that the mean THD for the PI control is 0.0125 and the maximum is 0.039. For the proposed control, the mean THD is 0.018 and the maximum is 0.023. Note that although the mean THD is similar for the PI and proposed controls, the maximum THD for the PI control is nearly twice that of the proposed control.

D. Flicker Mitigation

Voltage flicker is typically considered to be random variations in voltage that can by detected by the naked eye at a level to cause discomfort. The primary sources of flicker are industrial loads, usually arc furnaces, rolling mills, welding, and other manufacturing processes. To measure flicker, a flickermeter is typically comprised of a squaring demodulator to model the response of the lamp to supply voltage variation, a weighting filter to model perception ability of the human eye, and a squaring and first-order filter to model the memory tendency of the human brain. The IEC 1000-4-15 standard provides the specifics of a measurement approach for flicker [19]. The following transfer function:

$$H(s) = G\frac{\frac{2}{\omega_0}}{1 + 2z\frac{s}{\omega_0} + \frac{s^2}{\omega_0^2}} \quad (18)$$

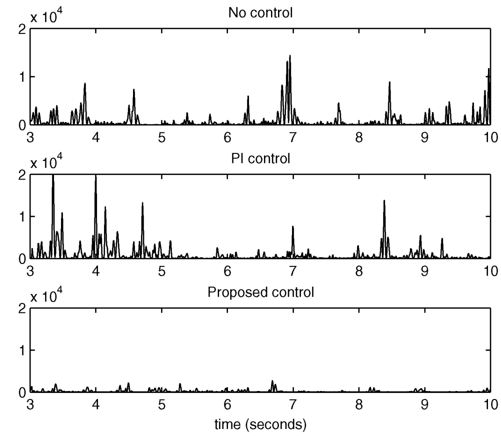


Fig. 13. Flicker measure of the PCC voltage (phase a).

is provided as a reasonable model for the human eye. The coefficients are given by the IEC for 230-V, 60-W incandescent lamps. The flicker meter proposed in [20] and shown in Fig. 12 is used to measure the flicker in the PCC voltage.

The flicker content of the PCC voltages is shown in Fig. 13. Note that the case of no control and the PI control have nearly the same qualitative content of flicker, whereas the proposed control is significantly lower. In fact, for most of the time interval, the proposed control reduced the flicker content by nearly a full order of magnitude from the case of no control.

V. Conclusion

In this paper, a multilevel STATCOM is used to mitigate voltage flicker induced by an electric arc furnace. The applied load is randomly fluctuating and unbalanced. A novel nonlinear control is proposed to provide improved control for rms voltage and line active power control. In addition, the traditional PI control is compared against the proposed control in reducing total harmonic content, flicker, and phase imbalance. In all cases, the proposed control produced similar or improved results when compared with the PI control. One additional advantage of the proposed control is that only one control parameter is required whereas the PI control requires four parameters to be tuned.

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