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]

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

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

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

where i_d and i_q are the dq-axis currents, ω_s is the synchronous angular frequency, V_{dc} is the voltage across the dc-link capacitor C_{dc}, $R_{\mathrm{dc}}L_s$ is the leakage reactance of the transformer, R_s and R_{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

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

and the injected reactive power is

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

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

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

The reactive power injection $Q^{\star}_{\mathrm{inj}}$ 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

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

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

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

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

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

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

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

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

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

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

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

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