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Energy and voltage management methods for multilevel converters for bulk power system power quality improvement

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ENERGY AND VOLTAGE MANAGEMENT METHODS FOR MULTILEVEL CONVERTERS FOR BULK POWER SYSTEM POWER QUALITY IMPROVEMENT

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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 disturbances. Also EAFs comprise a major portion of industrial loading on the bulk power system. Typically, a static VAR compensator (SVC) or Static Synchronous compensator (STATCOM) are use to provide the reactive power support in order to alleviate the fluctuations in voltage at PCC. Static Synchronous Compensators (STATCOMs) provide a power electronic-based means of embedded control for reactive power support. Integrating an energy storage system (ESS) such as large capacitors with the STATCOM will improve the device performance to have active power controllability as well as the reactive power.

A cascaded multilevel STATCOM has been utilized in order to compensate for all the fluctuations caused by an EAF both in the RMS of the voltage at PCC and also the active power generation. Designing a sophisticated controller, it is possible to get the STATCOM track the variations of active power in load. Therefore, the generator does not need to produce the random active power demanded by the load.

Throughout the study, power quality assessment has been done by measuring the flicker level and also the Total Harmonic Distortion of the three phase voltages. It has been seen that the nonlinear controllers will show better performances in case of improving power quality indices and they show more robustness.

ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my advisor, Dr. Mariesa L. Crow for my continuous guidance, advice and help during this research.

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1. INTRODUCTION

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 disturbances. Also EAFs comprise a major portion of industrial loading on the bulk power system. EAF flicker is induced by a low-frequency modulation (5- 35 Hz) of the voltage at the point of common coupling (PCC) with the system. Typically, a static VAR compensator (SVC) or Static Synchronous compensator (STATCOM) is used to provide the reactive power support in order to alleviate the fluctuations in voltage at PCC. Static Synchronous Compensators (STATCOMs) provide a power electronic-based means of embedded control for reactive power support.

A cascaded multilevel STATCOM has been utilized in order to compensate for all the fluctuations caused by an EAF both in the RMS of the voltage at PCC and also the active power generation. There are several compelling reasons to consider a cascaded multilevel converter topology for the STATCOM. These well known reasons include lower harmonic injection into the power system, decreased stress on the electronic components due to decreased voltages, and lower switching losses. Various multilevel converters also readily lend themselves to a variety of PWM strategies to improve efficiency and control. Third, the cascaded multilevel converter can achieve better voltage balancing across levels than other multilevel topologies. Sinusoidal Pulse Width Modulation (SPWM) has been used to control the switching pattern of the STATCOM.

The STATCOM was utilized to implement two control approaches. The first control approach was designed to track and counteract the variations in active power of the load. This minimizes the disturbance on the system and improves the power quality. The second approach was designed to control the average dc voltage across the capacitors and the RMS PCC voltage. Each control approach was implemented with linear and nonlinear control of the STATCOM. The linear controllers are traditional PI controllers. The nonlinear controllers have been designed based on Lypanov's criteria.

Throughout the study, power quality assessment has been performed by measuring the flicker level and also the Total Harmonic Distortion (THD) of the three phase voltages. It is shown that the nonlinear controllers provide better performances for improving power quality indices and are more robust.

The EAF load was developed in PSCAD and has been utilized within the IEEE 14 bus test system. The nonlinear controller is shown to provide constant active power generation and constant RMS PCC voltage. Also, fault studies have been performed on the network to further validate the effectiveness of the proposed nonlinear controller.

The complex topology of these inverters coupled with the large number of devices increase the probability of the STATCOM failure. As increasingly higher level converters are used for high output rating power applications, a large number of power switching devices will be used. Each of these devices is a potential failure point. Therefore it is important to design a sophisticated control to produce a fault-tolerant STATCOM. A faulty power cell in a cascaded H-bridge STATCOM can potentially cause switch modules to explode leading to fault conditions such as a short circuit or an overvoltage on the power system resulting in expensive down time. Subsequently, it is crucial to identify the existence of any fault and also to determine the location of the fault for it to be removed. In this dissertation, a fault detection method is proposed that requires only that the output DC link voltage of each phase be measured. This measurement is typically accomplished routinely for control purposes. If a fault is detected, the module in which the fault occurred is then isolated and removed from service. This approach is consistent with the modular design of cascaded converters in which the cells are designed to be interchangeable and rapidly removed and replaced. Until the module is replaced, the multilevel STATCOM continues to operate with slightly decreased, but still acceptable, performance. The proposed approach is validated through an analysis of the dynamic performance and the THD.

The primary contributions of this dissertation are grouped into two main areas. The first contribution area is the development of a STATCOM controller to mitigate the effects of electric arc furnace fluctuations. Specific developments include:

- Modeling of the EAF; A new model was developed for simulating the dynamic performance of an electric arc furnace through the application of varying resistances. Each phase is randomly varying and potentially unbalanced. This model was implemented in PSCAD. (all papers)
- Implementing redundant state selection (RSS); Redundant state selection has been utilized to balance the capacitor voltages in the eleven-level cascaded multilevel converter. This has been developed and implemented in PSCAD. (all papers)
- A novel nonlinear V_{PCC}-V_{dc} STATCOM control has been proposed and compared against a traditional PI controller. This has been developed and implemented in PSCAD on the EAF test system. (paper 1)

- A novel nonlinear V_{PCC}-P_{line} STATCOM control has been proposed and compared against a traditional PI controller. This has been developed and implemented in PSCAD on the EAF test system. (paper 2)
- Total Harmonic Distortion (THD); A THD analysis has been performed on the results from the proposed controllers and the traditional controllers. The mean and maximum THD for each method is compared. (all papers)
- Flicker Analysis; An IEC flicker meter has been developed and implemented in PSCAD for the EAF test system for the proposed and traditional controllers. (paper 2)
- Large scale system application: The proposed nonlinear control method is applied to the IEEE 14 bus test system with an EAF load. This has been developed and implemented in PSCAD. (paper 4)

The second contribution area is the development of a novel approach to identify and mitigate switch faults in a multilevel STATCOM. Specific developments include:

- Fault identification: A novel method has been proposed based on the DC voltage profile to identify the location of faulty switches in the multilevel converter without the aid of additional sensors. This has been developed and implemented in PSCAD. (paper 3)
- Multilevel converter reconfiguration: A method to remove the faulted module and corresponding modules is proposed. This has been developed and implemented in PSCAD. (paper 3)

- The impact of the reduced level STATCOM on system performance including dynamic control and THD is analyzed. (paper 3)

I. 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 uF parallel capacitor bank filter is used.

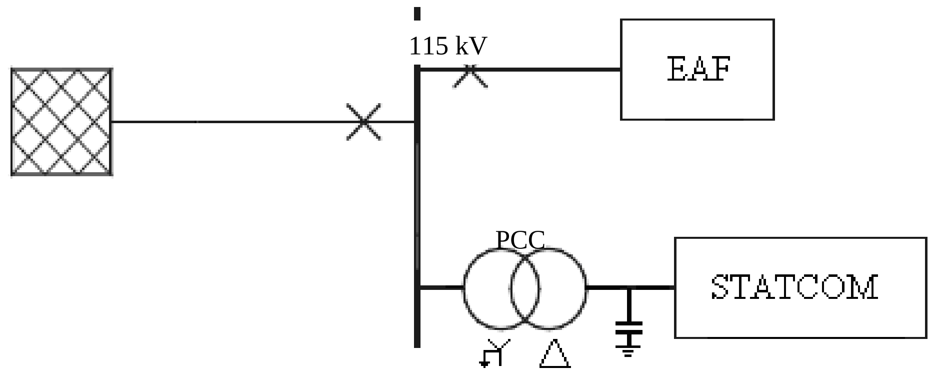


Fig. 1. Case Study Network

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

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

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.

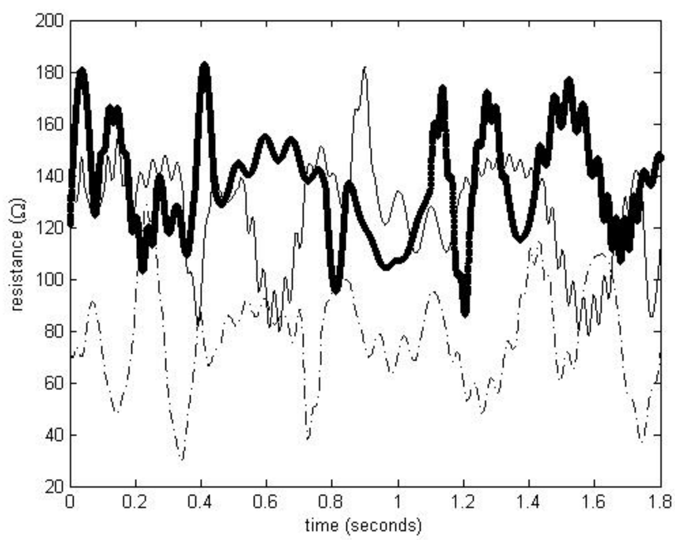


Fig. 2. EAF flicker waveform

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.

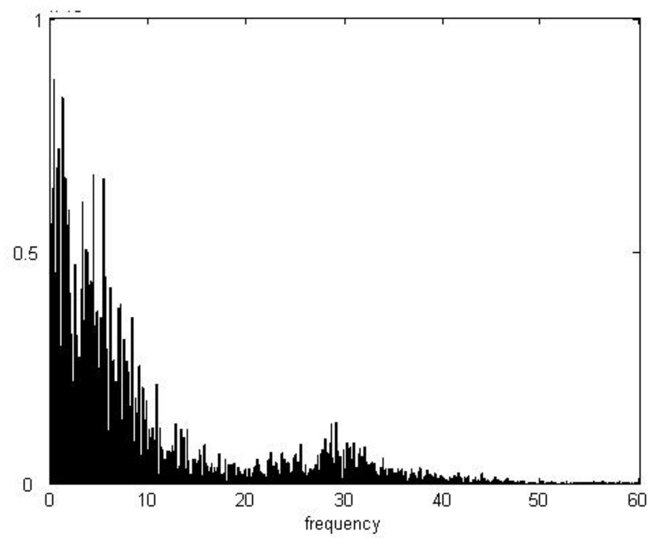


Fig.3. EAF flicker frequency spectrum

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 angleα.

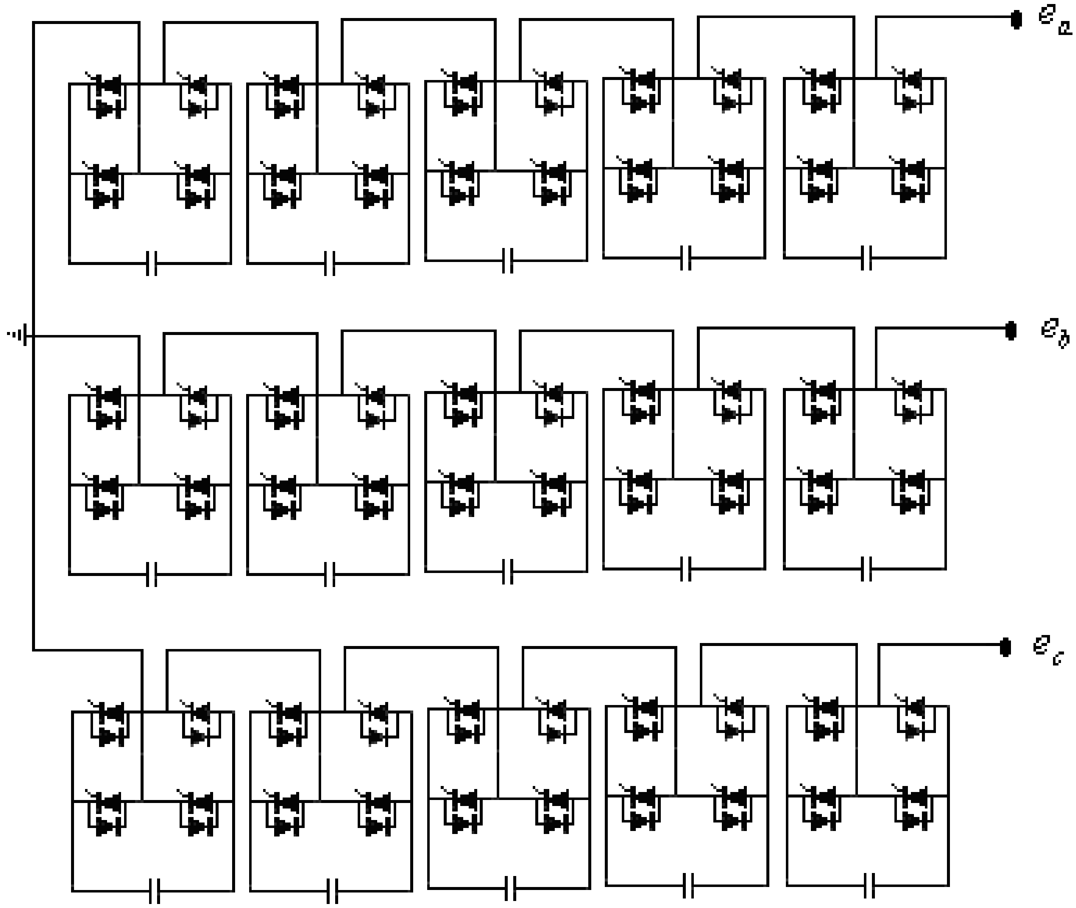


Fig. 4. Eleven Level Cascaded Multilevel Inverter (STATCOM)

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

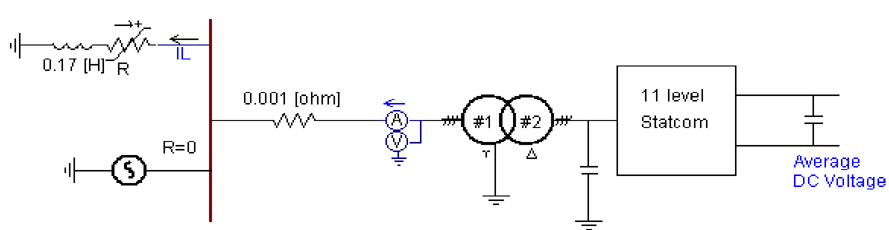
D. Pulse Width Modulation

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.

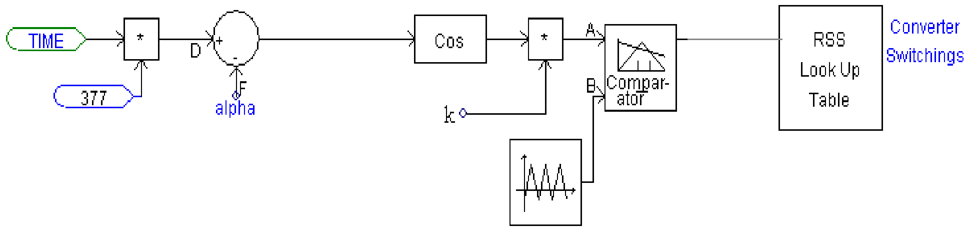
E. Capacitor Voltage Balancing using Redundant State Selection (RSS)

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. (cont) Control System

IV. OBTAINING THE CONTROL PARAMETERS

F. 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.

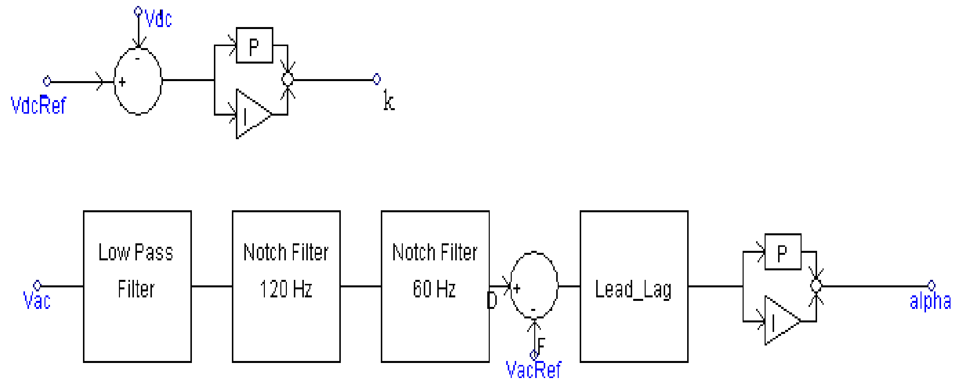


Fig. 6. Linear Control Block Diagram

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

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

The target values for the dq currents are given by

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

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

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:

$$e_d = i_d^{'*} - i_d^{'} \qquad (5)$$

$$e_q = i_q^{'*} - i_q^{'} \qquad (6)$$

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

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

Where the derivative of (7) is given by:

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

Where:

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

$$u_2 = k\sin(\alpha) \qquad (10)$$

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

$$\dot{e}_d = -c_1 e_d \qquad (11)$$

$$\dot{e}_q = -c_2 e_q \qquad (12)$$

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

$$e_d = -c_1 \frac{L'_s}{\omega_s}(i'^*_d - i'_d) - R'_s i'_d - L'_s i'_q - \left|V'\right| - \frac{L_s}{\omega_s}\dot{i}'^*_d \qquad (13)$$

$$e_q = -c_2 \frac{L'_s}{\omega_s}(i'^*_q - i'_q) - R'_s i'_q + L'_s i'_d - \frac{L'_s}{\omega_s}\dot{i}'^*_q \qquad (14)$$

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

$$k = \sqrt{e_d^{\ 2} + e_q^{\ 2}} \qquad (15)$$

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

V. POWER QUALITY ASSESSEMENT

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

H. 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 Vpcc. 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 Vpcc is obtained.

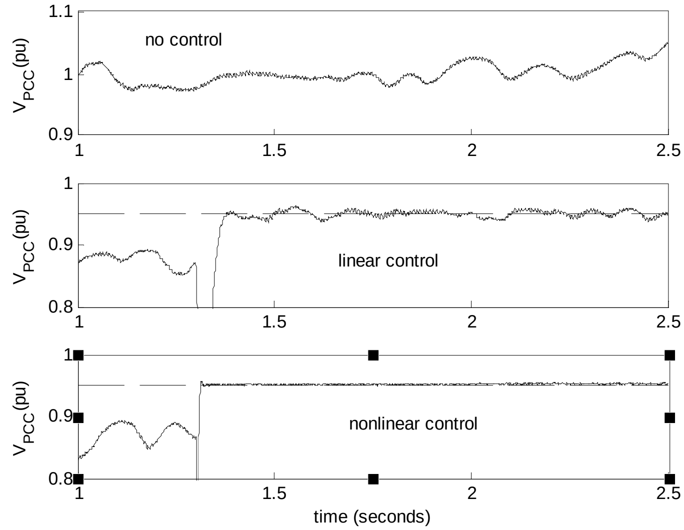


Fig. 7. RMS Value of Voltage at the PCC with no control (top), linear control (middle), and nonlinear control (bottom)

I. Voltage Balancing

Fig. 8 shows the impact of STATCOM on individual voltage phase balancing. In Figure 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.

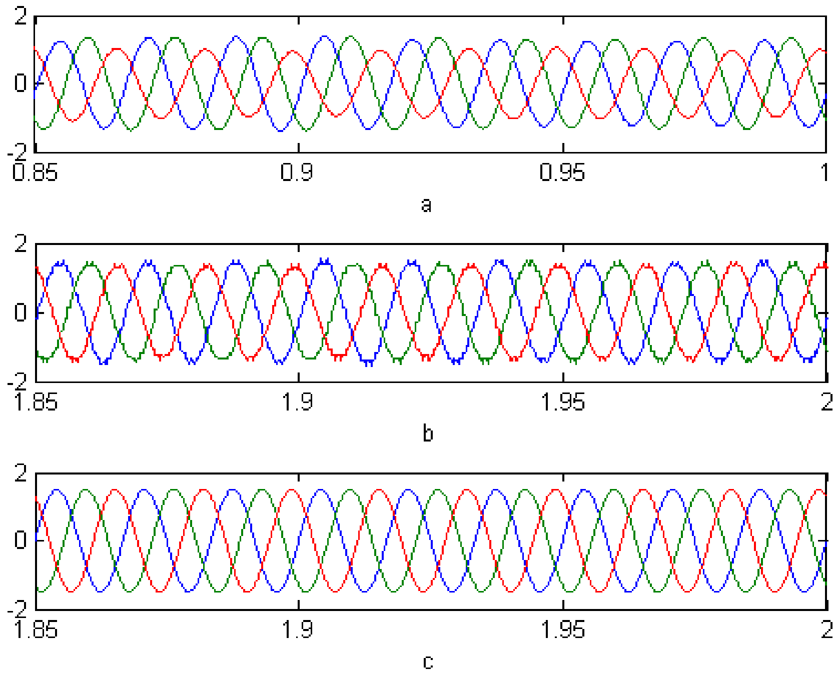


Fig. 8. Three phase voltages at PCC (a) without control, (b) linear control, and (c) nonlinear control.

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.

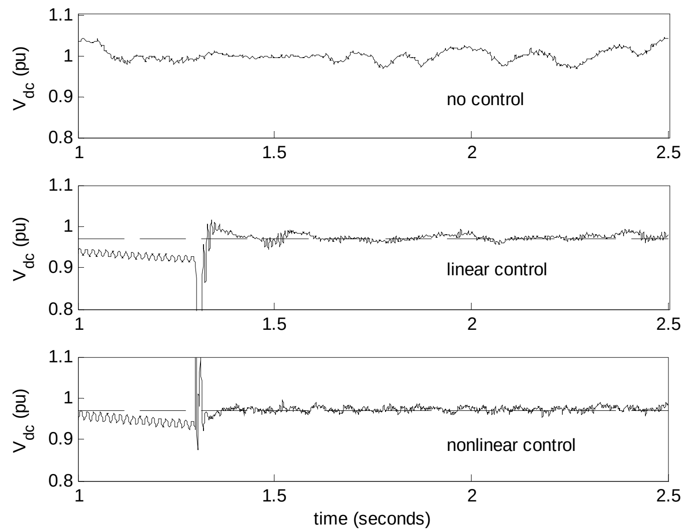


Figure 9: Average of the Internal DC Voltages Applying linear control (top) and nonlinear control (bottom)

J. 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.

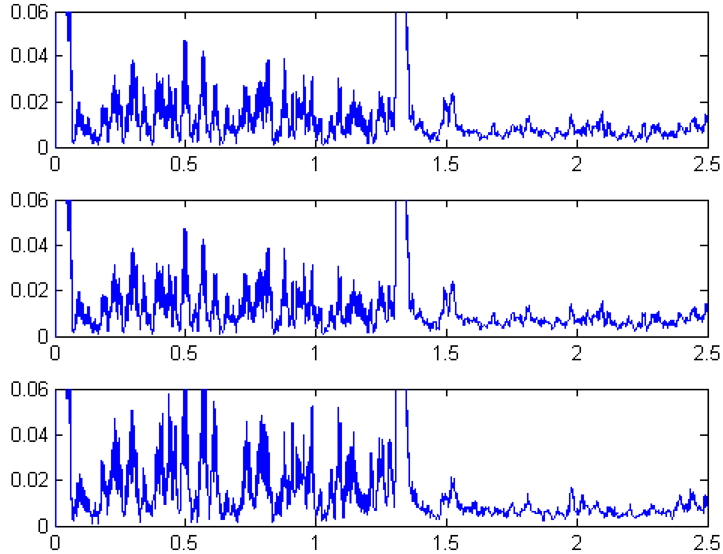


Fig. 10: The THD of the Three Phase Voltages at PCC Applying the Linear Controller

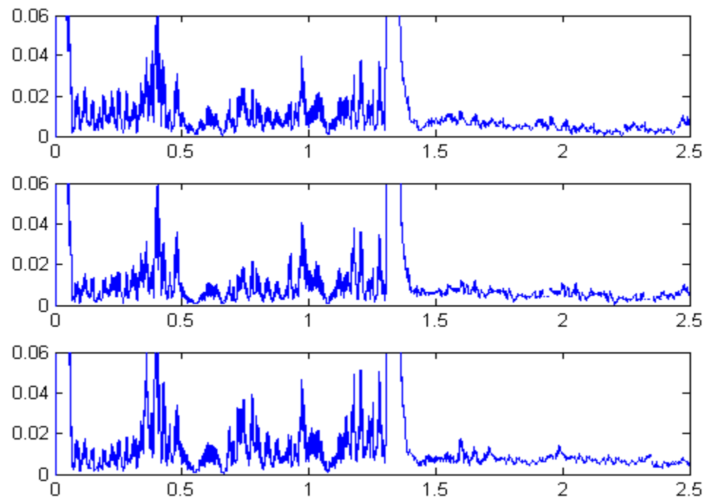


Fig. 11 THD of the Three Phase Voltages at PCC Applying the nonlinear control

K. 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.

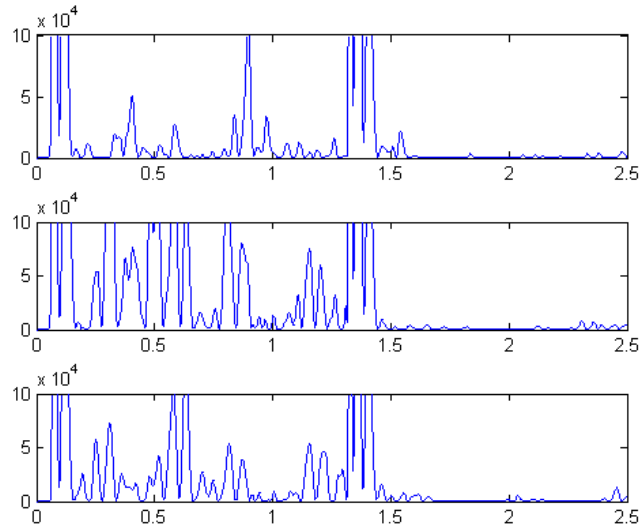


Fig. 12. Flicker meter signal at PCC with Linear Control

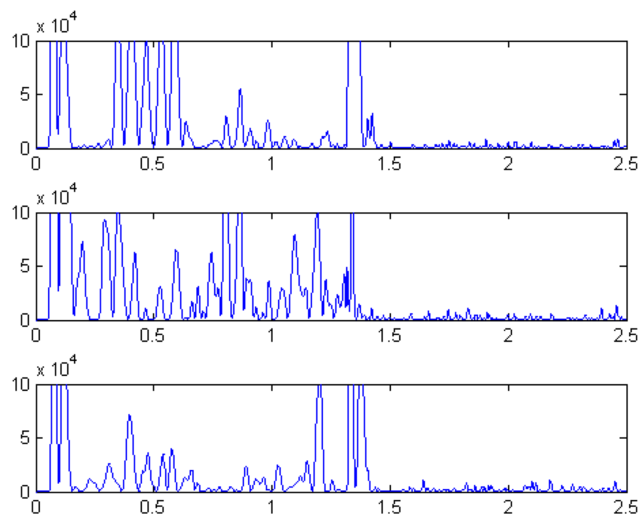


Fig. 13. Flicker meter signal at PCC with Nonlinear Control

VI. CONCLUSION

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

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ABSTRACT: Electric arc furnaces (EAF) 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 disturbances. Static Synchronous Compensators (STATCOMs) provide a power electronic-based means of embedded control for reactive power support and power quality 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 shown to have improved performance.

Index Terms – STATCOM, nonlinear control, arc furnace flicker

I. INTRODUCTION

Electric arc furnaces (EAF) comprise a major portion of industrial loading on the bulk power system. EAF flicker is induced by a low-frequency modulation (generally between 5-35 Hz) of the voltage at the point of common coupling (PCC) with the system.

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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) are added to compensate the reactive power fluctuation [1] -[3]. Analyses of EAF loads indicated that 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 both active and reactive power flows to mitigate electric arc furnace mitigations. 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 eleven level cascaded multilevel STATCOM with PWM control is introduced to compensate for a nonlinear load that emulates an electric arc furnace. Most STATCOM control proposed for EAF flicker mitigation have 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 work, 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 electric arc furnaces, the STATCOM may be located significantly distant from the generator such that a 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 the development 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 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, and
4) a comparison with a traditional PI control method.

II. A NEW NONLINEAR CONTROL FOR STATCOM

The STATCOM state equations are given by [10]

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

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

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

where i_d and i_q are the dq-axis currents, V_{dc} is the voltage across the dc-link capacitor C_{dc}, L_s is the leakage reactance of the transformer, R_s is a resistance that represents the losses in the converter, 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

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

and the injected reactive power is

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

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

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

The reactive power injection $Q^{\star}_{inj}$ is chosen such 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

$$\begin{bmatrix} i_d^\star \\ i_q^\star \end{bmatrix} = \begin{bmatrix} \cos\theta_i & \sin\theta_i \\ \sin\theta_i & -\cos\theta_i \end{bmatrix}^{-1} \begin{bmatrix} P_{inj}^\star / V_i \\ Q_{inj}^\star / V_i \end{bmatrix} \tag{4}$$

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

$$e_d = i_d^\star - i_d \tag{5}$$

$$e_q = i_q^\star - i_q \tag{6}$$

leading to new state equations:

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

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

Let control inputs be defined as

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

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

A positive definite Lyapunov function is given by

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

The derivative of V is given by

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

where

$$
\begin{aligned}
p_1 &= -c\frac{\omega_s}{L_s}V_{dc}\left(e_d\cos\theta_i + e_q\sin\theta_i\right)\\
p_2 &= c\frac{\omega_s}{L_s}V_{dc}\left(e_d\sin\theta_i - e_q\cos\theta_i\right)\\
p_3 &= c\left(e_d\frac{d}{dt}i_d^\star + e_q\frac{d}{dt}i_q^\star\right) + c\frac{R_s\omega_s}{L_s}\left(e_d i_d^\star + e_q i_q^\star\right)\\
&\quad -c\omega_i\left(e_d i_q^\star - e_q i_d^\star\right) + c\frac{\omega_s}{L_s}V_i\left(e_d\cos\theta_i + e_q\sin\theta_i\right)
\end{aligned}
$$

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

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

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

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

where

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

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

$$
k = \sqrt{u_1^2 + u_2^2} \tag{15}
$$

and

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

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.

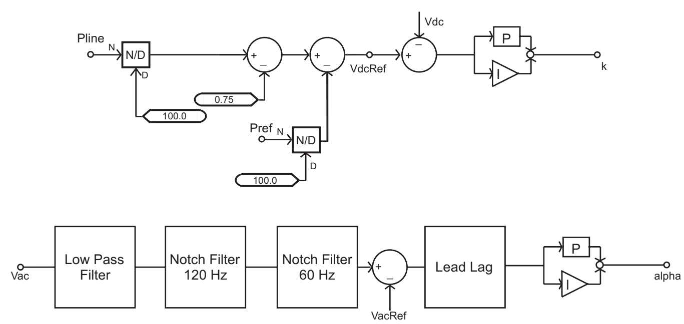


Fig. 1. PI Control

This control is compared against the traditional PI controller shown in Figure 1. The primary control targets of a STATCOM are to control the PCC RMS line voltage (Vstat) and the active power flow on the line. 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 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. THE TEST SYSTEM

The single line diagram of the electrical distribution system feeding an arc furnace is shown in Figure 2. The electrical network consists of a 115 kV generator and an impedance that is equivalent to that 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, and randomly fluctuating.

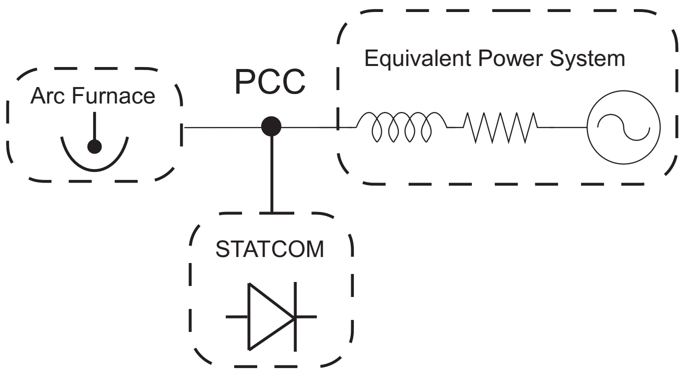


Fig. 2. Test System

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 inter-harmonics [12]. The flicker waveform has subsynchronous variations in the 5-35Hz range [4]. To synthesize the variations to the RMS waveform, an aperiodic waveform is generated by

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

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 such 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 5-35Hz range. The high frequency component ω_H should be centered about an odd integer multiple of ω_L. For example, one such generated flicker waveform can be produced from the following parameters:

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

A three-phase set of resistive loads generated by equation (17) are shown in Figure 3. Note that each phase contains considerable variance and multiple modal content. This is consistent with the analysis of 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 Figure 4. The waveform is aperiodic, but as expected, the frequency spectrum shows a primary concentration 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 an actual EAF 230kV RMS flicker shown in Figure 5. While the signal generator given in equation (17) incorporates a random

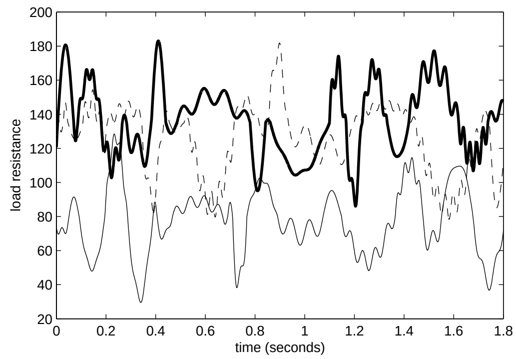


Fig. 3. EAF flicker waveform

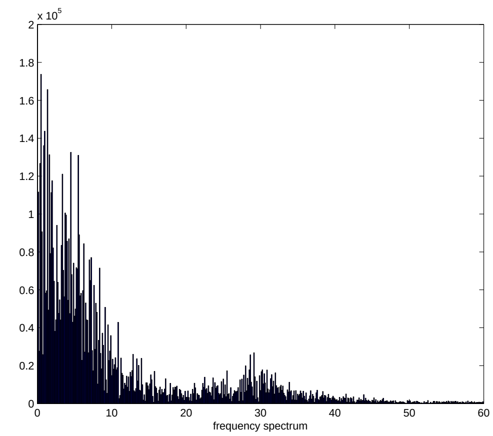


Fig. 4. EAF flicker frequency spectrum

component and cannot exactly reproduce actual signals, the qualitative behaviors are very similar between the generated flicker and the actual flicker of Figure 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.

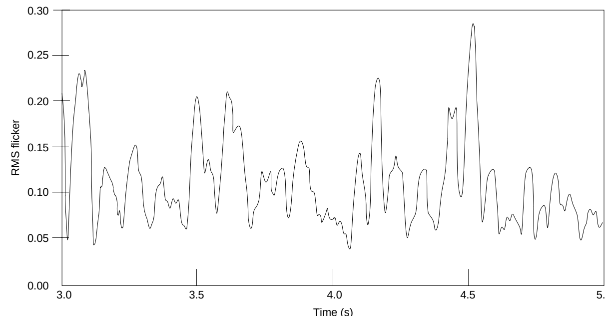


Fig. 5. Actual RMS EAF flicker waveform

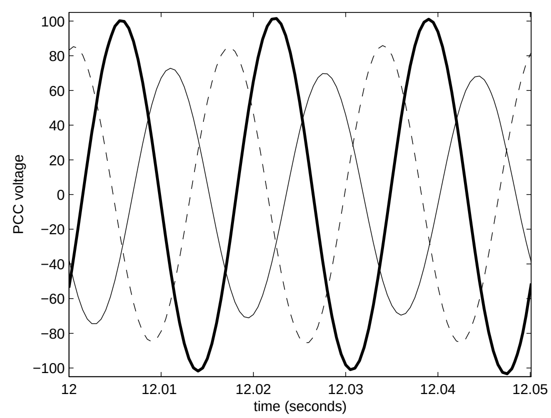


Fig. 6. Phase voltages at the PCC - no control

B. The STATCOM

The configuration of the STATCOM is shown in Figure 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 eleven-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 eleven. A multilevel configuration is used because it offers several advantages over other converter types [15]:

1) It is better suited for high-voltage, high-power applications than the conventional

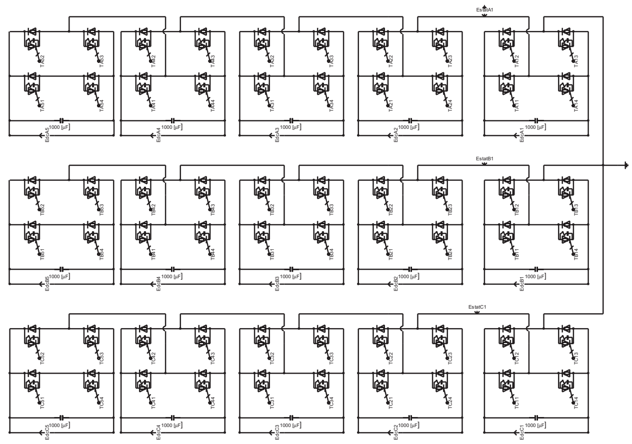


Fig. 7. Eleven level cascaded multilevel STATCOM

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, and
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 redundancy in switching states, there is frequently more than one state that can synthesize any given voltage level. Therefore, there exists a "best" state among all the possible states that produces 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 such that the capacitors with the lowest voltages are charged or conversely, the capacitors with the highest voltages are discharged.

The test system is simulated 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 multi-level 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 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), and
- flicker mitigation

A. RMS Voltage and Line Active Power

Figure 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 both the linear and nonlinear controllers improve the RMS voltage considerably, but the nonlinear controller shows better performance than the linear controller and is better able to control it to the specified reference voltage (0.9 pu). 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.

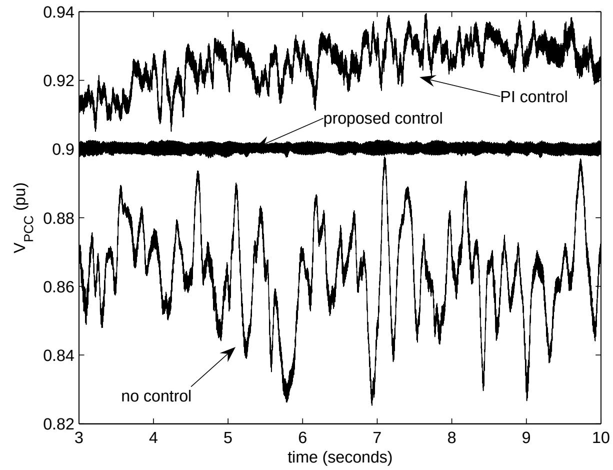
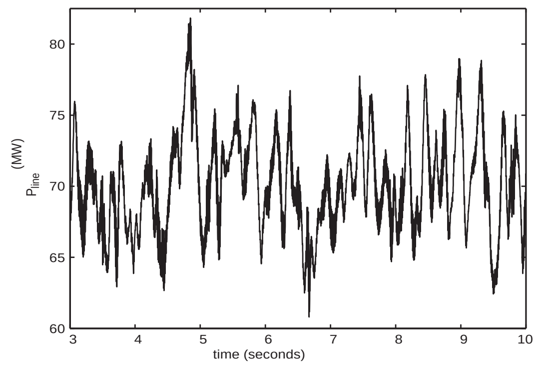


Fig. 8. RMS voltage for test system

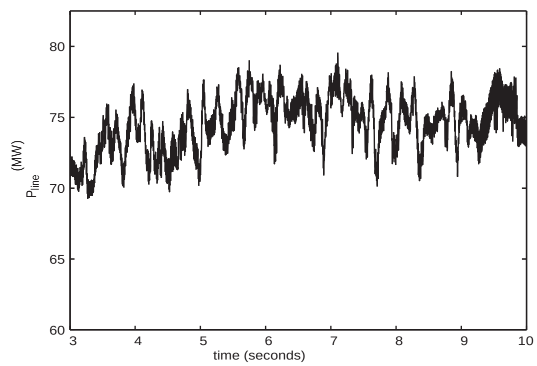
Figure 9 shows the active power load and the line active power for the PI and proposed control. Note that in addition to maintaining the bus voltage magnitude to a constant value, the STATCOM is also required to compensate for the variations in load such that the line active power from the system is 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

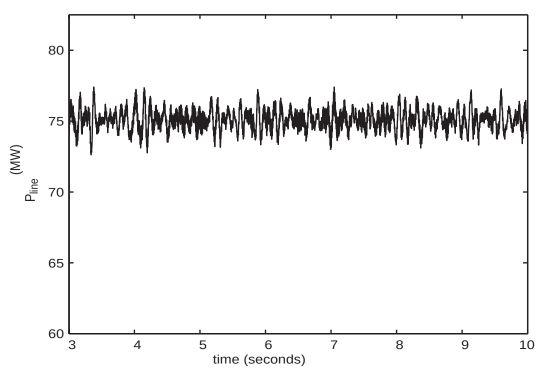
Numerous control approaches have been introduced to mitigate voltage unbalance in STATCOM applications. Voltage imbalance, if not controlled, can significantly affect the STATCOM's ability to provide reactive power compensation and voltage control at the PCC. IEC standards require that the steady-state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



(a) Active power drawn by load



(b) line active power with STATCOM PI control



(c) line active power with proposed control

Fig. 9. Load and Line active powers for test system

The use of a multi-level 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 over 20% with the difference in peak-peak voltage between phases of nearly 20kV. 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.

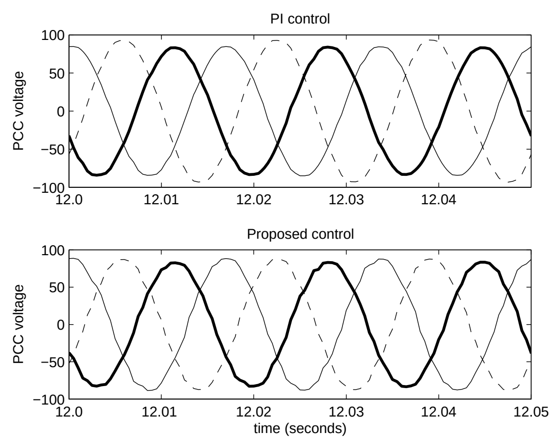


Fig. 10. Phase voltages at the PCC; PI control - top, proposed control - bottom

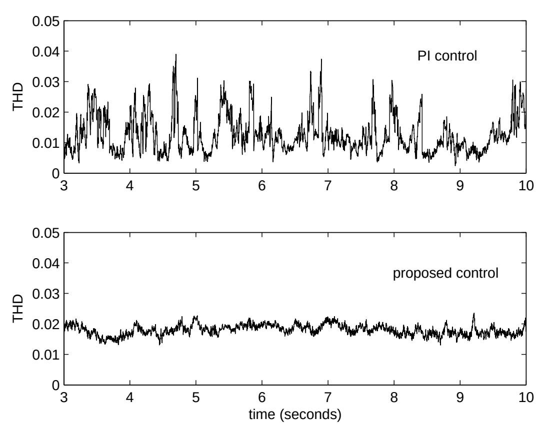


Fig. 11. THD of PCC voltage (phase a)

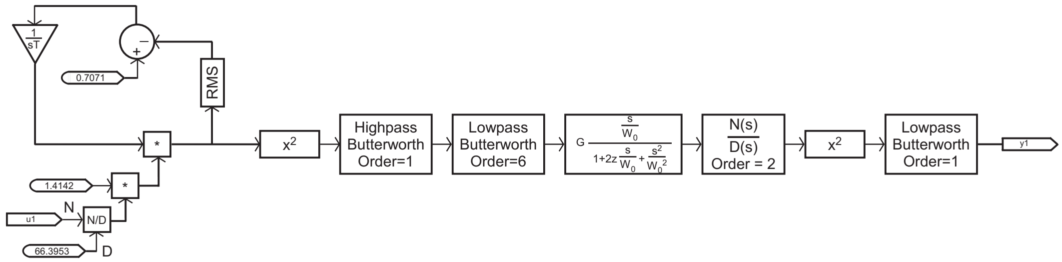


Fig. 12. Flicker measure of PCC voltage (phase a)

C. Total Harmonic Distortion (THD)

The total harmonic distortion of the system with the STATCOM under both two controls are shown in Fig. 11. The THD has been calculated 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

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

is provided as a reasonable model for human eye. The coefficients are given by the IEC for 230V, 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 are 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 contect by nearly a full order of magnitude from the case of no control.

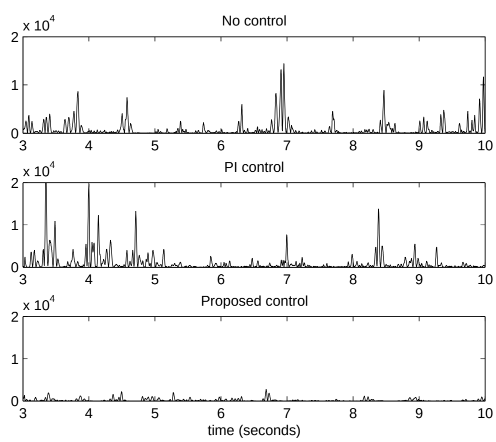


Fig. 13. Flicker measure of PCC voltage (phase a)

V. CONCLUSIONS

In this paper, a multi-level 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.

ACKNOWLEDGMENTS

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III. Fault Detection and Mitigation in Multilevel Converter STATCOMs

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ABSTRACT: Many STATCOMs utilize multilevel converters due to lower harmonic injection into the power system, decreased stress on the electronic components due to decreased voltages, and lower switching losses. One disadvantage, however, is the increased likelihood of a switch failure due to the increased number of switches in a multilevel converter. A single switch failure, however, does not necessarily force an *(2n+1)*-level STATCOM off-line. Even with a reduced number of switches, a STATCOM can still provide a significant range of control by removing the module of the faulted switch and continuing with *(2n-1)* levels. This paper introduces an approach to detect the existance of the faulted switch; identify which switch is faulty; and reconfigure the STATCOM. This approach is illustrated on an 11-level STATCOM and the effect on dynamic performance and the total harmonic distortion (THD) is analyzed.

Index Terms – STATCOM, multilevel converter, total harmonic distortion

I. INTRODUCTION

There are several compelling reasons to consider a multilevel converter topology for the STATCOM. These well known reasons include lower harmonic injection into the power system, decreased stress on the electronic components due to decreased voltages, and

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lower switching losses. Various multilevel converters also readily lend themselves to a variety of PWM strategies to improve efficiency and control. An eleven-level cascaded multilevel STATCOM is shown in Fig. 1. This converter uses several full bridges in series to synthesize staircase waveforms. Because every full bridge can have three output voltages with different switching combinations, the number of output voltage levels is $2n + 1$ where n is the number of full bridges in every phase. The converter cells are identical and therefore modular.

As increasingly higher level converters are used for high output rating power applications, a large number of power switching devices will be used. Each of these devices is a potential failure point. Therefore it is important to design a sophisticated control to produce a fault-tolerant STATCOM. A faulty power cell in a cascaded H-Bridge STATCOM can potentially cause switch modules to explode [1] leading to fault conditions such as a short circuit or an overvoltage on the power system resulting in expensive down time [2]. Subsequently, it is crucial to identify the existence of any fault and also to determine the location of the fault for it to be removed. Several recent works have focused on this aspect of multilevel converters.

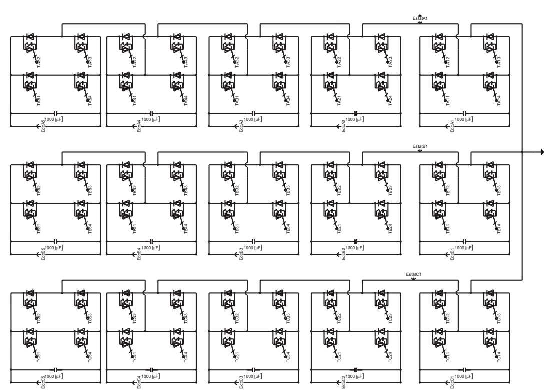

Fig. 1. Eleven level cascaded multilevel STATCOM

Many fault detection methods have been proposed over the last few years [1]-[5]. Resistor sensing, current transformation, and V_{CE} sensing are some of the more common approaches. For example, a method based on the output current behavior is used to identify IGBT short-circuits [3]. The primary drawback with the proposed approach is that the fault detection time depends on the time constant of the load. Therefore for loads with a large RL time constant, the faulty power cell can go undetected for numerous cycles, potentially leading to disasterous results. Another fault detection approach proposed in [4], is based on a switching frequency analysis of the output phase voltage. This method was applied to flying capacitor converters and has not been extended to cascaded converters. In [5], sensors are used to measure each IGBT current and to initiate forced switching if a fault is detected.

In this paper, the method we propose requires only that the output DC link voltage of each phase be measured. This measurement is typically accomplished anyway for control purposes. If a fault is detected, the module in which the fault occurred is then isolated and removed from service. This approach is consistent with the modular design of cascaded converters in which the cells are designed to be interchangeable and rapidly removed and replaced. Until the module is replaced, the multilevel STATCOM continues to operate with slightly decreased, but still acceptable, performance.

In summary, the proposed approach offers the following advantages:

- no additional sensing requirements,
- additional hardware is limited to one bypass switch per module,
- is consistent with the modular approach of cascaded multilevel converters, and
- the dynamic performance and THD of the STATCOM is not significantly impacted

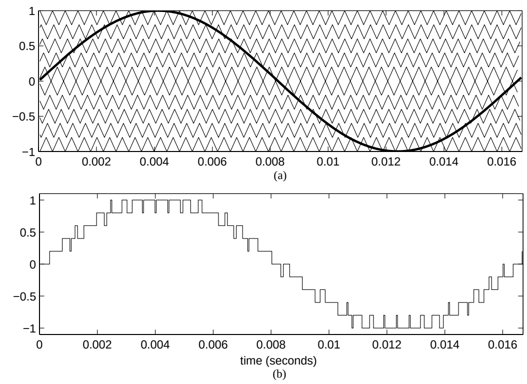

Fig. 2. (a) Carrier and reference waveform for PSPWM (b) Output waveform

II. THE MULTILEVEL 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. In the eleven-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 eleven. A multilevel configuration offers several advantages over other converter types [6]:

1) It is better suited for high-voltage, 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, and
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, variations in load cause the DC capacitors to charge and discharge unevenly leading to different voltages in each leg of each phase. However, because of redundancy in switching states, there is frequently more than one state that can synthesize any given voltage level. Therefore, there exists a "best" state among all the possible states that produces the most balanced voltages [7]. Since there are multiple possible switching states that can be used to synthesize a given voltage level, the particular switching topology is chosen such that the capacitors with the lowest voltages are charged or conversely, the capacitors with the highest voltages are discharged. This redundant state selection approach is used to maintain the total DC link voltage to a near constant value and each individual cell capacitor within a tight bound.

Different pulse width modulation (PWM) techniques have been used to obtain the multilevel converter output voltage. One common PWM approach is the phase shift PWM (PSPWM) switching concept [8]. The PSPWM strategy causes cancellation of all carrier and associated sideband harmonics up to the $(N-1)$th carrier group for an N-level converter. Each carrier signal is phase shifted by

$$\Delta\phi = \frac{2\pi}{n}$$

where n is the number of cells in each phase. Fig. 2 illustrates the carrier and reference waveforms for a phase leg of the 11-level STATCOM. In this figure, the carrier frequency has been decreased for better clarity. Normally the carrier frequency for PWM is in the range of 1-10 kHz.

III. FAULT ANALYSIS FOR THE MULTILEVEL STATCOM

A converter cell block as shown in Fig. 3 can experience several types of faults. Each switch in the cell can fail in an open or closed state. The closed state is the most severe failure since it may lead to shoot through and short circuit the entire cell. An open circuit can be avoided by using a proper gate circuit to control the gate current of the switch during the failure [9]. If a short circuit failure occurs, the capacitors will rapidly discharge through the conducting switch pair if no protective action is taken. Hence the counterpart switch to the failed switch must be quickly turned off to avoid system collapse due to a sharp current surge.

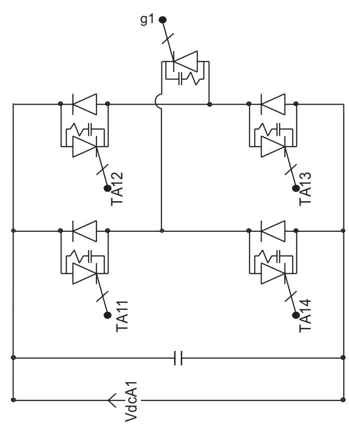

Fig. 3. Cell with fault switch

The staircase voltage waveform shown in Figure 2 is synthesized by combining the voltages of the various cells into the desired level of output voltage. At the middle levels of the voltage waveform, due to switching state redundancy, there are more than one set of switching combinations that may be used to construct the desired voltage level. Therefore by varying the switching patterns, the loss of any individual cell will not signifantly impact the middle voltages of the output voltage. However, the peak voltages require that all cells contribute to the voltage; therefore the short circuit failure of any one cell will lead to the loss of the first and $(2n+1)$ output levels and cause degradation

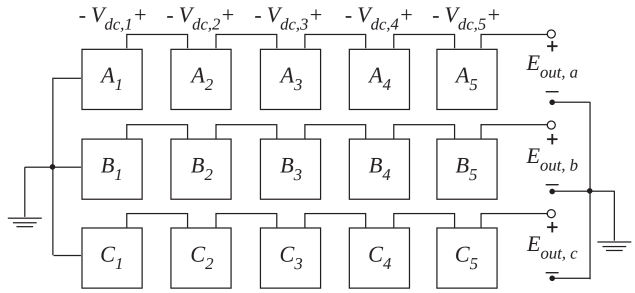

Fig. 4. Simplified eleven level cascaded multilevel STATCOM

in the ability of the STATCOM to produce the full output voltage level.

Consider the simplified 11-level converter shown in Fig. 4. The process for identifying and removing the faulty cell block is summarized in Fig. 5. The input to the detection algorithm is the filtered E_{out} for each phase. Although E_{out} is a DC voltage, it contains high-frequency ripple and sensor noise. It is passed through a low pass filter to extract the average $\hat{E}_{out}$ value for each phase. The average DC voltage $\hat{E}_{out}$ is then compared against V'_{dc}. The voltage V'_{dc} is chosen to be less than the reference value, $V_{dc,ref}$. The average DC link voltage will naturally vary with changes in the system, therefore it is prudent to have a “deadband” in the reference voltage levels. If there is a faulted module, the steady-state DC link voltage will be the voltage associated with $2(n-1)+1$ levels. In an 11-level converter, the faulted DC voltage will decrease by 20%. Therefore a good choice for V'_{dc} is $0.85V_{dc,ref}$.

If $\hat{E}_{out} < V'_{dc}$, then a fault has most likely occurred. The next step is to then determine which block is faulty so that it may be removed. By utilizing the switching signals in each converter cell, (i.e. A_{j1} and A_{j2}), it is possible to calculate all of the possible voltages that can be produced at any given instant. When there is a fault in the multilevel converter, the capacitor at the faulty block will rapidly discharge. This discharge results in a phase shift in the output AC voltage as well as a change in amplitude of voltage. The set of all possible phase a fault voltages for an 11-level converter is given by:

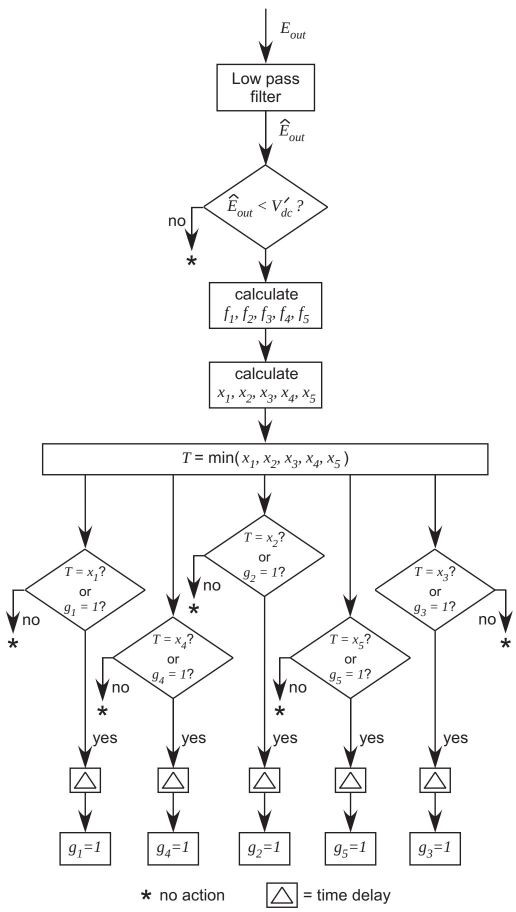

Fig. 5. Flow chart

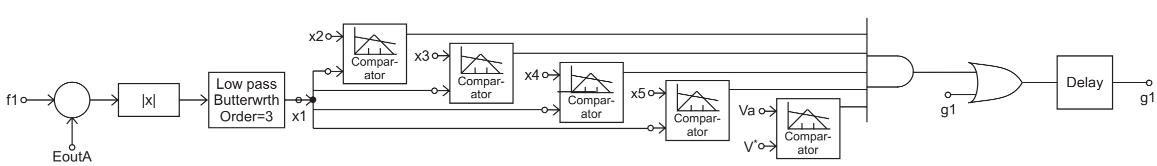

Fig. 6. Proposed fault detection and remediation control for cell1

$$f_i = V_{dc0} \sum_{\substack{j=1 \\ j \neq i}}^{n} (A_{j1} - A_{j2}) \quad i = 1, \ldots, n \tag{1}$$

where V_{dc0} is the ideal voltage across a single cell block. During a fault, only the f_i corresponding to the faulted cell will be low. Therefore, if

$$x_i = |E_{out} - f_i| \quad i = 1, \ldots, n \tag{2}$$

then the smallest x_i indicates the location of the faulted block. The last step is to actuate the module bypass switch g_i shown in Fig. 3. A slight time delay is added to the logic to neglect for momentary spikes that may occur in response to system faults. It is desirable to neglect momentary sags in the DC link voltage, but respond to sags of increased duration that indicate a faulted module. Fig. 6 shows the realization logic for the proposed fault detection and module removal method.

IV. EXAMPLE AND RESULTS

The single line diagram of the electrical distribution system feeding an arc furnace is shown in Figure 7. The electrical network consists of a 115 kV generator and an impedance that is equivalent to that of a large network at the point of common coupling (PCC). The STATCOM is connected to the system through a Y-Delta transformer. The electrical arc furnace load is non-sinusoidal, unbalanced, and randomly fluctuating. 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 [10]. The flicker waveform has subsynchronous variations in the 5-35Hz range [11]. Fig. 8 shows the active power drawn by the arc furnace. Note that the STATCOM is able to improve the line active power such that arc furnace variations do not propagate throughout the system as shown in Fig, 9.

A. Dynamic Performance

To test the proposed fault detection and mitigation approach, a faulty switch was initiated at 2.5 seconds. Within 300ms, the fault has been detected, the module removed, and the STATCOM restored to steady-state operation. The STATCOM bus voltage and line active powers are shown before the fault, during, and after the faulty module is removed. Note that both the bus voltage and line active power are adversely affected during the fault. In both cases, the high-frequency oscillations are increased. Once the faulty module is removed, the system returns to its pre-fault behavior. There is a small induced low-frequency oscillation that can be observed in the line active power, but this is rapidly damped by the STATCOM's control.

The average DC link voltage before, during, and after the fault is shown in Fig. 12. During the fault, the DC voltage drops rapidly as the faulted module capacitor discharges. When the faulty module is removed, the average DC voltage drops to roughly 80% of the initial voltage, as expected. The continued variation in the DC link voltage is due to the continual variation of the arc furnace load that is STATCOM is compensating and is normal.

Fig. 13 shows two cycles of the STATCOM multilevel voltage output. There are several

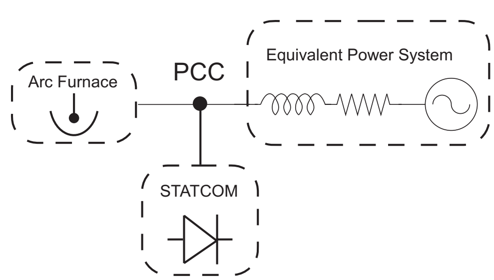

Fig. 7. Test system

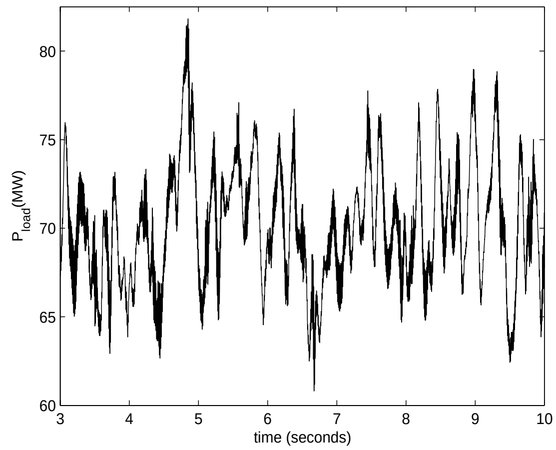

Fig. 8. Active power drawn by arc furnace load

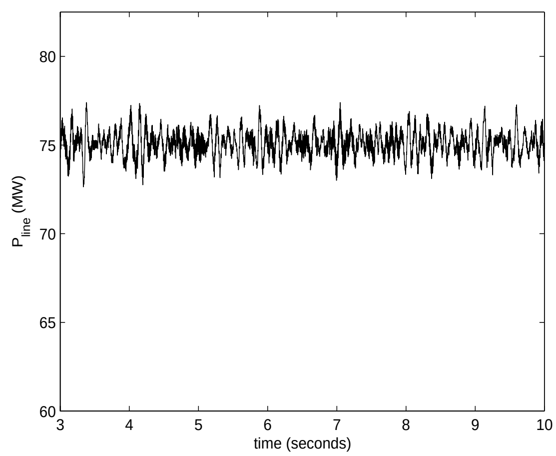

Fig. 9. Line active power

important aspects of this output waveform that have been highlighted. First, note the voltage collapse of the first level due to the faulted cell. This collapse in voltage will occur at the level that corresponds to the faulty cell. It is not possible to directly correlate the level number with the cell number (i.e. a collapse in level four does not necessarily indicate a fault in cell 4) because of the redundant state selection scheme that is used to balance the capacitor voltages.

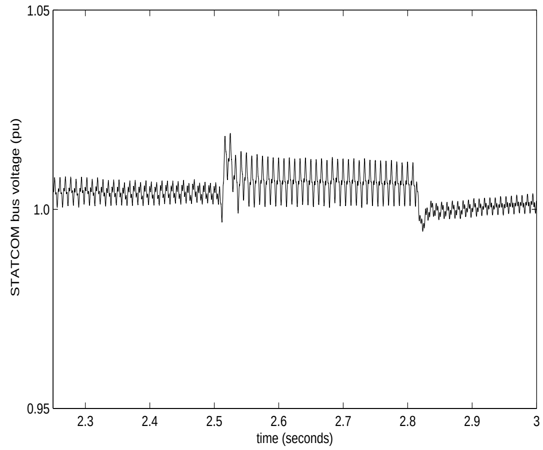

Fig. 10. STATCOM voltage before, during, and after fault

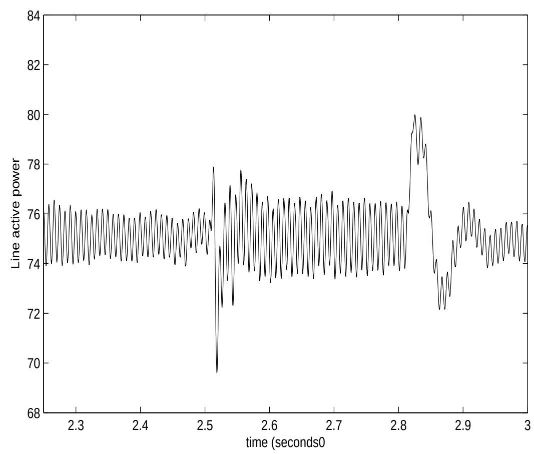

Fig.11. Line active power before, during, and after fault

A further aspect of note is the increase in length of the top level duration. This is due to the increase in the modulation gain k due to the decrease in DC link voltage. Since the STATCOM output voltage is directly proportional to

$$V_{stat} = kV_{dc}\cos\alpha$$

where k is the modulation gain and α is the phase angle. If V_{dc} decreases by 20%, then k

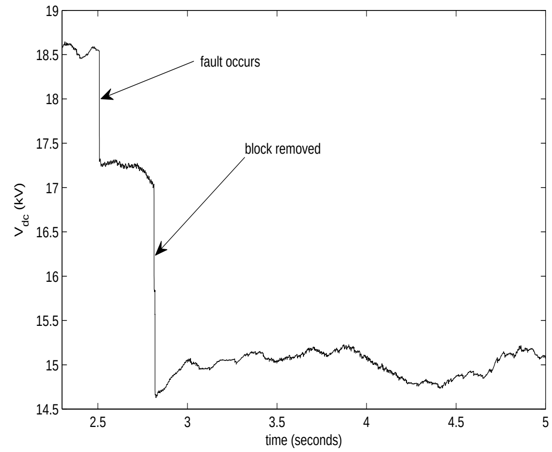

Fig. 12. DC voltage before, during, and after fault

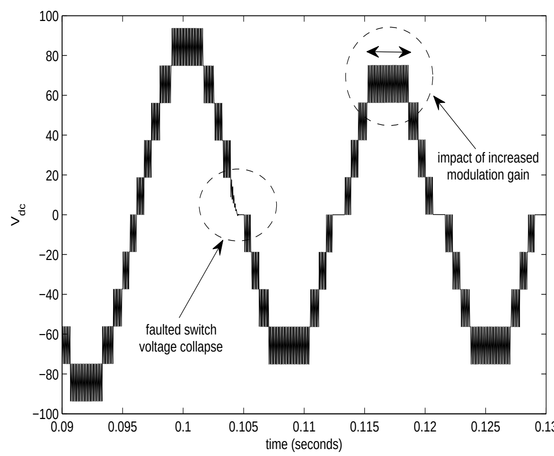

Fig. 13. Converter output with faulted cell

must increase by 20% to compensate. An increase of this magnitude in modulation gain takes the PWM into over-modulation where the magnitude of the reference waveform exceeds the magnitude of the carrier. This results in an increased length of time at higher voltage levels. Over-modulation may also result in the increase of lower frequency harmonics. The modulation gain k is shown in Fig. 14.

The individual module capacitor voltages in each phase for a faulty a phase switch are

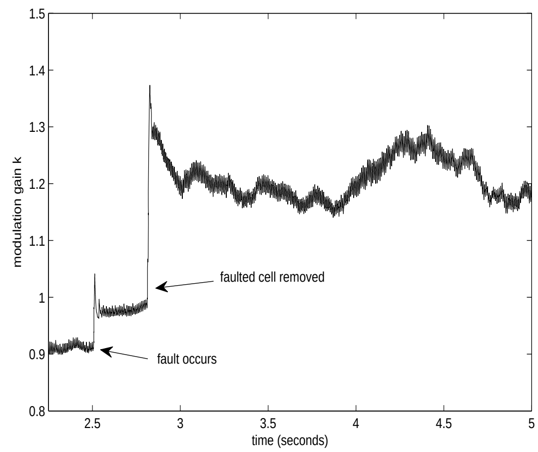

Fig. 14. Modulation gain k before, during, and after fault

shown in Fig. 15. Note that the faulted module voltage decays rapidly at 2.5 seconds (when the fault was applied). The remaining capacitor voltages in phase a show significant "chopping" as the redundant state selection approach rapidly alternates between modules to maintain the average DC link voltage. A crowbar circuit is used with each module to limit the maximum DC voltage, leading to the chopping behavior. Phase b shows a continual decline in all of the capacitor voltages until the corresponding faulty module is removed at 2.8 seconds. The capacitor voltages increase until they are in the nominal range and then exhibit similar "chopping" until they are regulated. Phase c does not exhibit chopping because all of the individual cell voltages are of similar magnitude and do not exceed the crowbar maximum.

B. THD Performance

A harmonic analysis has been performed on the output voltage at the point of common coupling. One of the primary reasons for using a multilevel converter is the reduction in harmonic content in the output waveform. Fig. 16 shows the total harmonic distortion

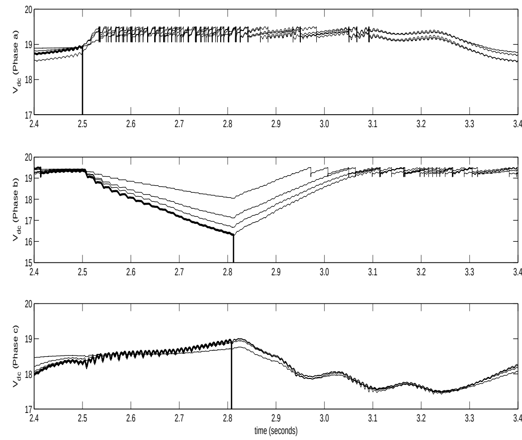

Fig. 15. Individual module capacitor voltages before, during, and after fault

levels at the STATCOM PCC before, during, and after the fault. Since this is measured at the PCC, the output waveform has already been filtered to remove high frequency components. Before the fault, the THD level is less than 1% which is quite good. During the fault, the THD increase significantly to over 5% which is unacceptably high. When the fault is removed, the THD decreases and settles at approximately 2.5% which is in the acceptable range for a 115 kV system [12]. Therefore the loss of one of the cells does not necessitate the immediate removal of the STATCOM from service.

The increase in THD after removing the faulty cell is due to several reasons. Firstly, the STATCOM filters were tuned to the resonant frequencies associtated with the 11-level converter and are not as effective when the converter topology changes to a 9-level. Secondly, the over modulation required for the 9-level converter increases the content of the lower frequency harmonics. This effect is illustrated in Fig. 17 which shows the content level of the third, fifth, and seventh harmonics. While the third harmonic is quite high during the fault, it returns to pre-fault levels after the fault is cleared, whereas the

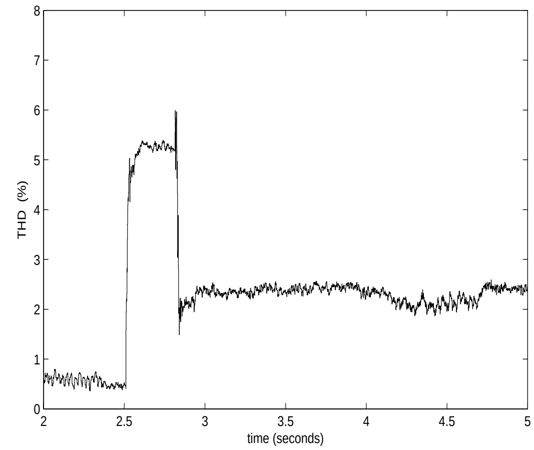

Fig. 16. Percent THD of the faulty phase before, during, and after fault

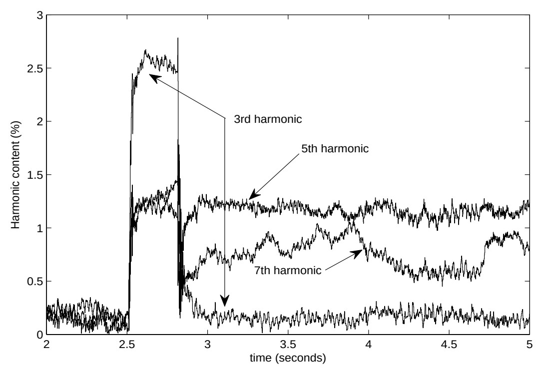

Fig. 17. Percent harmonic content of the fault phase before, during and after fault

fifth and seventh remain fairly high due to the over-modulation. Even though they are increased over the pre-fault value, they still remain under the 1.5% limit required of 115 kV systems [12].

V. CONCLUSIONS

In this paper, a fault detection and mitigation strategy for a multilevel cascaded converter has been proposed. This approach requires no extra sensors and only one additional bypass switch per module per phase. The approach has been validated on a 115 kV system with a STATCOM compensating an electric arc furnace load. This application was chosen since the arc furnace provides a severe application with its non-sinusoidal, unbalanced, and randomly fluctuating load. The proposed approach was able to accurately identify and remove the faulted module. In addition, the STATCOM was able to remain in service and continue to provide compensation without exceeding the total harmonic distortion allowances.

ACKNOWLEDGEMENTS

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IV. Application of STATCOM for Electric Arc Furnace Distortions Alleviation

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ABSTRACT— this letter presents the experimental results of IEEE 14 bus test system that is dealing with an Electric Arc Furnace (EAF). STATCOM is applied to alleviate the voltage and active power variations caused by the random nonlinear load (EAF). The studied topology for the STATCOM is a Multilevel Cascaded Converter. A nonlinear control has been used in order to obtain the control parameters of the converter.

Index Terms: Cascaded Multilevel Inverter, Electrical Arc Furnace, Nonlinear Control

I. INTRODUCTION

In this study, the impact of EAF in IEEE 14 bus system has been investigated. To alleviate the variations caused by the EAF a multilevel converter has been implanted. The STATCOM is a Cascaded Multilevel Converter and the switching of that is performed by Pulse Width Modulation (PWM). A nonlinear controller is used to get the control parameters of the PWM (k, α). The load is a random varying resistive load which models the Electric Arc Furnace.

II. OBTAINING THE CONTROL PARAMETERS OF PWM

A Nonlinear control has been implemented in PSCAD in order to use STATCOM as a source to provide both active and reactive variations of load at the point of common coupling. Equations (1) and (2) are describing the voltage balance across the lines that the STATCOM has been applied.

$$kV_{dc}^{'}\cos(\theta_{pcc}+\alpha)-V_{pcc}^{'}\cos(\theta_{pcc})=R^{'}i_{d}^{'}+\frac{L^{'}}{\omega}\frac{di_{d}^{'}}{dt}-L^{'}i_{q} \qquad (1)$$

$$kV_{dc}^{'}\sin(\theta_{pcc}+\alpha)-V_{pcc}^{'}\sin(\theta_{pcc})=R^{'}i_{q}^{'}+\frac{L^{'}}{\omega}\frac{di_{q}^{'}}{dt}+L^{'}i_{d} \qquad (2)$$

Assuming the generator is producing constant active power the angle of the voltage at PCC can be calculated by (3).

$$\theta_{pcc}=-\cos^{-1}\left(\frac{V_{pcc}{}^{2}-P_{const}\times Z_{g}}{V_{pcc}\times E}\right)-\theta_{g} \qquad (3)$$

V_{pcc} : Voltage at PCC

P_{const}: Desired Active Power Generation

E : Voltage at the Generator Bus

Z_g: Thevenin Equivalent Impedance seeing from PCC

θ_g: Angel of Z_g

Using (4) the P and Q can be converted to $i_d^{'}$ and $i_q^{'}$.

$$\begin{bmatrix} i_d^{'} \\ i_q^{'} \end{bmatrix} = \left(\frac{1}{V_{pcc}}\right) \begin{bmatrix} \cos(\theta_{pcc}) & \sin(\theta_{pcc}) \\ \sin(\theta_{pcc}) & -\cos(\theta_{pcc}) \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \tag{4}$$

P and Q can be obtained by (5) and (6)

$$P = P_{load} - P_{const} \tag{5}$$

$$Q = (V^* - V_{pcc})(k_p + \frac{k_i}{s}) \tag{6}$$

P_0 : Constant Active Power that is absorbed by the load

V^* : Commanded Voltage at PCC

Applying the $i_d^{'}$ and $i_q^{'}$ in (1) and (2) it is possible to obtain the control parameters (k, α).

III. TEST SYSTEM

In this study an Electric Arc Furnace Load has been supplied through the IEEE 14 bus test system [1]. Figure 1 shows the test system.

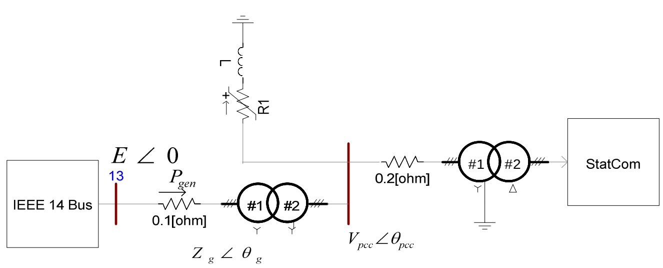

Fig. 1. Test System

The system is working on 100 MVA and 115 kV RMS.

IV. EXPERIMENTAL RESULTS

In order to have a constant RMS voltage at PCC and also eliminate the need of random active power generation, STATCOM is applied to the IEEE 14 bus system that is supplying the random EAF load. Figure 2 shows the RMS of the voltage at PCC before having STATCOM and after that.

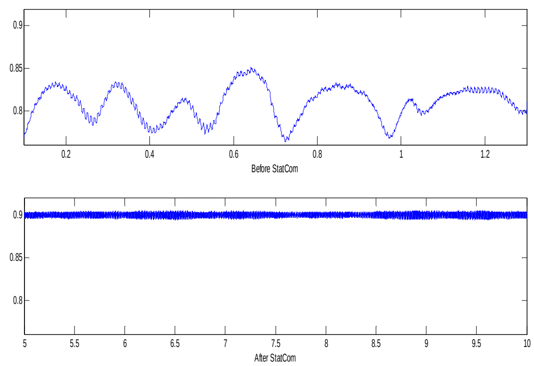

Fig. 2 RMS of the Voltage at PCC, Before STATCOM (top), After STATCOM (bottom)

Figure 3 shows the active power that passes through the thevinin impedance. This is the overall active power generation of the IEEE 14 bus system. This power is illustrated as P_{gen} in figure 1.

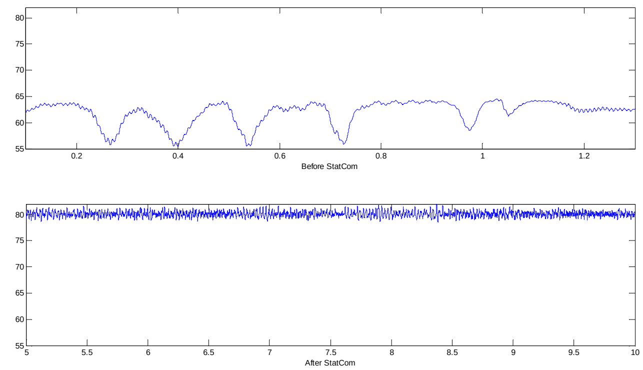

Fig. 3 Active Power from the System, Before STATCOM (top), After STATCOM (bottom)

Figure 4 illustrates the active power that passes through the STATCOM line. As it can be seen STATCOM is picking up all the variations of the load.

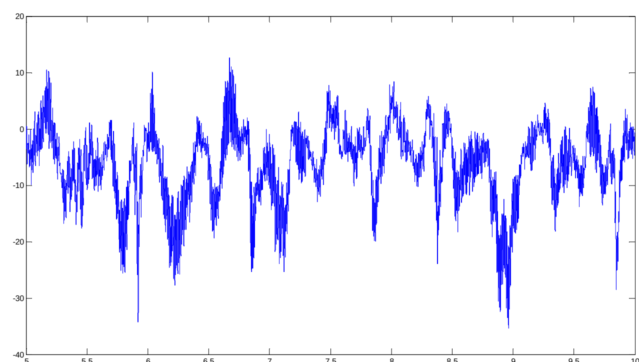

Fig 4. Active Power through the StatCom Line

The effect of fault in system has been studied. A solid fault applied to the bus 5 of the IEEE test system. In order to clear the fault the line between buses 5 and 1 has been removed. From figures 5 and 6, it is apparent that the controller is pretty robust in case of fault. In figure 5, the RMS of the voltage before fault, during the fault and after that is shown. In figure 6 the defined P_{gen}, before fault, during the fault and after that is illustrated. Fault happens at 3 sec. and is cleared at 3.1 sec.

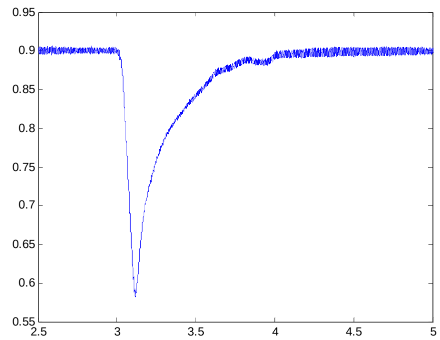

Fig. 5- RMS of the Voltage at PCC before Fault, During the Fault and After Fault

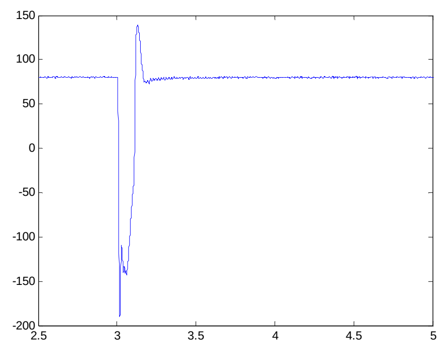

Fig. 6. P_{gen} Before Fault, During the Fault and After Fault

Figure 7 shows the THD of the three phase voltages at PCC. By applying the STATCOM, we will have 40% of improvement in maximum of THD.

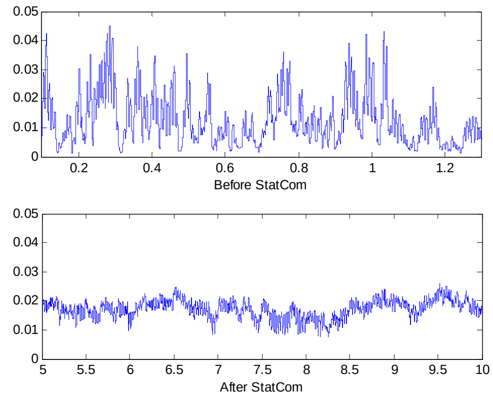

Fig. 7. THD of the Three Phase Voltages at PCC, Before STATCOM (top), After STATCOM (bottom)

V. CONCLUTION

The proposed controller has been tested when there is a $\pm 10\%$ change in Thevenin impedance. The output results are as expected. Therefore, without knowing the exact parameters of the lines, the controller still have a valid performance. Also, it can be seen from the results the proposed controller is very robust in case of fault.

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2. CONCLUSIONS

Electric arc furnaces (EAF) are prevalent in the steel industry to melt iron and scrap steel. Electric arc furnaces frequently cause large amplitude random and unbalanced fluctuations of active and reactive power and are the source of significant power quality disturbances. Static Synchronous Compensators (STATCOMs) provide a power electronic-based means of embedded control for reactive power support and power quality improvement. This dissertation introduces two new nonlinear controls for a multi-level STATCOM that provide significant reduction in EAF-induced aperiodic oscillations on the power system. These controls are a V_{PCC}-V_{dc} control and a V_{PCC}-P_{line} control. These proposed methods are compared with traditional PI controls and shown to have improved performance. In all cases, the proposed controls produced similar or improved results when compared with the PI control in terms of total harmonic distortion reduction, dynamic response, and flicker mitigation. Furthermore, the proposed controllers were validated on the IEEE 14 bus test system including response to faults. In all cases, the controllers continued to provide consistently good results.

Many STATCOMs utilize multilevel converters due to lower harmonic injection into the power system, decreased stress on the electronic components, decreased voltages, and lower switching losses. One disadvantage, however, is the increased likelihood of a switch failure due to the increased number of switches in a multilevel converter. This dissertation introduces an approach to detect the existence of the faulted switch; identify which switch is faulty; and reconfigure the STATCOM. This approach requires no extra sensors and only one additional bypass switch per module per phase. The approach has been validated on a 115 kV system with a STATCOM compensating an electric arc furnace load. This application was chosen since the arc furnace provides a severe application with its non-sinusoidal, unbalanced, and randomly fluctuating load. The proposed approach was able to accurately identify and remove the faulted module. This work showed that a STATCOM can still provide a significant range of control by removing the module of the faulted switch and continuing with a reduced number of levels. In addition, the STATCOM was able to remain in service and continue to provide compensation without exceeding the total harmonic distortion allowances.

APPENDIX A.

BACKGROUND ON REDUNDANT STATE SELECTION

The Redundant State Selection (RSS) is a method to get the capacitor voltages balanced in Cascaded Multilevel Converter. The Pulse Width Modulation will dictate a certain voltage level and this voltage level should be made by proper capacitors. Figure 1 shows one of the phases of the cascaded multilevel converter. If I_{phase} is positive, therefore the capacitors are getting discharged. Thus, the most charged capacitors should provide the desired voltage. If I_{phase} is negative, the capacitors are charging up and therefore the least charged capacitors should make the desired voltage. Figure 2 shows the PSCAD realization of the RSS. For each phase the RSS has been made. As it can be seen in figure 2, the input of each block is the capacitor voltages and also the switchings that has been made by PWM and the output of each block is the new switchings.

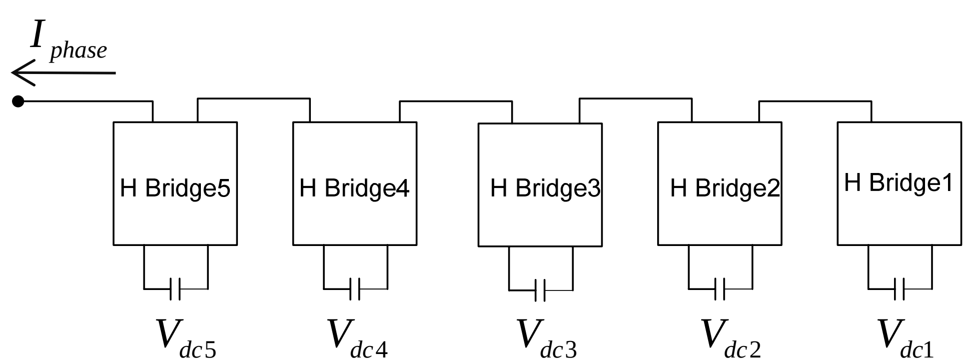

Fig. 1. One Phase of the Cascaded Multilevel Converter

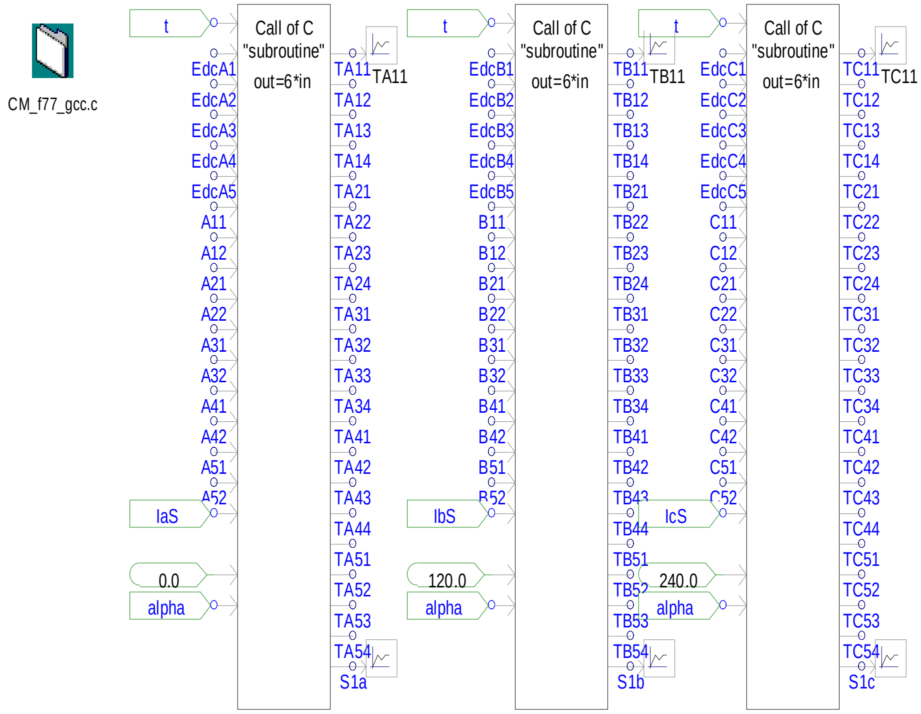

Fig. 2. PSCAD Realization of the Redundant State Selection

APPENDIX B.

BACKGROUND ON CROW BAR

Capacitor voltages in the cascaded multilevel converter may not stay at theit designed point, especially when there is no control on them. Therefore if the STATCOM is absorbing a small amout of active power, this will result in capacitor voltages to go up. Therefore, chopper circuit can be used in order to maintain the capacitor voltages at the desired point. Figure 1 shows the chopper circuit and which is called Crow Bar. Whenever the capacitor voltage gets larger than the designed value the illustrated switch in the crow bar will turn on and will chop the voltage down to the desired value.

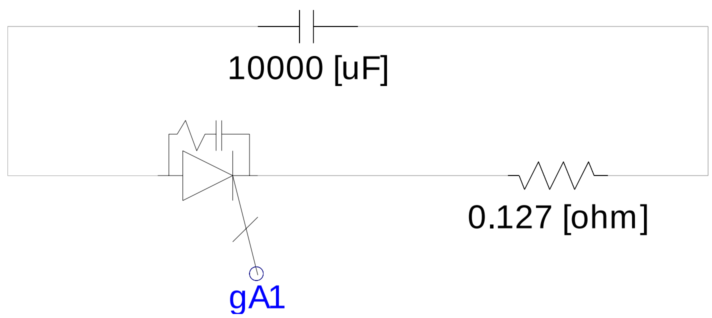

Fig. 1. Crow Bar Circuit

APPENDIX C.

BACKGROUND ON FAULTED CELL IN A MULTILEVEL CONVERTER WITH BATTERIES

If the output voltage of each block in the multilevel converter was strictly constant (i.e. using batteries instead of capacitors) the effect of having faults on different modules could be investigated from the output voltage. Each H-Bridge will produce three different voltage levels (-1, 0, 1). In the following figures the top one shows the case when there is fault on one of the switches that is producing the positive voltage and the bottom one shows when the fault is on one of the switches that produces the negative voltage.

Figure 1 shows the output voltage of STATCOM when there is fault in the first block.

Figure 2 shows the output voltage of STATCOM when there is fault in the second block.

Figure 3 shows the output voltage of STATCOM when there is fault in the third block.

Figure 4 shows the output voltage of STATCOM when there is fault in the fourth block.

Figure 5 shows the output voltage of STATCOM when there is fault in the fifth block.

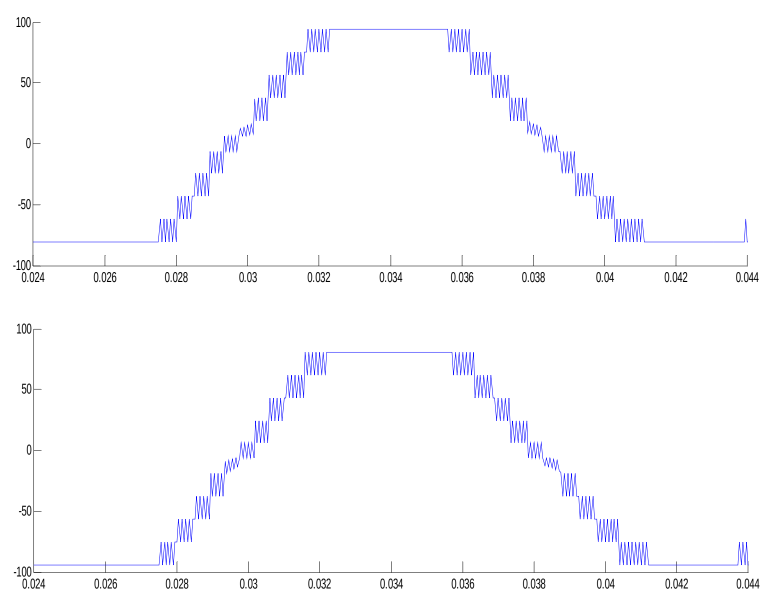

Fig. 1. Output Voltage of STATCOM in Case of Having Fault in the First Block

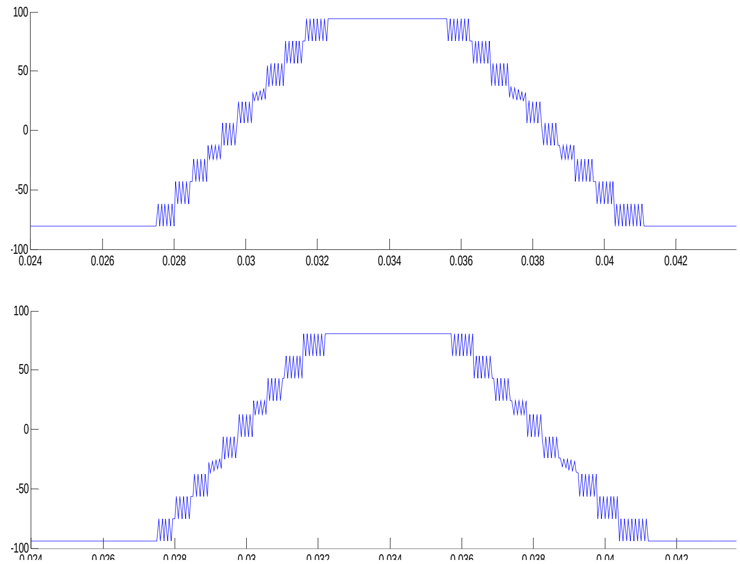

Fig. 2. Output Voltage of STATCOM in Case of Having Fault in the Second Block

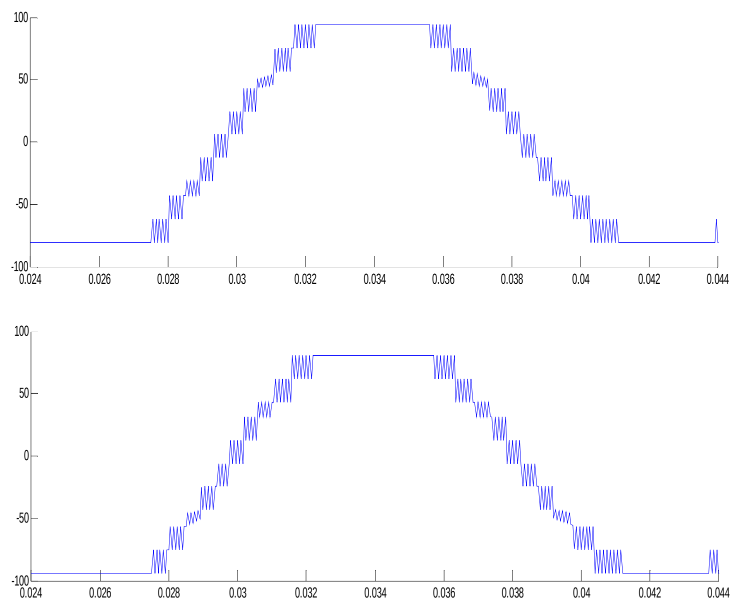

Fig. 3. Output Voltage of STATCOM in Case of Having Fault in the Third Block

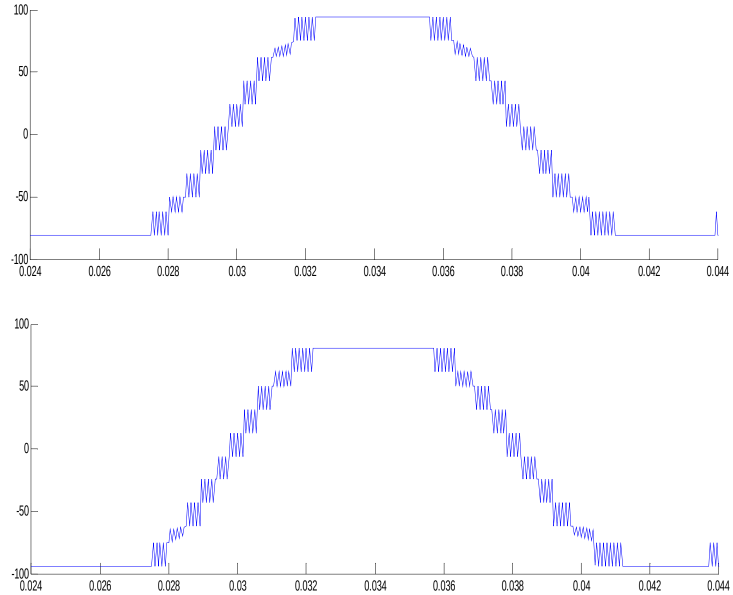

Fig. 4. Output Voltage of STATCOM in Case of Having Fault in the Fourth Block

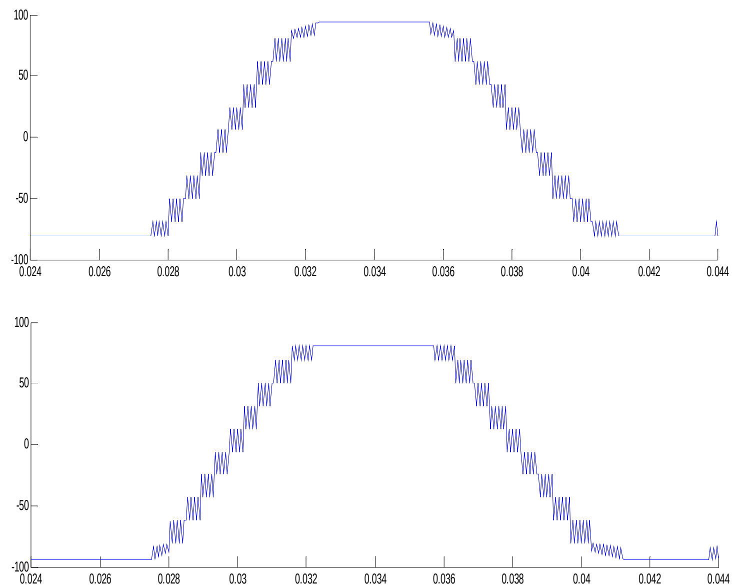

Fig. 5. Output Voltage of STATCOM in Case of Having Fault in the Fifth Block

APPENDIX D.

IEEE 14 BUS TEST SYSTEM DATA

Figure 1 shows the one line diagram of IEEE 14 bus test system.

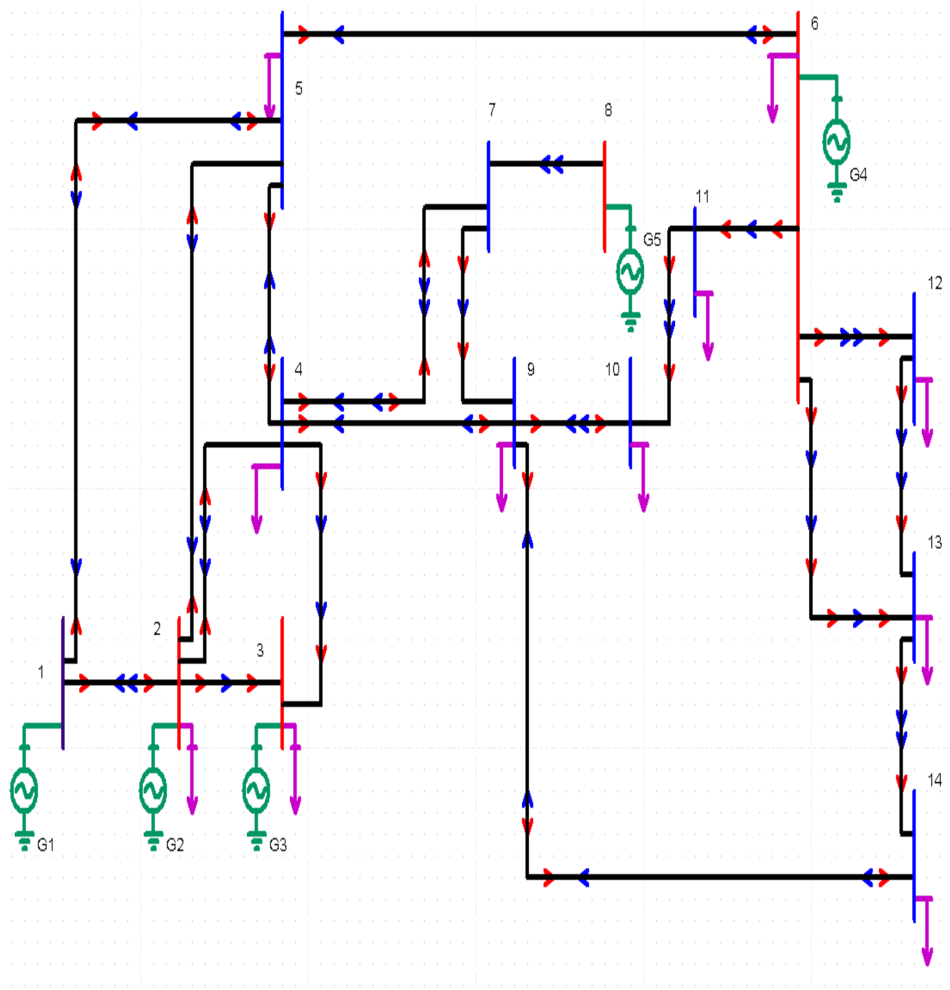

Fig. 1. IEEE 14 Bus Test System One Line Diagram

Table 1 contains the bus data of the system and table 2 contains the line data of the system.

Table 1 Bus Data

Bus No.	Bus Type	Bus Voltage	Bus Angle(deg)	P_{load} (MW)	Q_{load} (MVAR)	P_{gen} (MW)	Q_{gen} (MVAR)
1	SL	1.06	0	0	0	232.4	-16.9
2	PV	1.045	-4.98	21.7	12.7	40	42.4
3	PV	1.01	-12.72	94.2	19	0	23.4
4	PQ	1.019	-10.33	47.8	-3.9	0	0
5	PQ	1.02	-8.78	7.6	1.6	0	0
6	PV	1.07	-14.22	11.2	7.5	0	12.2
7	PQ	1.062	-13.37	0	0	0	0
8	PV	1.09	-13.36	0	0	0	17.4
9	PQ	1.056	-14.94	29.5	16.6	0	0
10	PQ	1.051	-15.1	9	5.8	0	0
11	PQ	1.057	-14.79	3.5	1.8	0	0
12	PQ	1.055	-15.07	6.1	1.6	0	0
13	PQ	1.05	-15.16	13.5	5.8	0	0
14	PQ	1.036	-16.04	14.9	5	0	0

Table 2 Line Data

From	To	R(pu)	X(pu)	B(pu)
1	2	0.0194	0.0592	0.0528
1	5	0.054	0.223	0.0492
2	3	0.047	0.198	0.0438
2	4	0.0581	0.1763	0.034
2	5	0.057	0.1739	0.0346
3	4	0.067	0.171	0.0128
4	5	0.0134	0.0421	0
4	7	0	0.2091	0
4	9	0	0.5562	0
5	6	0	0.252	0
6	11	0.095	0.1989	0
6	12	0.1229	0.2558	0
6	13	0.0662	0.1303	0
7	8	0	0.1762	0
7	9	0	0.11	0
9	10	0.0318	0.0845	0
9	14	0.1271	0.2704	0
10	11	0.082	0.1921	0
12	13	0.2209	0.1999	0
13	14	0.1709	0.348	0

VITA

Atousa Yazdani was born on June 5th 1975 in Tehran, Iran. She received her BSc degree from Tehran University in 1997 and her MSc from Amirkabir University (Tehran Polytechnics) in 2001. She joined the Electrical and Computer Engineering Department of the Missouri University of Science and Technology in May 2005 to get her PhD degree. She got her PhD in May 2009. Her research interests include Applying Power Electronic Devices to enhance the Power System Performance, Power System Modeling, Power System Dynamics and FACTS devices.