

Frequency Domain Based Adaptive Phase-lead Controllers for Single-Phase Inverters

(Invited Paper)

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Abstract- In this paper novel adaptive control approaches for control of single-phase Current Regulated PWM (CRPWM) inverters are proposed. The optimal tracking feature that is tracking the reference signal with low phase and amplitude errors is one of the main goals in inverter systems. Conventional controllers such as Proportional-Integral (PI) controllers cannot guaranty satisfactory tracking capability for many applications. This paper presents frequency domain based adaptive mechanisms to mitigate the phase and gain errors while the inverter system is treated as a multivariable system. One strategy uses Band Pass Filters (BPF) with adjustable center frequencies tuned by a Neural Network system, and the other employs a fixed BPF plus an adjustable time delay. In the first, the filters are adjusted by a neural network based adaptive system for perfect tracking, whereas in the second strategy, the simpler one, a simple adjustable digital time delay removes the phase error of the overall system. The simulation results obtained through MATLAB / SIMULINK software show the successful operation of the proposed systems.

Key-Words: - PWM Inverters, Adaptive Control, Multivariable System, Variable Delay, System Identification, Phase Equalizer, Neural Networks.

1 Introduction

Current regulated inverters have wide applications such as control of ac electric machines, static reactive power compensators, UPS systems, and active power filters. In such applications, the inverter must synthesis the reference signal, which is usually a pure sinusoidal or a periodic signal containing harmonics. The later appears in active power filter applications in which a non-sinusoidal current must be synthesized by the inverter to compensate the undesired harmonics of the under compensation load. A key problem in such applications is the need for an inverter can synthesize the desired currents, defined by the reference signal, with low error. Phase and amplitude errors in this tracking problem are quite important. For good tracking, the system should have wide bandwidth comprising low phase lag and unity amplitude response at those frequencies that the reference signal has dominant harmonic components. Pulse width modulation (PWM), hysteresis, and delta modulation schemes are the well known strategies for controlling current regulated inverters. Regardless of control strategy

used, higher bandwidth usually results in lower phase and amplitude errors. But that requires higher switching frequency that in turn causes higher switching loss. Though, current regulated PWM inverters (CRPWM) have poor phase characteristics, nonetheless they are almost the most popular schemes still being used for many applications. They are usually used as a closed loop system with proportional-integral (PI) controllers. There are some other control approaches that are inherently closed loop with relatively high bandwidth and small phase error. However, some of them such as Hysteresis Controllers (HC) impose higher switching frequency and loss. HC also produces non-predictable frequency spectra.

Recently, some advanced control systems such as deadbeat [1], sliding mode [2], predictive [3,4], adaptive [5], multi rate feed forward [6], and adaptive predictive [7] control systems have found successful applications for reducing the tracking error of inverters. Deadbeat and predictive control strategies provide good tracking ability, but they require the exact model of the inverter. Because of

high-gain feedback, the resulting stability robustness in conventional deadbeat control is weak [6].

Another control approach has been developed based on the concept of Synchronous frame PI controller [8,9]. In this control approach, a high gain notch filter is placed through the feedback loop to provide high loop gain and therefore guaranty a low tracking error at the center frequency of the notch filter. However, this control system has the problem of successful implementation of the notch filters due to their high gain and high sensitivity. They also cannot easily be applied to single-phase inverters.

In this paper a new adaptive phase and amplitude equalizer structure is presented. The paper also proposes a simplified adaptive system that uses a fixed BPF with a variable delay to compensate the error of the inverter. Section 2 presents the control structure and the concept of the phase equalizing. The proposed system identification method and the neural network based adaptation mechanism are presented in sections 3. Simplified control system is explored in section 4.

2 Adaptive Equalizing System

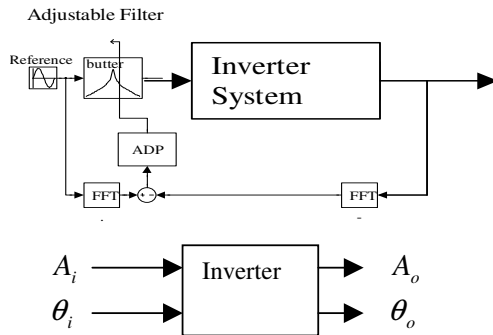


Fig. 1: a) Block diagram of the proposed adaptive control system of inverters
b) Inverter as a MIMO system

2.1. Modeling Inverter as a MIMO plant

Consider a reference signal defined as $I_{ref} = A_i \sin(\omega t + \theta_i)$ in the time domain. It can be treated as an input vector $[A_i \ \theta_i]^T$ to the inverter in the frequency domain as shown by Fig. 1.b. Hence, by this representation, the inverter system can be considered as a multivariable (MIMO) plant must track two constants or very slowly varying quantities, i.e. A_i and θ_i . The inverter system by itself can be modeled as a linear system for the frequencies lower enough than the switching

frequency. Hence, by considering the phase and gain responses at steady state as the input and output quantities, the under study system is exactly a diagonal system with no interactions between θ_i and A_o as well as A_i and θ_o .

2.2 Control Mechanism

Fig. 1.a shows the block diagram of the recently proposed adaptive system in which the adjustable BPF bank has a key role in reducing the phase and gain errors of the inverter system. The inverter under control can be either an open or a closed loop system with any pulse modulation strategy. In the proposed system a tunable digital BPF bank is inserted in cascade with the inverter system to equalize the phase and amplitude of the inverter's frequency response. The controller takes role only at the frequencies where the overall system should track the reference signal with no phase/gain error. Consider a simple BPF. Its amplitude response shows a peak near the center frequency f_c while its phase response is a monotone function decreasing with frequency with zero phase at f_c . It shows leading phase characteristics for the frequencies lower than f_c , whereas shows a lagging phase characteristics for the frequencies greater than f_c . Suppose that the reference signal is a sinusoidal signal with frequency f_0 . The phase equalizing can easily be done by tuning the center frequency f_c of the filter around its nominal center frequency f_0 . Now, if the center frequency of the filter is changed to $f_c = f_0 + df$, where df is a small positive deviation around the center frequency, that causes a leading phase $d\phi$. It also changes the filter's gain at f_0 . In contrast, the lagging cases occur for negative values of df . Hence, the sign and value of the filter's phase can be controlled via changing the center frequency of the filter. The gain error of the combined inverter and filter at f_0 can easily be corrected by adjusting the relevant filter's gain. In case the inverter is to track a harmonic signal, a set of BPFs with center frequencies at the harmonics of the reference signal should be used.

3 Neural Network Adaptive Control

3.1 System Identification

To compensate the phase and amplitude errors of the system (inverter +BPF) we need to know the

frequency response of the system only at one or few frequencies depending on content of the reference signal. Hence, rather than using a complicated identification method, a very simple system identification method is recommended. By applying the time varying Fourier operator expressed by Equ. (1) over one period of the reference signal (T) to the input (input of the BPF) and output (output of the inverter), the instantaneous phase and amplitude errors can be calculated.

$$C_1(t) = \frac{1}{T} \int_{t-T}^t x(\tau) e^{j\frac{2\pi}{T}\tau} d\tau \quad (1)$$

3.2. Neural Network Based Adaptation

In each identification step, the value of df is corrected based on the amount of the phase error calculated. A higher phase error requires a greater df . This scenario is repeated until the phase error reaches zero. In this study, df is updated as follows:

$$df(n) = -\alpha \cdot \phi(n) + df(n-1) \quad (2)$$

where $\phi(n)$ is the system phase error in radian at the n -th identification cycle and α is a positive constant. Any increase in α may speed up the adaptation process, but it in turn may lead to instability or an oscillatory response. After converging the phase adaptation process, the amplitude response of the overall system can simply be adjusted.

As aforementioned, based on the df obtained in the each adaptation iteration, we need to redesign the filter. Filter design algorithm usually requires a computer with high level programming capability. To remove the need for a complicated hardware/software system, using a simple three-layer feed forward perceptron neural network (NN) is suggested [12]. NN is powerful tools for approximating wide range of nonlinear and complicated functions [13].

A BPF filter, like any other filters, can be characterized by a set of coefficients of its numerator and denominator polynomials, or by a set of its dc gain, zeros, and poles. It also can be characterized by its state space model. For the applications where the reference signal has harmonics, the range of variation in center frequency of the filter can be very wide (from around zero frequency to the frequency of the highest harmonics). So, the NN system must be trained for a wide range of the input variable (df), while the NN outputs are the corresponding

Butterworth filter parameters. Based on the author's experience, even significant changes in the center frequency may cause only quite small changes in the filter's parameters, off course when it is represented by transfer function or state space models. Hence, it is difficult to train a NN system successfully. After carefully investigating the problem, the zeros{Z}, poles{P}, and dc gain{K} representation has been chosen. Ref[12] explores the variations in real and imaginary parts of zeros, poles, and dc gain for a 4th order band pass Butterworth filter. Also, Fig. 2 explores the variation of poles' real (Pr) and imaginary (Pi) parts as a function of f_0 . The NN used in this study has one input and 3 groups of outputs (K,Pr,Pi) with 9 elements in total. Because of low changes in K and Pr, they can be considered as constants. Also, poles are in complex conjugate form, hence it is enough to consider just one half of the Pi's elements.

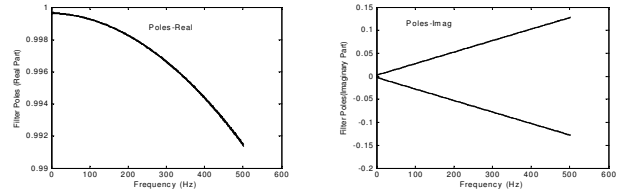


Fig. 2: Variations in Real Part (left) and imaginary parts(right) of the filter versus f_0

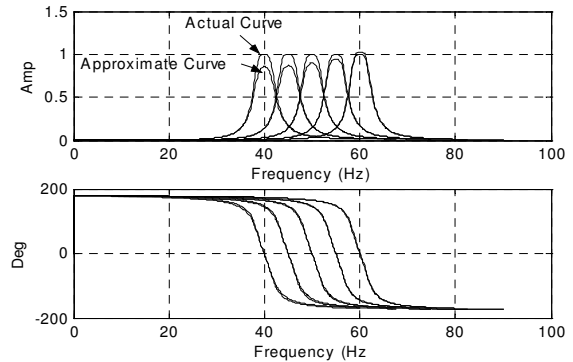


Fig. 3: The filters response designed by NN System in compare with the exact calculation. $f_0=50\text{Hz}$ and Pr and K are considered constant

Some NN systems have successfully been trained using Marquart method [10], a very efficient and fast training algorithm, and implemented using MATLAB Neural Networks Toolbox [11]. Fig. 3 indicates the filters' response obtained from NN system in compare with the exact curves when the nominal value of f_0 is equal to 60Hz. The NN system under study has 1,2, and 4 nodes in layers 1 to 3 respectively. As results explore, the NN system

introduces just some gain error where the f_0 does not equal the nominal frequency 60 Hz.

3.3. Simulation Results

All parts of the control system including identification system, digital BPF filter, neural network, and the closed loop CRPWM inverter with PI controller has been simulated in MATLAB / SIMULINK environment. Fig. 4 indicates the block diagram of the under study system. The Inverter system injects a sinusoidal current

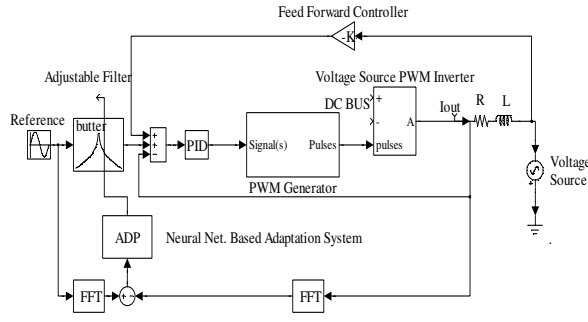


Fig. 4: Block diagram of the adaptive crpwm inverter. $R=1 \Omega$, $L=1\text{mH}$, $V = 40 \sin(100\pi t)$

to the power network as a simplified active filter. It benefits a feed forward controller with a constant gain ($=1$) for reducing the effect of the source voltage V . The reference signal is a 350Hz sinusoidal. Also the inverter system has an inner loop with a conventional PI controller ($K(s)=0.5+10/s$). Switching frequency has been selected to be equal to 25 kHz. Fig. 5 shows the reference and output signals of the system before adaptation, and as seen, the existing controllers cannot guaranty zero error accomplishment. The Figure clearly shows the phase lag impact of the system. The results obtained from NN based self-tuning adaptive system is shown in Fig. 6 and as appears, the system represents excellent response at steady state. Also, Fig 7 shows the system's phase error after the each iteration. To gain good results, each identification iteration is started when the transient response caused by the previous iteration has been damped, that is after 20 cycles of the reference signal. That reduces the adaptation mechanism speed. However, the results confirm the successful operation of the proposed control system in tracking the sinusoidal reference signals at steady state. The approach can easily be extended to the harmonic reference cases.

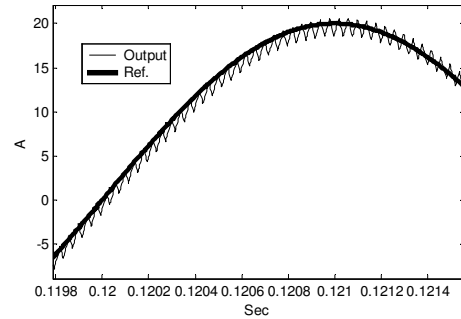


Fig 5: Reference and output signals of the inverter before adaptation.

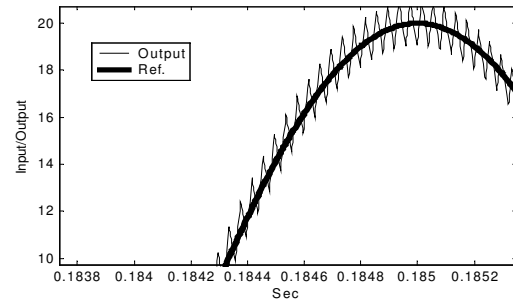


Fig. 6: Reference and output signals of the inverter after adaptation.

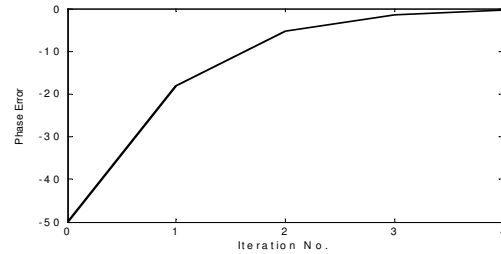


Fig.7: Phase error (ϕ) after each step .

4 Simplified Adaptive Controller

4.1 System Structure

In this section a new and practically interesting adaptive controller based on the concept of phase lead compensation is proposed. This system is a simplified version of the controller introduced in section 3 with no need to use a Neural Network equalizer. Fig. 8 shows the block diagram of the proposed system. As seen, a fixed BPF is used to provide a leading phase at the frequency of the input reference. That requires adjusting the center frequency of the filter to be slightly greater than the reference frequency. The proposed system also uses a variable delay that together with the aforementioned BPF can create an adjustable

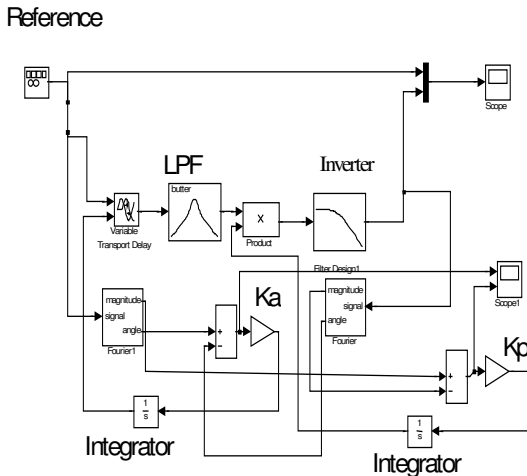


Fig. 8: Block diagram of the adaptive control system with variable delay time

phase-lead controller. Such time delay can easily be produced by a delay loop in microprocessor/ DSP based realization of the controller. The control system calculates both phase and gain error of the overall system (inverter/delay/BPF) and then tunes the delay and gain of the controller to remove the existing errors. As shown in Fig. 8, we need a multivariable controller. One controller is required for the phase loop, and the other for the gain loop. As a primary design, both controllers are considered pure integral controllers to just guaranty a zero steady state error condition for both phase and gain. As already addressed, the inverter system with the aforementioned variables is inherently a decoupled MIMO system. However, the concept is true only at steady state that is if we apply the FFT operator when the system is at steady state. But, in the proposed system, the phase and amplitude of the inverter output is calculated by means of a moving window expressed by Eq. (1), because it is

state and then attempt to improve the errors. That fact requires us to calculate tracking errors while the output signal is still being affected by the transient behavior of the BPF/inverter system. That introduces additional errors in calculations and in the control results as well. Moreover, that causes interactions between all of the input-output pairs. That is because any changes, for example caused by the gain loop, will introduce a transient response that clearly affects both amplitude phase of the output signal.

4.2 Simulation Results

As an initial study of the proposed system, a pure integral controller is considered for each control loop i.e. gain and phase loops. The BPF used in this system is an order two butterworth filter. Fig. 9 shows the closed loop system response as well as the reference signal when the loops gain K_a and K_p are as follow. They were selected by trial and error:

K_a (for gain loop)=10

K_p (for phase loop)= 1/9000

Figure 10 also shows the instantaneous phase and gain errors respectively. As seen in the figures, the gain and the phase errors reach zero fast.

The results confirm the ability of the proposed system in excellent tracking the sinusoidal references. Further studies can be carried out to find optimal loop gains with different linear controllers such as PI or PID controllers.

5 Conclusion

In this paper new adaptive control structures were proposed for compensating the phase and gain error of the inverter systems. One proposed scheme is a neural network based adaptive control system which

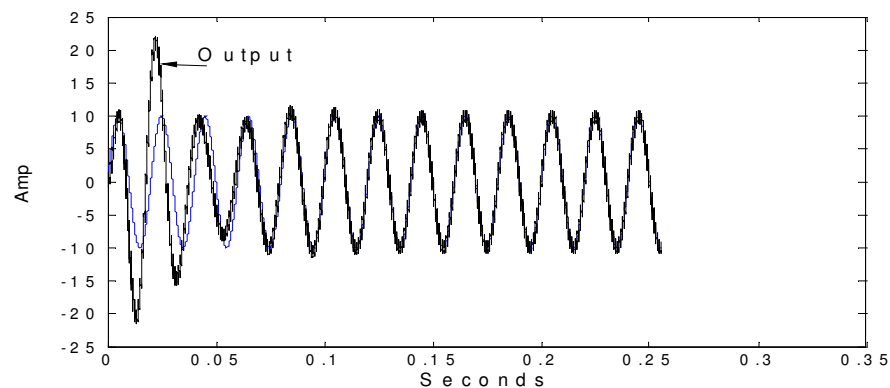


Figure 9 : Output versus input signal of the CRPWM Inverter impossible to wait for a long time to reach steady

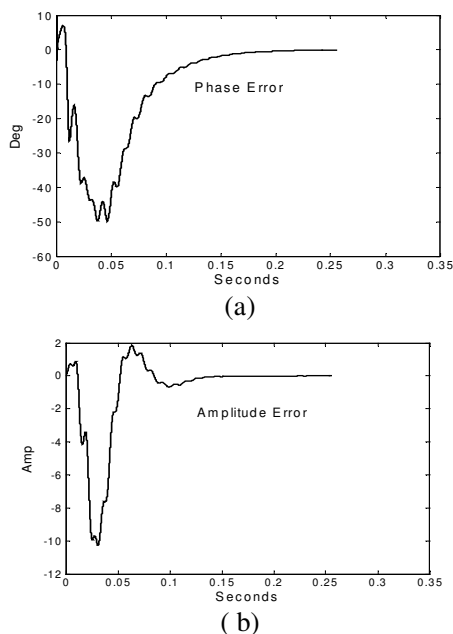


Fig. 10: a) phase error, b) amplitude error.

tunes the center frequencies of some cascaded band pass filters to correct the phase error of the under compensation system. The neural network system, which is a simple feed forward network, takes role as a simple filter designer for tuning the filter's center frequency. Also, the paper presented a simple version of the adaptive controller that employs an adjustable digital time delay to compensate the phase error of the inverter system. The results obtained in MATLAB and SIMULINK environments showed the superiority of the proposed control systems. Further studies can be done to improve the transient response of the proposed systems.

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