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Adaptive predictive voltage control of three-phase PWM-VSCs in UPS applications

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***Abstract*— In this study, adaptive predictive voltage control of three phase pulse-width modulated voltage source converter for uninterruptible power supply application is investigated. In recent years, predictive control strategies have attracted considerable attention due to their simple concepts and inherent adaptability to digital implementation. In contrast, sensitivity to parameter uncertainties and computational delays can degrade the performance and even end to instability. So in this paper and in order to overcome these problems, an improved predictive control based on the model reference adaptive observer is proposed. Adaptive observer helps compensate the computation and system delays and reduce the system sensitivity to parameter uncertainties. The proposed adaptive observer estimates the system states and disturbance inputs for the one sample ahead. The performance of the proposed method is investigated under various conditions. The simulation results confirm the excellent performance of the proposed technique in steady-state and transient conditions.**

Keywords—Adaptive observer; Predictive control; Uninterruptible power supply; Voltage source converter

I. INTRODUCTION

With rapid growth of critical loads, especially in military centers, hospitals, communication and data processing systems, which must be supplied with a high quality and secure power, attentions to uninterruptible power supplies (UPSs) have been attracted. The main goal in UPS systems is to generate a sinusoidal output voltage waveform with minimum distortions under various conditions such as linear or nonlinear loading [1-22].

To achieve this goal and gain the maximum benefits from the UPS system many control strategies have been reported, the main being proportional-integral (PI) [2-4], repetitive [5-7], proportional-resonant (PR) [8-11], sliding mode [12-14], adaptive [15-17] and predictive control [18-22]. The PI control is a common and simple control method adopted to UPS applications. Poor performance under nonlinear loads is known as a main drawback of this method. In these situations, harmonic compensators are proposed, which itself leads to control complexity and extra computational burden [2-4]. Repetitive control is able to eliminate periodic disturbances and reduce the total harmonic distortion (THD) of the output voltage under nonlinear loads. However, slow dynamic response and large memory requirement limit the practical application of this method [5-7]. The PR voltage control is known as a popular method to eliminate the steady-state tracking error of AC signals. Simple harmonic compensation and sinusoidal output voltage under nonlinear loads are known as other advantages of the PR voltage controller. Exponentially decaying transient response and high sensitivity to phase shift of measured output voltages are major disadvantages of this method [8-11].

The sliding mode control offers a good performance in the transient and the steady-state conditions. Design complexity, sensitivity to loading conditions and high switching and sampling frequencies are mentioned as the major drawbacks of this method [12-14]. Methods based on the adaptive control have low sensitivity to parameter mismatches. But, in these methods there is always a possibility of divergence and instability originating from improper controller gain tuning [15-17].

Contrary, control strategies based on the predictive theory have excellent dynamic and steady-state performance. Simple concepts and ease of implementation are other advantages of the predictive based methods. On the other hand, parameter uncertainties and computational delays can degrade the performance and even end to instability [18-22]. In this paper and in order to gain the maximum benefits from the predictive control method and at the same time to alleviate its limitations, the combination of the predictive control method and the model reference adaptive observer is proposed. In the proposed method, an augmented model is derived for the UPS system, which includes all uncertainties. Eventually, the predictive control law is calculated based on the augmented model, which decreases the sensitivity to uncertainties. The adaptive observer is used to predict states and disturbances one step ahead which facilitates proper compensation of system and control delays.

II. SYSTEM DESCRIPTION

A. UPS state space equation

The block diagram of a UPS system based on the PWM-VSC is shown in Fig. 1. In this structure, a LC-type low pass filter is employed to attenuate harmonics due to switching action of the power converter. Based on this figure, system state space equation can be readily written as:

$$\frac{dx(t)}{dt} = Ax(t) + Bv(t) + Gi_o(t)$$

$$x = \begin{bmatrix} i_f \\ v_o \end{bmatrix}, A = \begin{bmatrix} \frac{-r_L}{L} & \frac{-1}{L} \\ \frac{1}{C} & 0 \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, G = \begin{bmatrix} 0 \\ \frac{-1}{C} \end{bmatrix} \tag{1}$$

where, L, r_L and C are filter inductance, its equivalent series resistance and filter capacitance, respectively. Also, i_f, i_o, v_o and v are filter current, load current, load voltage and AC output voltage of the converter, respectively. The AC output voltage of the converter can be calculated with respect to the status of switches and the DC link voltage, as [22]:

$$\begin{cases} v_\alpha = \sqrt{\frac{2}{3}} V_{dc}(S_a - 0.5(S_b + S_c)) \\ v_\beta = \sqrt{\frac{1}{2}} V_{dc}(S_b - S_c) \end{cases} \tag{2}$$

S_a, S_b and S_c show the status of switches of each leg of the converter. If one, then the upper switch of the leg is on and the lower one is off and vice versa. Considering that the DC-side must not be short circuited and the AC-side must not be opened, only eight switching states are allowed, which correspond to situations that in each leg one of the switches is on and the other is off. If the output voltages that are produced by these eight permitted switching states are calculated from (2), then six active and two zero vectors are obtained, which are already shown in Fig. 2.

The discrete state space model, which is required for deriving the digital controller equations can be concluded from (1) as (3), in which $v(k)$ is one of the vectors shown in Fig. 2:

$$\begin{aligned}
& x(k+1) = A_d x(k) + B_d v(k) + G_d i_o(k) \\
& A_d = e^{(AT_{samp})} = L^{-1}[sI - A]^{-1} = \begin{bmatrix} A_{d11} & A_{d12} \\ A_{d21} & A_{d22} \end{bmatrix} \\
& A_d = \begin{bmatrix} \cos(\omega_r T_{samp}) & \sin(\omega_r T_{samp}) \times (-1/\mathrm{L}\omega_r) \\ \sin(\omega_r T_{samp}) \times (1/\mathrm{C}\omega_r) & \cos(\omega_r T_{samp}) \end{bmatrix} \\
& B_d = \left[e^{(AT_{samp})} - I \right] A^{-1} B = \begin{bmatrix} B_{d1} \\ B_{d2} \end{bmatrix} = \begin{bmatrix} \sin(\omega_r T_{samp}) \times (1/\mathrm{L}\omega_r) \\ 1 - \cos(\omega_r T_{samp}) \end{bmatrix} \\
& G_d = \left[e^{(AT_{samp})} - I \right] A^{-1} G = \begin{bmatrix} G_{d1} \\ G_{d2} \end{bmatrix} = \begin{bmatrix} 1 - \cos(\omega_r T_{samp}) \\ \sin(\omega_r T_{samp}) \times (-1/\mathrm{C}\omega_r) \end{bmatrix}
\end{aligned} \tag{3}$$

It should be noted that to calculate (3), the equivalent series resistance of the inductor is neglected.

B. Augmented system state space equation

Since both converter and load parameters have variations and uncertainties, these effects must be considered in the controller design procedure.

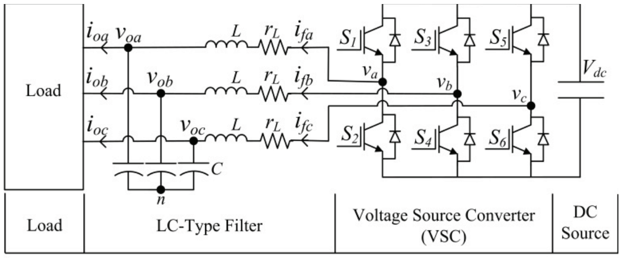

Fig. 1: Three-phase voltage source converter in UPS applications

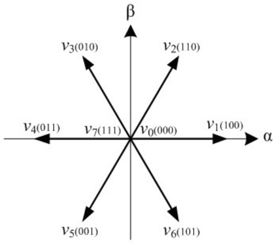

Fig. 2: Voltage vectors generated by the converter of Fig. 1 [22].

With considering the overall effect of all uncertainties, the state space equations can be rewritten as:

$$\begin{aligned}
& x(k+1) = A'_d x(k) + B'_d v(k) + G'_d i_o(k) \\
& A'_d = \begin{bmatrix} A_{d11} + \Delta A_{d11} & A_{d12} + \Delta A_{d12} \\ A_{d21} + \Delta A_{d21} & A_{d22} + \Delta A_{d22} \end{bmatrix} = A_d + \begin{bmatrix} \Delta A_{d11} & \Delta A_{d12} \\ \Delta A_{d21} & \Delta A_{d22} \end{bmatrix} \\
& B'_d = \begin{bmatrix} B_{d1} + \Delta B_{d1} \\ B_{d2} + \Delta B_{d2} \end{bmatrix} = B_d + \begin{bmatrix} \Delta B_{d1} \\ \Delta B_{d2} \end{bmatrix} \\
& G'_d = \begin{bmatrix} G_{d1} + \Delta G_{d1} \\ G_{d2} + \Delta G_{d2} \end{bmatrix} = G_d + \begin{bmatrix} \Delta G_{d1} \\ \Delta G_{d2} \end{bmatrix}
\end{aligned} \tag{4}$$

where, parameters without Δ are calculated based on the nominal values of the LC-type filter parameters and the parameters with Δ denote variations from the nominal values. With considering the parameter uncertainties and the load current as input disturbances, (4) can be rearranged as (5).

$$\begin{aligned}
& x(k+1) = A_d x(k) + B_d v(k) + G_{dd} w(k) \\
& w = \begin{bmatrix} \frac{\Delta A_{d11}}{G_{d1}} i_f + \frac{\Delta A_{d12}}{G_{d1}} v_o + \frac{\Delta B_{d1}}{G_{d1}} v + (1 + \frac{\Delta G_{d1}}{G_{d1}}) i_o + n_1 \\ \frac{\Delta A_{d21}}{G_{d2}} i_f + \frac{\Delta A_{d22}}{G_{d2}} v_o + \frac{\Delta B_{d2}}{G_{d2}} v + (1 + \frac{\Delta G_{d2}}{G_{d2}}) i_o + n_2 \end{bmatrix} \\
& G_{dd} = \begin{bmatrix} G_{d1} & 0 \\ 0 & G_{d2} \end{bmatrix}
\end{aligned} \tag{5}$$

where, n_1 and n_2 denote the overall effect of un-modeled dynamics and w represents all uncertainties, such as the parameter variations and the load.

III. PROPOSED PREDICTIVE CONTROL STRATEGY

Proposed control strategy is based on the two-step predictive control. In this method, in each sampling period and based on the predicted converter quantities, the converter reference voltage is calculated for the next sampling period. In such a way, if this voltage is applied in the beginning of the next sampling instance, the voltage tracking error is forced to zero at the end of that sampling period. So in the two-step predictive control a whole sampling period is available for computations and consequently, delays due to calculations and digital implementation are removed perfectly. To implement the two-step predictive voltage control, some sort of prediction of the output voltage for the two samples ahead is necessary. It is achieved here by using (5) as shown in (6).

$$\begin{aligned} v_o(k+2) &= A_{d21} if(k+1) + A_{d22} v_o(k+1) \\ &\quad + B_{d2} u(k+1) + G_{d2} w_2(k+1) \end{aligned} \tag{6}$$

Assuming that $i_f(k+1)$ ،$v_o(k+1)$ and $w(k+1)$ are known, then $v_o(k+2)$ can be predicted for seven different converter voltage vectors. Finally, by evaluating the following cost function, optimal voltage vector that minimizes the cost function is selected:

$$J = \left(v_{o,ref}(k+1) - v_o(k+2) \right)^2 \tag{7}$$

This method does not need any modulator, because the switching states are assigned directly by evaluating (7). As seen from (6), the proposed method needs a prediction of states and disturbances ($i_f(k+1)$ ،$v_o(k+1)$ and $w(k+1)$) for the next sampling period. To do this, an adaptive observer is proposed to predict these variables that is presented in the next section.

IV. ADAPTIVE MODEL REFERENCE OBSERVER

Based on the augmented model, a simple adaptive observer with the following input-output relation can be written:

$$\begin{cases} e = x(k) - \hat{x}(k) \\ \hat{x}(k+1) = Ax(k) + B_d u(k) + G_{dd} \hat{w}(k) \\ \hat{w}(k+1) = \hat{w}(k) + MG_{dd} e \end{cases} \tag{8}$$

In this equation, superscript ^ denotes estimated variables. Also, M is known as the adaption gain. A large value for M causes a fast convergence rate at the risk of large overshoots and even instability. A small value for M causes a high computational burden and a slow convergence rate. So, the proper selection of the adaption gain has a considerable effect on the system stability and convergence rate. In [23-24] a suitable method based on the Lyapunov stability theory is presented. Based on this method, the permitted range for M is:

$$0 < M < \frac{2}{G_{dd}{}^2} \tag{9}$$

Eventually, the complete structure of the proposed control method is shown in Fig. 3.

V. SIMULATION RESULTS

In order to confirm the validity of the proposed algorithm, a simulation model is developed in MATLB/Simulink. The simulation parameters, which are from a 5.5 kW UPS are summarized in table I. The steady-state performance of the proposed control strategy under a linear resistive load and a highly nonlinear load (Fig. 4) are illustrated in Fig. 5 and Fig. 6. In these figures, three-phase output voltages, tracking error, filter currents and load currents are shown, which confirm the excellent performance of the proposed method to generate sinusoidal voltages with minimum error and distortions. Moreover, the superior dynamic performance of the proposed method is shown in Fig. 7 and Fig. 8. Transient waveforms in response to a step change in the load (from no-load to full load) are shown in Fig. 7 and transient waveforms in response to step jump and fall of the reference voltage amplitude are shown in Fig. 8. Clearly, a fast response with almost no oscillations can be detected.

It is worth noting that these figures confirm the excellent disturbance rejection performance of the proposed method, under various disturbances, such as linear and nonlinear loads, load changes, and step changes in the reference voltage amplitude. Furthermore, these features are achieved without using any load sensors, which reduces the system cost and size. Finally in Fig. 9, outputs of the adaptive observer are presented. This Figure confirms the excellent performance of the adaptive observer to estimate states (i_f, v_o) and input disturbance (w_1, w_2) with minimum errors.

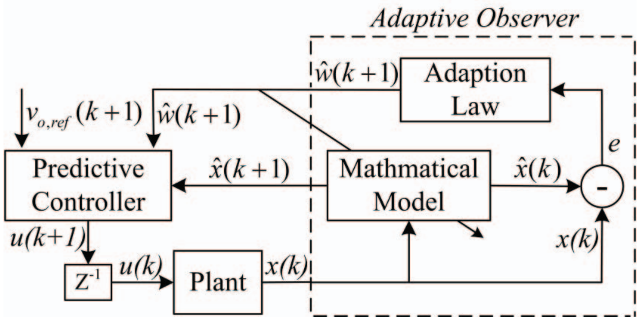

Fig. 3: Block diagram of the proposed adaptive-predictive control

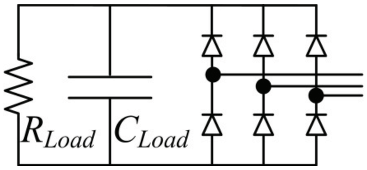

Fig. 4: Three-phase diode bridge rectifier as the nonlinear load.

Table I. Simulation parameters

Uninterruptible power supply (UPS)	
Nominal output voltage	110 (Vrms)
Nominal output frequency	50 (Hz)
Sampling and switching frequencies	40 (kHz)
Filter inductance and resistance	4 (mH), 0.1 (Ω)
Filter capacitance	47 (μF)
DC link voltage	520 (V)
Linear load	
Resistance	15 (Ω)
Nonlinear load	
Resistance	60 (Ω)
Capacitance	6000 (μF)

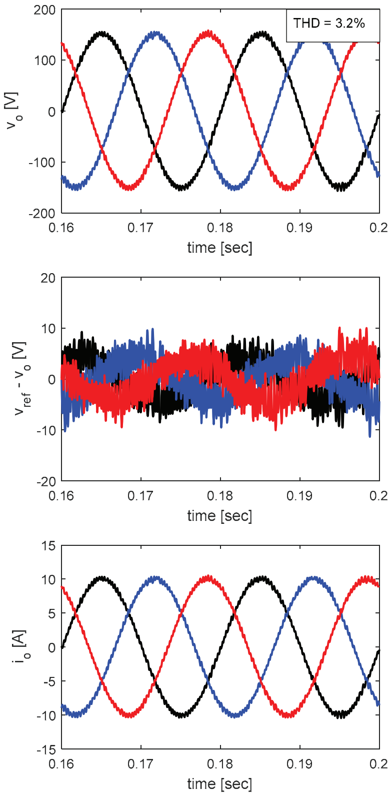

Fig. 5: Steady state performance under linear resistive load.

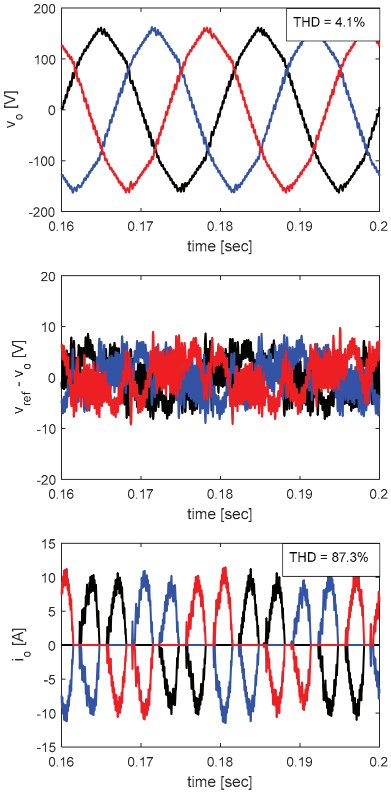

Fig. 6: Steady state performance under nonlinear load.

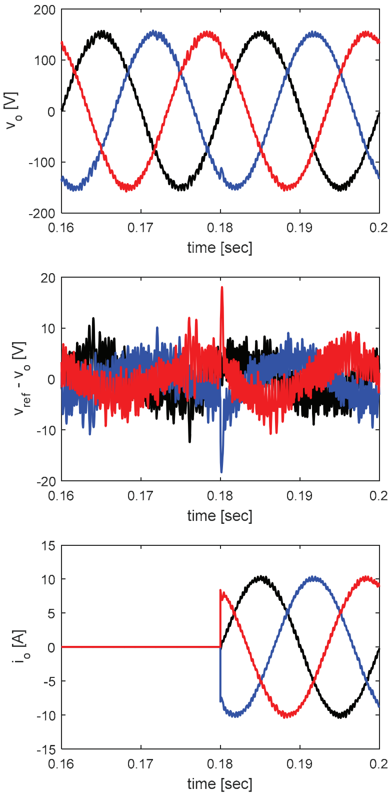

Fig. 7: Response to step load change (no-load to full resistive load).

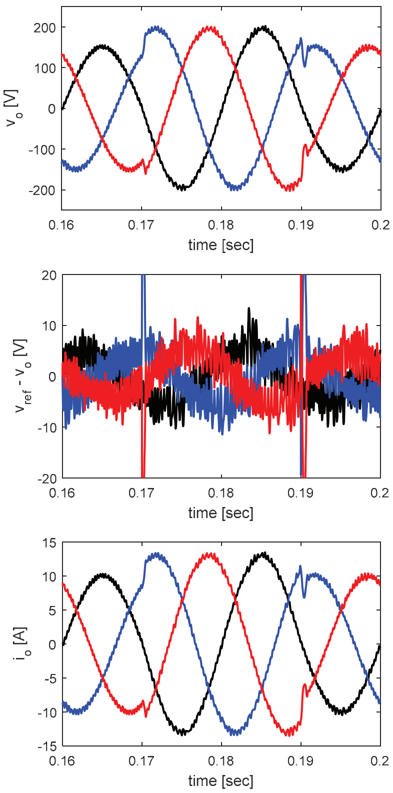

Fig. 8: Response to step changes in reference voltage amplitude.

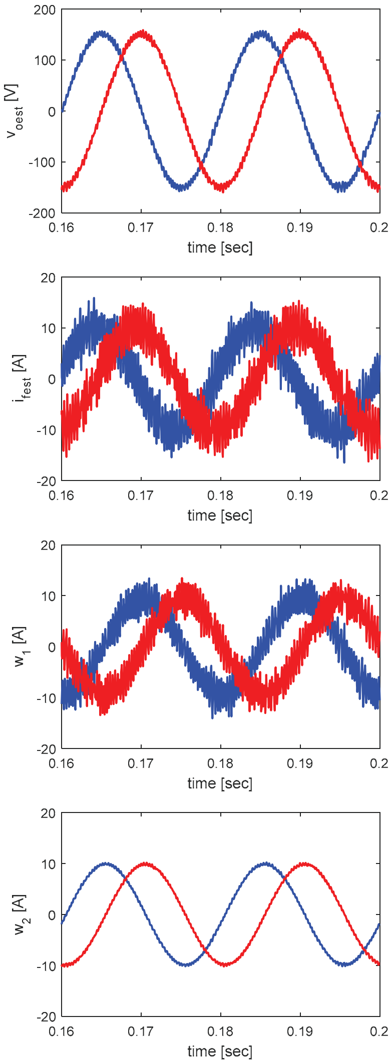

Fig. 9: Outputs of adaptive observer.

VI. CONCLUSION

In this study, an adaptive predictive voltage control for the three-phase UPS systems was proposed. Firstly, an augmented state space model was presented, which contains all system uncertainties. Afterwards, the predictive control law was developed based on the augmented model that reduces the system sensitivity to uncertainties. Moreover, an adaptive observer is added to the proposed control structure. Adaptive observer predicts states and disturbances, which makes it possible to implement the two-step predictive control and consequently compensate the system delays. Excellent steady-state and transient performance, simple concepts, ease of digital implementation and no need to voltage modulator are some of the important advantages of the proposed method that are confirmed through extensive simulation tests.

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