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A new approach to design an observer for load current of UPS based on *Fourier* series theory in model predictive control system

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ABSTRACT

In this paper, the model predictive control (MPC) system based on the state space is designed to generate the appropriate switching pulses for UPS inverters. The fast dynamic response and the capability in assessment of various cost functions are some advantages of the predictive control system. The equations concerning the control system show that the load current should be measured. To eliminate the required sensor for load current measurement a new observer is proposed, so the amount of cost can be reduced and the reliability of the system also enhanced. Ordinary observers like *Luenberger* in terms of stability and design encounter several difficulties. The proposed observer is developed based on *Fourier* series and instantaneous power theories. This observer is doing well in estimating the load current and renders superior performance regarding the dynamic behavior, stability and convergence. Furthermore, in this observer there is no need for any parameters adjustment and the load current is accurately observed using the measured output voltage and the filter current. To examine the operation of the system the necessary simulations and laboratory experimental results are provided on a 3-phase 220 V UPS. The obtained results are then compared to those obtained by the *Luenberger* observer.

1. Introduction

The control of inverters with output filters is important in applications where a high quality of power is the primary concern. The uninterruptable power supply (UPS) is one of such application in which the regulated output voltage with a minimum level of harmonic is intended [1,2]. To provide such a desired output an inverter with a suitable filter is required [3]. However, the filter will make the controller design more complicate. So, to eliminate the switching frequency harmonics and extract the main component of the voltage, various types of filters have been suggested in the literature [4–9] including *LC*, *LLCL*, *LCL*, and thereof. The *LC* filter possess fewer components than the high order filters, so its implementation and design of elements are fairly simple. As this filter has second-order transfer function, the control parameters can be easily adjusted compared with other structures [10].

Various control systems are proposed for inverters with *LC* filters which are used in UPS. The predictive control is the most promising one regarding its fast dynamic response [11]. The most popular controller in this category is the dead-beat controller which has been used in different applications [12,13]. In order to make such controllers robust against uncertainties, several approaches have been employed as reported in [14–17]. The MPC is another approach in which, based on the system model, the behavior of the system is predicted considering a cost function as a criterion [18]. This control system is also applied on UPS in [9,10,19,20]. The MPC is a flexible and a suitable one in controlling the nonlinear and constrained systems. The MPC in comparison with the classic controller has several applications due to its numerous benefits. But the need for several sensors to predict the behavior of the system in the desired time horizon is its drawback. A large number of voltage and current sensors in UPS system makes the implementation of the predictive control system costly and also in case of sensor malfunction or failure, the performance of the control system is jeopardized. Therefore, by eliminating or reducing the number of sensors the cost of UPS is decreased and its reliability is greatly improved.

Reference [21] has proposed that by derivation of the filter inductance current some parameters can be estimated, but due to the existence of noise in the system, the noise is strengthened. In references [22–26] the use of the virtual estimator based on active and reactive powers is proposed. In this approach, first the instantaneous power is estimated by measured currents, DC-link voltage and the inverter switching states. Then, by using this estimation, the instantaneous value of voltage is estimated. As in [27] mentioned, this method requires a high sampling frequency and contains a significant error in the estimation.

In [28,29] the estimator based on virtual flux is proposed and analyzed. In this method, the power grid and the filter are treated as an

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induction motor and the integral of grid voltage is taken as the air gap flux of the induction machine. By converting the virtual flux from synchronous *abc* frame work to $\alpha\beta$ frame work, the derivation of flux in α-axis is proportional to the flux of β-axis and the derivation of flux in β-axis is proportional to the flux of α-axis, thereby the grid voltage is estimated. In this method, although the integrator term reduces the effects of noise, but slows down the dynamic response of the control system.

In reference [20] the *Luenberger* observer is proposed to estimate the load current of the UPS. This observer is performing on line at each sampling time through some complicated calculations. Therefore, the authors have been forced to use the high-speed microcontrollers. In this observer the UPS system is model as a three dimensional state space and the estimated load current is provided by solving the state space equations. The stable performance of this observer depends on the observer's gain that will be different in different load conditions.

In [30] the fault detection for the DC-link voltage sensor and its tolerant control scheme are presented for a three-phase AC/DC/AC PWM converter, where the *Luenberger* observer is employed to estimate the DC-link voltage. For this estimation scheme, the PWM converter is modeled as a nonlinear system resulting from including the power balance between the input and output. The *Luenberger* observer is applied to estimate the DC-link voltage, since it can provide a good performance regarding the faster responses and the higher reliability.

In [31–33] an estimator based on the *Kalman* filter is proposed to estimate the instantaneous grid voltage in distributed generation systems. In this method, the *Kalman* filter gain is adjusted to improve the stability and eliminate the noise of the control system. But this method suffers from the complexity of calculation and adjustment of the noise covariance matrix.

In [34] to control the performance of the PMSM servo system, the simplified model of predictive functional control method is used to predict the future q-axis current. To achieve the satisfying effect in the presence of disturbances, an extended state observer adds a feedforward item in the control loop. The proposed estimation is based on the prediction of speed and the calculated error of speed in predictive control loop. In this method an external speed sensor is used in comparison with the predictive torque control.

In [35] the proposed composite nonlinear MPC method obtains not only promising robustness and disturbance rejection performance but also optimized nominal tracking control performance. The proposed method is based on the minimization derivatives of disturbances and considering the error derivatives in each sample of period. The proposed method is interesting but suffered from computing burden.

In [36] an optimized active disturbance rejection control approach is proposed for the output voltage regulation of DC-DC buck converters without adopting integral control action. Rather than utilizing traditional generalized proportional integral observer (GPIO), a new reduced-order GPIO was firstly constructed to estimate the state and also the time varying uncertainties and disturbances simultaneously. Both the state and disturbance estimations are then introduced for output voltage prediction via *Taylor* series expansion. An optimized active disturbance rejection control law is finally derived by solving a receding optimization problem. The proposed observer suffers from computational burden.

In [37] a continuous-time offset-free MPC approach based on prediction accuracy enhancement via a disturbance observer is developed for a general disturbed system, which can be viewed as a parallel combination of the continuous-time analog and the existing discrete time offset-free MPC. The prominent disturbance rejection performance of the proposed method is achieved without sacrificing the nominal tracking performance. Moreover, unlike the existing offset-free MPC approach, in proposed method it is not required to solve the online optimization problem for the target state and input planning, so the computational load is significantly reduced.

In the present paper the MPC based on the state space model is used to generate the appropriate firing pulses for a 3-phase inverter of UPS with an *LC* filter. Furthermore, to alleviate the noise effects in the feedback loop of output current of inverter, and also to reduce the number of sensors for reliability improvement, an observer based on the *Fourier* series theory is proposed. However, in compare with *Luenberger* observer, its performance is superior when the load is nonlinear in which a lower estimating error is observed. In addition, the proposed method provides further advantages including the less computational burden and ease of implementation.

The novelty of this paper is highlighted below.

- Design of a new load current observer (LCO) characterized by lower computational burden, fast dynamic response and high accuracy.
- Implementation of the proposed observer in the state space model predictive control system.
- Application of the proposed system to control the output voltage of a 3-phase, 220 V, 50 Hz UPS.

The paper is organized as follows. In Section 2, the modeling of the studied system comprises a UPS having 6 switches and an *LC* filter is provided. In Section 3 a brief explanation of *Luenberger* observer along with the mathematical equations regarding the proposed observer are presented. In Section 4, the predictive control system based on the states space model is introduced and its performance is examined.

To validate the performance of the developed system, the necessary simulations are carried out in *Matlab/Simulink* environment and the laboratory experimental results are provided. Finally, the conclusions of our work are made in Section 6.

2. UPS model

The studied system comprises a DC supply, 6 switches, a 3-phase inverter, an *LC* filter, and either linear or nonlinear loads. They are all describing in the following sections.

2.1. Three-phase voltage-source inverter

The inverter along with an *LC* filter employed in UPS is shown in Fig. 1. The inverter and the filter models are presented in this section.

The states of different switching of inverter for three legs a, b, and c are defined by switching functions S_a, S_b, and S_c.

As it mentioned in [38–40], these switching functions define the voltages v_{iN}, v_{io} for $i = a$, b, and c as;

$$v_{iN} = S_i V_{DC} \tag{1}$$

where V_{DC} is the voltage of the DC side of inverter supplied by a battery or rectifier.

2.2. LC filter

The block diagram of *LC* filter is shown in Fig. 2.

where i_f is the filter inductance current, v_c is the filter capacitance voltage and i_o is the load current.

L_f and R_f denote the inductance and resistance of inductive element of filter and C_f is the capacitance of filter.

Considering the state variables of inductance current and capacitance voltage of filter, the equations governing the *LC* filter are:

$$\frac{d}{dt}\begin{bmatrix} i_f \\ v_c \end{bmatrix} = \begin{bmatrix} \frac{-R_f}{L_f} & \frac{-1}{L_f} \\ \frac{1}{C_f} & 0 \end{bmatrix}\begin{bmatrix} i_f \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L_f} \\ 0 \end{bmatrix} V_i + \begin{bmatrix} 0 \\ \frac{-1}{C_f} \end{bmatrix} i_o \tag{2}$$

In order to summarize the above equations, some variables are changed as below, and the equations are rewritten: