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Simplified model for predictive direct power control with fixed switching frequency for grid-tie inverters

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Abstract. This study exhibits a simplified direct power control strategy based on the model predictive control for grid-tie inverters. To solve the problem of the variable switching frequency in the classical finite control set model predictive control (FCS-MPC), we combined the inverse predictive model and space vector modulation to calculate the desired inverter voltage. Furthermore, the computational burden is reduced thanks to the elimination of the optimization loop. A comparative study indicated that the proposed approach achieved better steady-state control performance concerning the low total harmonic distortion of the current model compared with the traditional FCS-MPC while guaranteeing a fast dynamic response. The effectiveness and feasibility of the proposed method were confirmed via simulations and experimental results.

Keywords: model predictive control, fixed switching frequency, direct power control, grid-tie inverters

1 Introduction

In recent years, the finite control set model predictive control (FCS-MPC) has been widely applied to electrical applications, especially for power converters thanks to straightforward consideration of the nonlinear system, multiple control objectives, further constraints, and delayed compensation [1–3]. Despite this interest, the conventional FCS-MPC has some drawbacks, such as variable switching frequency, spread harmonic spectrum, and high computational burden. This reason causes the deterioration of the steady-state control performance in terms of the total harmonic distortion (THD) of the output voltage and current, leading to difficulty in the filter designing process.

Several approaches have been proposed to address this problem. In [3, 4], the authors employed a modulated model predictive control for various converters, such as three-level neutral point clamped inverters and indirect matrix converters. However, these methods have to evaluate appropriate cost functions for each distinct sector at each sampling interval, leading to a high calculation effort. Another technique [5, 6] deployed optimal switching sequences for grid-connected converters by considering a control set consisting of a restricted number of feasible switching sequences during sampling. Although this approach is interesting, the selections of the optimal switching sequence and optimal duty cycles are more complex, resulting in a high computational burden. An alternative approach is presented for inverters by using the virtual state vectors [7, 8]. This technique determined the optimal duty cycle based on the real and virtual state vectors. Nevertheless, the main disadvantage of this method is the large number calculation due to the increase in the number of virtual state vectors, leading to the requirement of a powerful control platform for implementation.

To solve the aforementioned problem, a simplified direct power control-based model predictive control with a fixed switching frequency is proposed for grid-tie inverters in this paper. The main contribution of this study is the incorporation of the inverse predictive model to calculate the necessary inverter voltage based on the predictive power, desired power, and voltage with the space vector modulation technique for ensuring the constant switching frequency. Moreover, this approach provides a powerful method for implementation because there is no need for the evaluation of the optimization loop. A comparative study indicated a better steady-state control performance of the suggested technique in terms of low THD of the current compared with the traditional FCS-MPC while assuring the fast transient response. Simulations and experimental results verified the effectiveness and feasibility of the proposed method.

2 Simplified direct power control based model predictive control with fixed switching frequency

2.1 Dynamic model of grid-connected inverters

Fig. 1 shows a simplified configuration of three-phase grid-tie inverters. The dynamic model of the grid side can be expressed as

$$u_{inv} = u_g + R_f i_g + L_f \frac{di_g}{dt}, \tag{1}$$

where u_g, i_g, u_{inv} denote the grid voltage, grid current, and inverter output voltage. R_f and L_f represent the filter resistance and inductance, respectively.

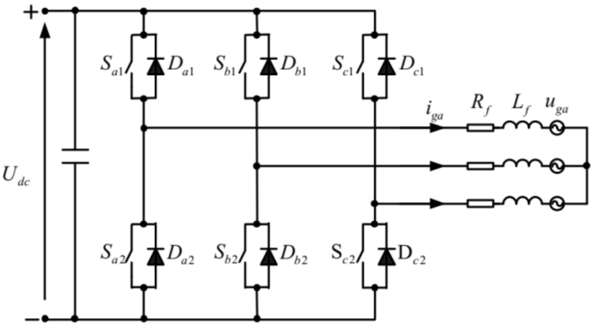

Fig. 1. Simplified configuration of grid-connected inverters

Using Clark transformation, we rewrite the system in the stationary frame (αβ)

$$\begin{aligned} L_f \frac{di_{g\alpha}}{dt} &= u_{inv\_\alpha} - u_{g\alpha} - R_f i_{g\alpha}, \\ L_f \frac{di_{g\beta}}{dt} &= u_{inv\_\beta} - u_{g\beta} - R_f i_{g\beta}. \end{aligned} \tag{2}$$

The power exchange of the grid can be achieved from the grid voltage and current as follows:

$$\begin{aligned} P_g &= \frac{3}{2}\left(u_{g\alpha} i_{g\alpha} + u_{g\beta} i_{g\beta}\right), \\ Q_g &= \frac{3}{2}\left(u_{g\beta} i_{g\alpha} - u_{g\alpha} i_{g\beta}\right). \end{aligned} \tag{3}$$

For the sake of simplicity, we assume that the filter resistance can be neglected due to a small value in the practical system. Therefore, the discrete time of the grid current is derived from equation (2) by employing the first-order Euler approximation as follows:

$$\begin{aligned} i_{g\alpha}(k+1) &= i_{g\alpha}(k) + \frac{T_s}{L_f}\left(u_{inv\_\alpha}(k) - u_{g\alpha}(k)\right), \\ i_{g\beta}(k+1) &= i_{g\beta}(k) + \frac{T_s}{L_f}\left(u_{inv\_\beta}(k) - u_{g\beta}(k)\right). \end{aligned} \tag{4}$$

where T_s is the sampling period.

Similarly, considering the constant grid voltage in terms of the short sampling period, we

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have the variation of active and reactive powers during T_s as

$$P_g(k+1) = P_g(k) + \frac{3}{2}u_{g\alpha}(k)\left(i_{g\alpha}(k+1) - i_{g\alpha}(k)\right) + \frac{3}{2}u_{g\beta}(k)\left(i_{g\beta}(k+1) - i_{g\beta}(k)\right), \quad (5)$$
$$Q_g(k+1) = Q_g(k) + \frac{3}{2}u_{g\beta}(k)\left(i_{g\alpha}(k+1) - i_{g\alpha}(k)\right) - \frac{3}{2}u_{g\alpha}(k)\left(i_{g\beta}(k+1) - i_{g\beta}(k)\right).$$

The control goals of our method are to track the grid power reference. Hence, we can consider

$$P_g^*(\mathrm{k+1}) = P_g(\mathrm{k+1}), Q_g^*(\mathrm{k+1}) = Q_g(\mathrm{k+1}) \quad (6)$$

where $P_g^*(\mathrm{k+1}), Q_g^*(\mathrm{k+1})$ are the future reference values of grid active and reactive powers that can be calculated by using Lagrange extrapolation

$$P_g^*(k+1) = 3P_g^*(k) - 3P_g^*(k-1) + P_g^*(k-2),$$
$$Q_g^*(k+1) = 3Q_g^*(k) - 3Q_g^*(k-1) + Q_g^*(k-2). \quad (7)$$

Combining equations (4), (5), and (6), we derive the required inverter output voltage in the stationary reference frame as

$$u_{inv\_\alpha}^*(k) = u_{g\alpha}(k) + \frac{3L_f}{2T_sU_{am}}u_{g\alpha}(k)\left(P_g^*(k+1) - P_g(k)\right) + \frac{3L_f}{2T_sU_{am}}u_{g\beta}(k)\left(Q_g^*(k+1) - Q_g(k)\right), \quad (8)$$
$$u_{inv\_\beta}^*(k) = u_{g\beta}(k) + \frac{3L_f}{2T_sU_{am}}u_{g\beta}(k)\left(P_g^*(k+1) - P_g(k)\right) - \frac{3L_f}{2T_sU_{am}}u_{g\alpha}(k)\left(Q_g^*(k+1) - Q_g(k)\right),$$

where $U_{am} = u_{g\alpha}^2 + u_{g\beta}^2$.

2.2 Simplified proposed direct predict power control with fixed switching frequency

With the conventional finite control set model predictive control, the control objectives of the system are to track the reference grid's active and reactive powers throughout optimizing the cost function [9–14]. FCS-MPC has some advantages compared with the traditional control method such as a fast transient response, simple control strategy, and a better control performance. However, the main drawback of the conventional FCS-MPC is that the variable switching frequency reduces the steady-state control performance by increasing the total harmonic distortion of the output voltage and current, leading to the difficulty in the filter designing process. To solve this problem, we propose a simple control method by combining FCS-MPC with space vector modulation. The components of reference inverter voltage in the stationary frame are determined by using equation (8) based on the predictive power, desired power, and the voltage in the first step. Then, the control signals are applied to the inverters via space vector modulation. For the lack of space, the detail of the space vector modulation is absent in this paper. Therefore, the proposed control strategy guarantees the benefit of the conventional FCS-MPC concerning fast dynamic response while enhancing the lower THD of the output because of the fixed switching frequency. Moreover, our method has several practical applications thanks to the decrease in the high computational burden of the optimization problem, leading to easy implementation in the real system. Fig. 2 shows the overall proposed control strategy for the grid-tie inverters.

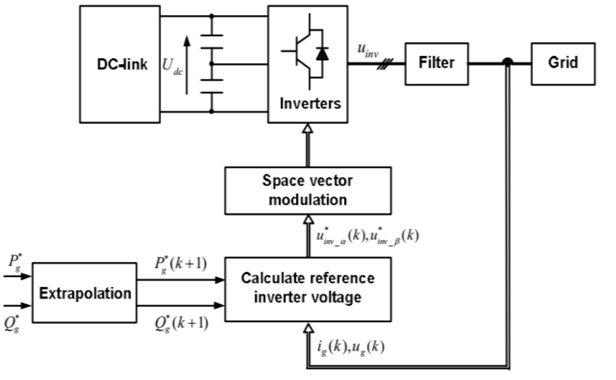


Fig. 2. Overall control strategy of the proposed method

3 Simulation and experimental results

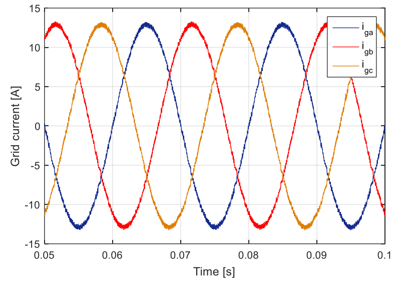
To verify the effectiveness of the proposed control strategy, we conducted the simulation investigations using Matlab software under both transient-state and steady-state conditions. The parameters of the system are listed in Table 1.

Table 1. Parameters of the system

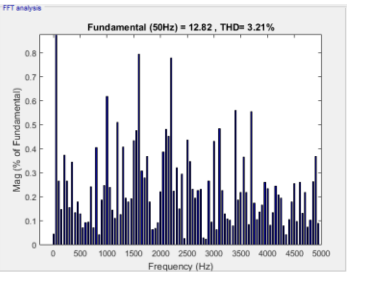
Parameters	**Value**
DC-link voltage	600 V
Filter resistance	1 Ω
Filter inductance	15 mH
Grid voltage	220 V
Sampling time	50 μs

3.1 Steady-state analysis

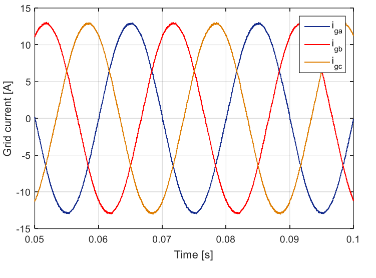
A comparison with the conventional FCS-MPC [1] was conducted to prove the better control performance of the proposed method. Fig. 3 illustrates the steady-state performance of the two control methods at 6 kW of the active power and unity power factor. Three phases corresponding to the grid currents are presented in Figs. 3a and 3c. It can be seen from Fig. 3c that the grid current of the offered approach has a sinusoidal wave form. The THD of the grid current is figured out via a Fast Fourier Transform of the PowerGUI toolbox in Simulink. The THD of the grid current for the conventional FCS-MPC is 3.21% while the corresponding value of the proposed method is only 0.81%. Figs. 3b and 3d indicate that the proposed technique exhibits a better harmonic performance compared with the conventional FCS-MPC because of the benefit of fixed switching frequency.



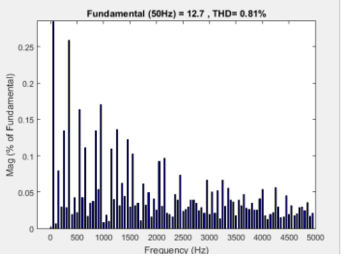
a) Three-phase grid current of the conventional method



b) FFT of grid current for the conventional method



c) Three-phase grid current of the proposed method



d) FFT of grid current for the proposed method

Fig. 3. Steady-state of two controllers

3.2 Transient-state analysis

The active power reference was stepped from 3 kW to 6 kW at time 0.01 s while the reactive power was set at zero. Fig. 4a depicts the dynamic behavior of active and reactive powers for the two control methods. As shown in Fig. 4, the proposed method achieves a rapid transient response

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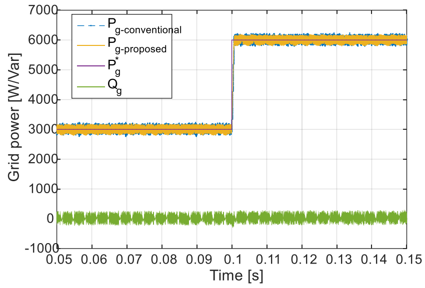
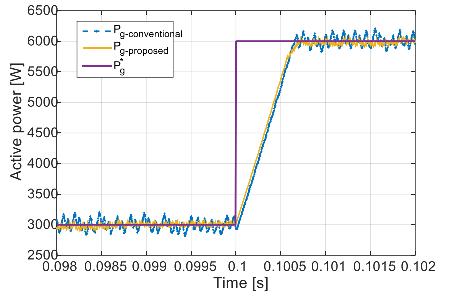
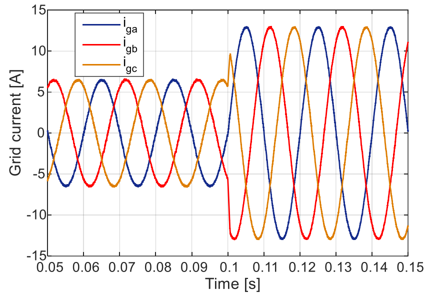
similar to the traditional FCS-MPC. In fact, the active power of the two controllers completes a steady state of the dynamic reaction within about 0.7 ms, as illustrated in Fig. 4b. Significantly, the power ripples of the proposed method are lower than those of the conventional FCS-MPC. The grid current and inverter output voltage of the proposed approach are presented in Figs. 4c and 4d. Therefore, our technique shows a clear advantage over the harmonic distortion of the current and power ripples compared with the conventional FCS-MPC while ensuring a fast dynamic response.



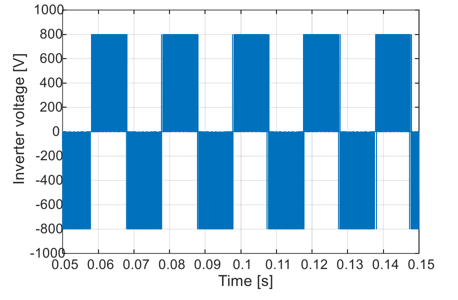
a) Active and reactive powers



b) Zoom of transient active power



c) Three-phase grid current



d) Inverter output voltage

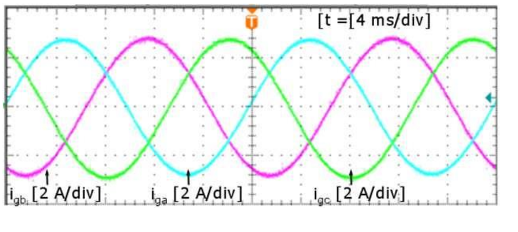
Fig. 4. Transient response simulation results

Table 2. Performance comparison of two control methods

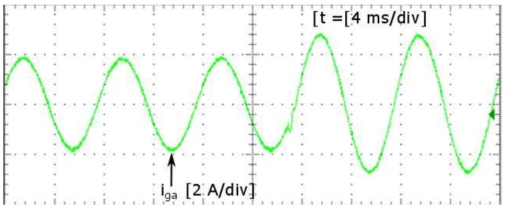
Control method	**Setting time, ms**	**THD of current, %**
Conventional FCS-MPC	0.7	3.21
Proposed method	0.7	0.81

3.3 Experimental results

To validate the feasibility of the proposed technique, we constructed a scaled-down prototype in the laboratory. A digital signal processing (DSP) TMS320F28335 was used to implement the control algorithm. The DC input voltage was set at 600 V; whereas, the line-to-line voltage and frequency of the grid were fixed at 220 V and 50 Hz, respectively. Fig. 5a demonstrates the steady-state performance of the three-phase grid current with an active power of 1.5 kW and a unity power factor. Moreover, the active power reference was raised from 1 kW to 1.5 kW to verify the tracking behaviour of the suggested approach. Fig. 5b shows the dynamic response of the grid current. It is noted that the grid current accomplishes the steady state after a short transient time.



a) Steady state of three-phase grid current



b) Transient state of grid current

Fig. 5. Experimental results of the proposed method

4 Conclusions

This paper proposes a simplified direct power control scheme based on model predictive control for grid-tie inverters. The principal advantage is that we combine the inverse predictive model to calculate the required inverter voltage with space vector modulation for assuring the constant switching frequency. Furthermore, the high calculation effort decreases thanks to the elimination of the optimization loop. A comparison examination demonstrates that the proposed approach accomplishes a better steady-state control performance in terms of low THD of the current compared with the classical FCS-MPC while ensuring a fast transient response. The simulations and experimental results prove the effectiveness and feasibility of the proposed technique.

Acknowledgment

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