Modulated Finite Control Set – Model Predictive Control for Harmonic Reduction in a Grid–connected Inverter

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ABSTRACT

This paper presents an improved current control strategy for a three–phase grid–connected inverter under distorted grid conditions. Distorted grid condition is undesirable due to negative effects such as power losses and heating problem in electrical equipments. To enhance the power quality of distributed generation systems under such a condition, a modulated finite control set – model predictive control (MFCS–MPC) scheme will be proposed, in which the optimal switching signals of inverter are chosen by online basis using the principle of current error minimization. In addition, the moving average filter (MAF) is used to improve the phase–lock loop in order to obtain the harmonic–free reference currents on the stationary frame. The usefulness of the proposed MFCS–MPC method is proved by the comparative simulation results under different operating conditions.

1. Introduction

Recently, a grid–connected inverter has drawn a lot of attention from academia due to the growth of distributed generation (DG) systems using renewable sources. One of the most fundamental issues regarding a grid–connected inverter is to ensure a good quality for the injected power to the utility grid, which has become a challenge when the main grid is contaminated with distorted voltages[1].

Traditionally, a PI–based controller is used to control the grid–connected inverter due to its simplicity and stability. The PI controller generally gives a good performance under the ideal grid condition. However, its performance is deteriorated when the grid voltage contains harmonic distortions. To deal with this problem, several approaches such as the sliding mode control have been proposed[2]. Although this method has successfully suppressed the harmonic contents in inverter output currents, the system exhibits slow transient response due to the use of the band pass filter as a harmonic extractor. Such a slow response may increase the possibility of instability during the transient duration. As another way of improving the current quality, the model predictive control has been applied for a three–phase active rectifier[3].

This paper presents a modulated finite control set – model predictive control (MFCS–MPC) scheme with moving average filter (MAF), which produces not only better current quality in steady state. The effectiveness of the proposed scheme is confirmed through simulation results.

2. Proposed Current Controller

The continuous–time description of a three–phase inverter connected to the grid through L filters is given in the synchronous reference frame as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \qquad (1)$$

where $\mathbf{x} = \begin{bmatrix} i_\alpha & i_\beta & e_\alpha & e_\beta \end{bmatrix}^T$ is the state vector, $\mathbf{u} = [v_\alpha \quad v_\beta]^T$ is the control vector, and

$$\mathbf{A} = \begin{bmatrix} -\frac{R_S}{L_s} & 0 & -\frac{1}{L_s} & 0 \\ 0 & -\frac{R_s}{L_s} & 0 & -\frac{1}{L_s} \\ 0 & 0 & 0 & -\omega \\ 0 & 0 & \omega & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

The discrete model of the grid–connected inverter can be written as follows:

$$\mathbf{x}[k+1] = \mathbf{A_d}\mathbf{x}[k] + \mathbf{B_d}\mathbf{u}[k] \qquad (2)$$

where $\mathbf{A_d}$ and $\mathbf{B_d}$ are the system and control matrices of the state–space model and can be calculated as

$$\mathbf{A_d} = e^{\mathbf{A}T_s} = I + \frac{\mathbf{A}T_s}{1!} + \frac{\mathbf{A}^2 T_s^2}{2!} + \ldots. \qquad (3)$$

$$\mathbf{B_d} = \mathbf{A}^{-1}(\mathbf{A_d} - \mathbf{I})\mathbf{B} \qquad (4)$$

$$A_d = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}, B_d = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \\ b_{31} & b_{32} \\ b_{41} & b_{42} \end{bmatrix}. \qquad (5)$$

In order to compensate the delay introduced by digital controller, the two–step ahead prediction is used. Based on the model (2), the prediction of output current can be calculated as

$$\mathbf{x}[k+2] = \mathbf{A_d}\mathbf{x}[k+1] + \mathbf{B_d}\mathbf{u}[k+1]. \qquad (6)$$

The reference voltages can be calculated as follows:

$$V_\alpha[k+1] = \frac{i_\alpha^*(k+2) - i_\alpha^0(k+2)}{b_{11}} \qquad (7)$$

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$$V_\beta[k+1] = \frac{i_\beta^*(k+2) - i_\beta^0(k+2)}{b_{22}} \quad (8)$$

where $i_\alpha^*(k+2)$ and $i_\beta^*(k+2)$ are the reference currents, and $i_\alpha^0(k+2)$ and $i_\beta^0(k+2)$ are the predicted currents when the zero voltage vector is applied.

The duty interval in which each vector is applied can be calculated as follows:

$$d_1 = \frac{V_\beta[k+1]v_\alpha^j - V_\alpha[k+1]v_\beta^j}{v_\alpha^j v_\beta^i - v_\alpha^i v_\beta^j} \quad (9)$$

$$d_2 = \frac{V_\beta[k+1]v_\alpha^i - V_\alpha[k+1]v_\beta^i}{v_\alpha^i v_\beta^j - v_\alpha^j v_\beta^i} \quad (10)$$

$$d_o = 1 - d_1 - d_2 \quad (11)$$

where (i,j) denotes the values of adjacent active voltage vectors as

$$(i,j) = (1,2),(2,3),(3,4),(4,5),(5,6),(6,1). \quad (12)$$

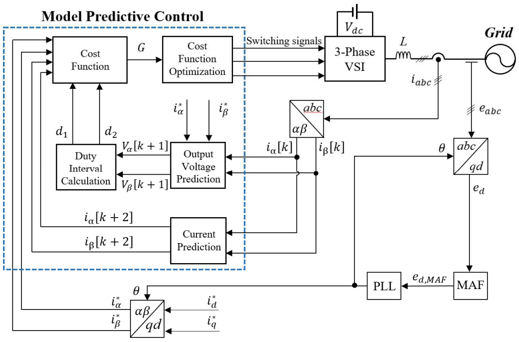

Fig. 1 Block diagram of the proposed MFCS−MPC.

The cost function is calculated based on current prediction and duty interval as

$$G^i = \sqrt{\left(i_\alpha^*[k+2] - i_\alpha^i[k+2]\right)^2 + \left(i_\beta^*[k+2] - i_\beta^i[k+2]\right)^2} \quad (13)$$

$$G^j = \sqrt{\left(i_\alpha^*[k+2] - i_\alpha^j[k+2]\right)^2 + \left(i_\beta^*[k+2] - i_\beta^j[k+2]\right)^2} \quad (14)$$

$$G = d_1 G^i + d_2 G^j. \quad (15)$$

In each sampling period, the values of the cost functions G are calculated for every pair of vectors defined in (12). The pair of vector that minimizes the cost function will be applied to the inverter. In addition, the MAF phase-lock loop is used to eliminate harmonic components in the reference currents in the stationary frame[1]. Fig. 1 shows the block diagram of the proposed scheme.

3. Simulation Results

To validate the effectiveness of the proposed controller, the simulations have been carried out. The harmonic compensation capability of the proposed control scheme is evaluated under distorted grid conditions. For an adverse grid condition, the 5th and 7th harmonics with 10% of the fundamental component and the 11th and 13th harmonics with 10% of the fundamental component are added to the ideal grid voltages.

Fig. 2 and Fig. 3 show the performance of the PI decoupling controller and the proposed scheme under adverse grid condition. It is clear that phase currents are more sinusoidal in the proposed scheme regardless of highly distorted grid voltages. The THD value of the proposed scheme is 1.67%, which is lower than that of the PI controller (3.57%).

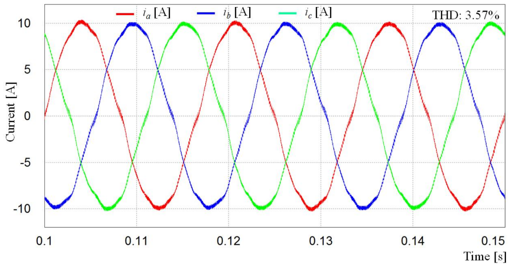

Fig. 2 Response of the PI decoupling controller.

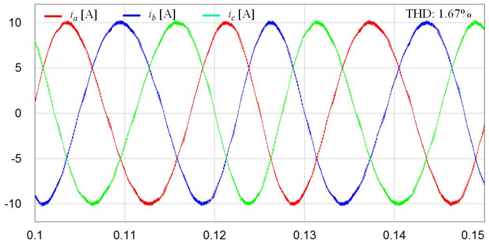

Fig. 3 Response of the proposed controller.

4. Conclusion

To effectively enhance the power quality of DG system by suppressing the harmful harmonic contents in inverter output currents, this paper has presented a MFCS-MPC scheme. The simulation has confirmed a significant improvement in terms of current quality in comparison to the conventional controller.

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5. References

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