The Improved Model Predictive Control Based on Novel Error Correction Between Reference and Predicted Current

Guiping Du, Jiajian Li, Zhifei Liu
School of Electric Power
South China University of Technology
Guangzhou, China
ljj_re@126.com

***Abstract*—This paper proposes an improved model predictive control based on novel error correction between reference and predicted current. The proposed control strategy introduces novel error correction between reference and predicted current to improve robustness and steady-state performance of the system. The control coefficient is computed by the error between the *k*th instant and the (*k*-1)th instant without trial, and its range is limited by the Lyapunov stability theorem. Moreover, it modifies the control law of the conventional finite control set model predictive control to reduce the computational burden. The encouraging performances are tested under a single-phase voltage source rectifier. The simulated and experimental results demonstrate that the proposed control strategy not only offers good robustness but also leads to better steady-state performance while retaining fast dynamic response.**

Keywords—error correction; model predictive control; robustness; steady-state performance

I. INTRODUCTION

As microprocessors develop, digital control especially model predictive control (MPC) has gradually adopted in many aspects like industrial application[1-4]. In [5-7], it is depicted that MPC shows outstanding advantages than other conventional linear control strategies. For example, it can be applied in various situation and multivariable systems. And it can easily incorporate nonlinearities and constraints. Unlike PI controller, it is easy to achieve better control performance without parameter tuning.

According to [8], MPC is a union of controllers that use the model of systems to control the tracking error.[9-10] show that three key issues are significant in MPC application. They are prediction model, cost function and rolling optimization.[8] also classifies MPC methods into two categories, continuous MPC(CCS-MPC) and finite control set MPC(FCS-MPC).CCS-MPC always includes a modulator to translate the continuous control signal to the desired output voltage [11-14]. CCS-MPC can produce a fixed switching frequency but its formulation is complex. Unlike CCS-MPC, FCS-MPC uses the discrete nature of the converter and cost function to compute the switching states and apply them to the converter directly without modulation[15-17].Thus, FCS-MPC presents faster dynamic response compared to other control with modulation. However, FCS-MPC has not yet been implemented in industrial applications because of some disadvantages, such as high computational burden, various switching frequency with a widespread spectrum of controlled variable, time delay and model mismatch[18-21].The problems mentioned above have stopped the development of FCS-MPC.

As for time delay, [21] proposes a simplified model predictive control to reduce the computational burden to relieve the influence of time delay. [22] tries to predict the current value at the (*k*+2)th instant to solve time delay. In [23], a combination of predictive control with a delay estimator is considered to improve the performance of the system. Multi-step model predictive control are now useful ways to eliminate the influence of time delay.

Besides time delay, model mismatch will also deteriorate the performance of the system. [24-25] study the effect of errors in the value of the load inductance and resistance in the average square error of the load current of the two level three phase voltage inverter (2L-VSI). The study shows that the load resistance has a very small effect on the prediction and it could be neglected, and the errors in the load inductance have a major influence on the load current prediction, and estimating a lower value of the inductance has a deepest effect in the current error than estimating a higher value. In [26], A Luenberger observer based on MPC is constructed for parameter mismatch and model uncertainty. In [27], Extended state observer is proposed to estimate the disturbances and adds a feed-forward compensation item to the MPC controller, achieving better control performance and robustness. [28] presents an adaptive robust predictive current control for grid-connected 2L-VSI.Some researchers are aiming to reduce the influence brought by disturbance of power converters effectively by adding the feedback correction. [29-30] introduce a modeling error compensation method for FCS-MPC. Experimental results demonstrate the effectiveness.

Basing on [21] and [29-30], this paper proposes an improved model predictive control based on novel error correction between reference and predicted current to improve the robustness of the conventional FCS-MPC. The proposed

---

Application of Science and Technology Research and Development Project for Guangdong Province (2015B020238012).

978-1-5386-1180-7/18/$31.00 ©2018 IEEE

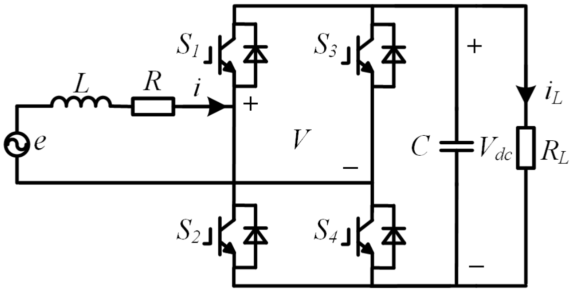


Fig.1. The topology of the single-phase voltage source rectifier

control strategy introduces novel error correction with a coefficient between reference and predicted current to improve robustness and steady-state performance of the system. The control coefficient is calculated by the error between the kth and the(k-1) instant. Furthermore, the coefficient range is limited by the Lyapunov stability theorem to ensure the stability of the system. In order to testify the validity of the proposed control strategy, a single-phase voltage source rectifier(S-VSI) is built. Simulated and experimental results show better steady-state performance and stronger robustness.

II. MODELLING OF THE SYSTEM

The single-phase voltage source rectifier is shown in Fig.1. The equation of the converter can be described as:

$$L\frac{di}{dt} = e - Ri - V \tag{1}$$

where e, i and V are the grid voltage, the grid current and the rectifier voltage. L and R are filter inductance and its equivalent series resistance.

According to forward Euler, approximating the derivative di/dt by

$$\frac{di}{dt} \approx \frac{i(k+1) - i(k)}{T} \tag{2}$$

(1) can modified as

$$i(k+1) = (1 - \frac{RT}{L})i(k) + \frac{T}{L}(e(k) - V(k)) \tag{3}$$

where $i(k+1)$ is the (k+1)th instant value of the grid current. $e(k)$, $i(k)$ and $V(k)$ are the kth instant value of the grid voltage, the grid current and the rectifier voltage. L, R and T are the filter inductance, its equivalent series resistance and the sampling period.

Assuming the switching state of each bridge leg

$$S_a = \begin{cases} 1 & \text{if } S_1 \text{ is on and } S_2 \text{ is off} \\ 0 & \text{if } S_1 \text{ is off and } S_2 \text{ is on} \end{cases} \tag{4}$$

$$S_b = \begin{cases} 1 & \text{if } S_3 \text{ is on and } S_4 \text{ is off} \\ 0 & \text{if } S_3 \text{ is off and } S_4 \text{ is on} \end{cases} \tag{5}$$

So the rectifier voltage $V(k)$ can be described as

$$V(k) = V_{dc}(S_a - S_b) \tag{6}$$

where V_{dc} is the output voltage.

III. THE PRINCIPLE OF THE PROPOSED CONTROL STRATEGY

A. Predicition Model Construction and Cost Funvtion Defined

The prediction model of the conventional FCS-MPC is always defined as

$$i^p(k+1) = (1 - \frac{RT}{L})i(k) + \frac{T}{L}(e(k) - V(k)) \tag{7}$$

where $i^p(k+1)$ is the predicted current value at the (k+1)th instant.

(7) reveals that we need to predict four times in one control period, which will aggravate the computational burden and time delay. Thus [21] presents a simplified FCS-MPC(S-FCS-MPC), which only needs to predict one time. It is depicted as

$$V_r(k) = e(k) + (\frac{L}{T} - R)i(k) - \frac{L}{T}i^*(k+1) \tag{8}$$

where $V_r(k)$ is the desired rectifier voltage and $i^*(k+1)$ is the reference value of the grid current at the (k+1)th instant.

Model mismatch and time delay are the key issues in FCS-MPC, deteriorating the performance of the system. Assume these problems may cause error between $i(k+1)$ and $i^p(k+1)$, increasing the error between the predicted current and the reference current. For compensation, we define a novel current error,

$$\Delta i(k) = i^*(k) - i_{opt}(k) \tag{9}$$

where $i^*(k)$ is the reference current value at kth instant and $i_{opt}(k)$ is the predicted current calculated at (k-1)th instant, which can be expressed as,

$$i_{opt}(k) = (1 - \frac{RT}{L})i(k-1) + \frac{T}{L}[e(k-1) - V_{opt}(k-1)] \tag{10}$$

Define

$$i^*(k+1) - i_{opt}(k+1) = \alpha[i^*(k) - i_{opt}(k)] \tag{11}$$

where α is the control coefficient.

In order to eliminate the error between $i(k+1)$ and $i^p(k+1)$, we hope the error correction will satisfy

$$i^*(k+1) - i(k+1) = i^*(k+1) - i_{opt}(k+1) \tag{12}$$

So (12) can be modified as

$$i^*(k+1) - i(k+1) = \alpha[i^*(k) - i_{opt}(k)] \tag{13}$$

Adding (13) into (8), the prediction model of the proposed control strategy is written as

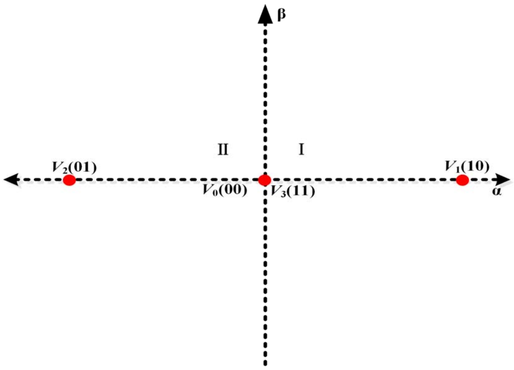


Fig.2. The alternative voltage vectors of $V(k)$

$$V_r(k) = e(k) + (\frac{L}{T} - R)i(k) - \frac{L}{T}i^*(k+1) + \alpha\frac{L}{T}[i^*(k) - i_{opt}(k)] \quad (14)$$

MPC strategies always use a cost function to solve an optimization problem and to define the control signal to be applied to the system[8]. The usual form of the cost function is defined as

$$f = \left|i^*(k+1) - i(k+1)\right| \quad (15)$$

or

$$f = (i^*(k+1) - i(k+1))^2 \quad (16)$$

But these forms mentioned above don't meet (14), thus a new cost function is defined to decide the desired switching states

$$f = \left|V_r(k) - V(k)\right| \quad (17)$$

where $V(k)$ is the alternative rectifier voltage vectors , shown in Fig.2.

B. The Range Limitation of the Control Coefficient

MPC are always considered as the nonlinear control method, and so all analytical methods for linear control methods are not suitable for MPC analysis. The Lyapunov stability theorem is proper to analyze the stability of all control methods.[31-34] modify the existed control strategies with the Lyapunov stability theorem to offer the stability of the system. To ensure the stability, the Lyapunov stability theorem is adopted into the proposed control strategy to limit the range of the control coefficient.

According to the discrete Lyapunov method, the system should satisfy the following condition,

1) $L(0)=0$;

2) $L(x(k))>0$ for all $x(k)\neq 0$;

3) $L(x(k)) \rightarrow \infty$ as $\| x(k) \| \rightarrow \infty$;

4) $\Delta L(x(k))<0$ for all $x(k)\neq 0$.

Define the Lyapunpv function,

$$\begin{aligned} L(\Delta i(k)) &= [\Delta i(k)]^2 \\ &= [i^*(k) - i_{opt}(k)]^2 \end{aligned} \quad (18)$$

Thus the increment Lyapunov function can be written as,

$$\begin{aligned} \Delta L(\Delta i(k+1)) &= [\Delta i(k+1)]^2 - [\Delta i(k)]^2 \\ &= [i^*(k+1) - i_{opt}(k+1)]^2 - [i^*(k) - i_{opt}(k)]^2 \end{aligned} \quad (19)$$

Combing (11) and (19), the increment Lyapunov function is modified as,

$$\Delta L(\Delta i(k+1)) = (\alpha^2 - 1)[i^*(k) - i_{opt}(k)]^2 \quad (20)$$

According to the stability conditions of the Lyapunov method above, α is limited as

$$-1 < \alpha < 1 \quad (21)$$

The error correction introduced can eliminate the influence of disturbance gradually. The convergence of current error can be described as

$$\gamma = \frac{L(\Delta i(k))}{L(\Delta i(k+1))} = \frac{1}{\alpha^2} \quad (22)$$

(22) shows that error between reference and predicted current is decreasing. We assume the rate between two instants are constant because the control frequency is much larger than 50Hz. As a result, we can calculate α by

$$\alpha = \frac{i^*(k) - i_{opt}(k)}{i^*(k-1) - i_{opt}(k-1)} \quad (23)$$

IV. SIMULATED AND EXPERIMENTAL RESULTS

To verify the proposed control strategy, an experimental test was performed under a single phase voltage source rectifier in a DSP system based on TMS320F28069.The experimental parameters are listed in Table I.

TABLE I. EXPERIMENTAL PARAMETERS

System Parameters	**Symbol**	**Value**
Grid Voltage (RMS)	e	50V/50Hz
Filter Inductance	L	6.8mH
Equivalent Series Resistance	R	0.3Ω
DC Side Capacitor	C	1000μF
Sampling Period	T	5e-5s

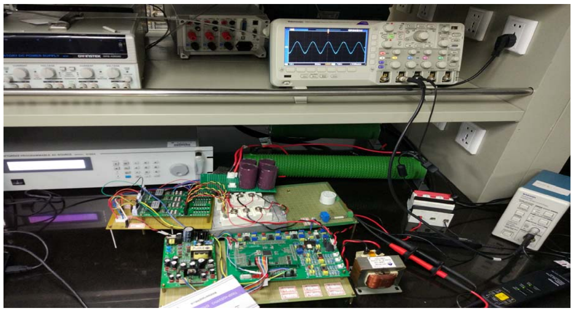
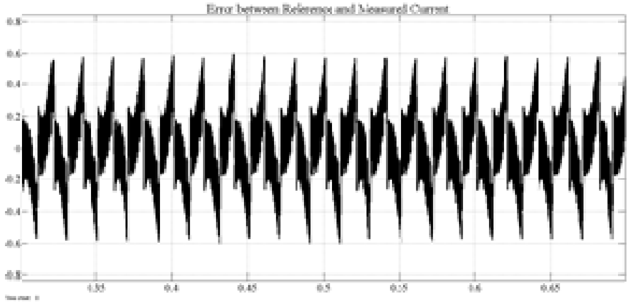
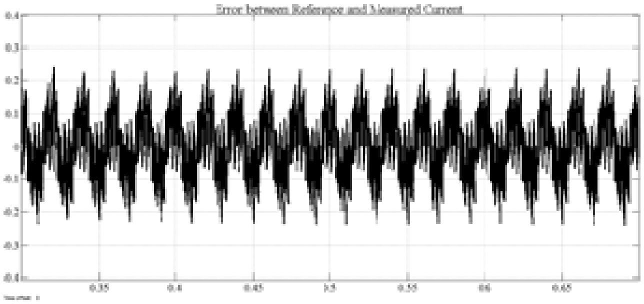


Fig.3. The experiment prototype of S-VSI



(a)The conventional FCS-MPC



(b)The proposed control strategy

Fig.4. The tracking error of the grid current

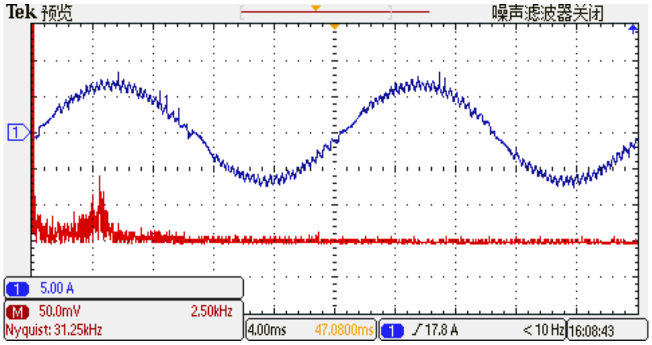


Fig.5. The harmonic spectrum of the grid current for the conventional FCS-MPC

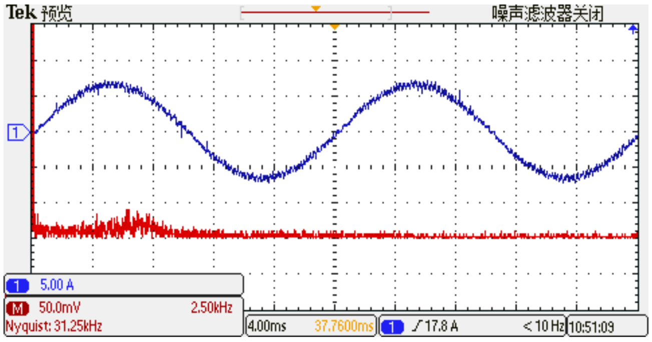


Fig.6. The harmonic spectrum of the grid current for the proposed control strategy

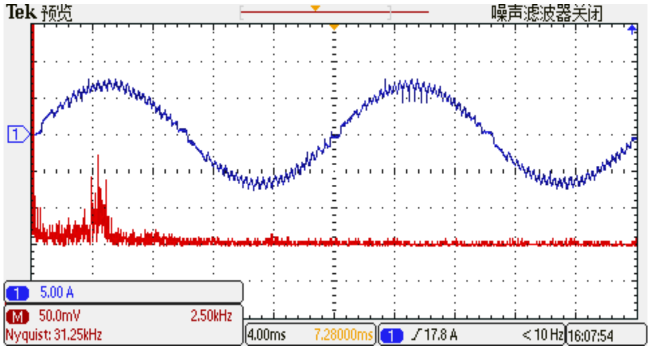


Fig.7. The harmonic spectrum of the grid current for the conventional FCS-MPC(*L*-15%)

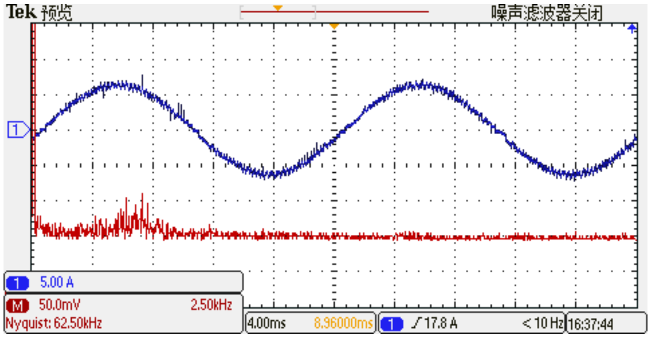
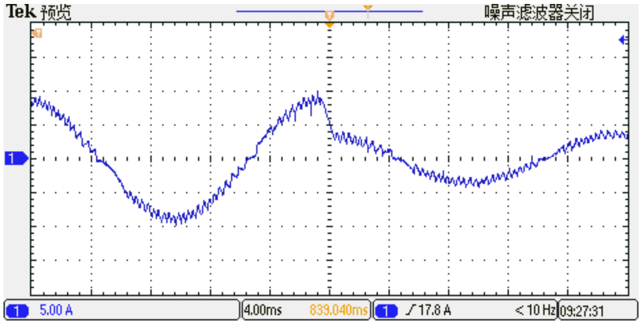
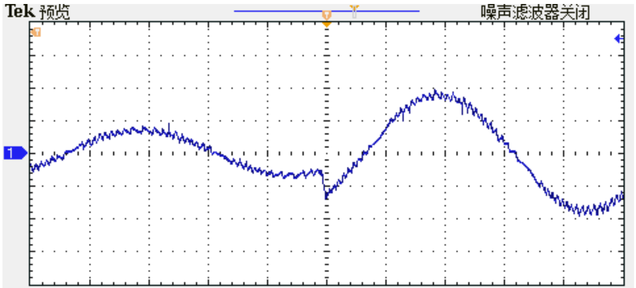


Fig.8. The harmonic spectrum of the grid current for the proposed control strategy(*L*-15%)

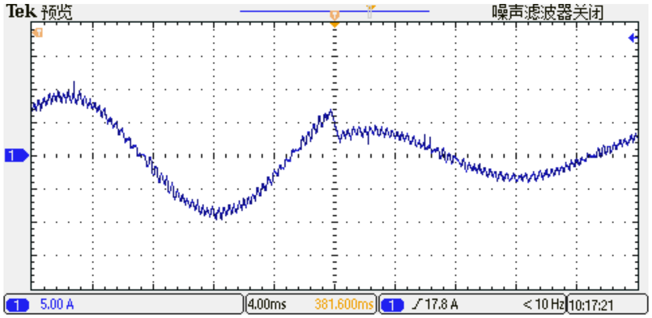


(a)Step change from 8.5- to 3.5-A peak.

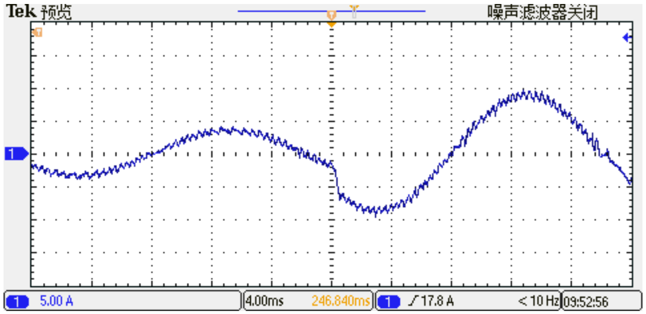


(b)Step change from 3.5- to 8.5-A peak.

Fig.9. Dynamic response of the conventional FCS-MPC during the reference step.



(a)Step change from 8.5- to 3.5-A peak.



(b)Step change from 3.5- to 8.5-A peak.

Fig.10. Dynamic response of the proposed control strategy during the reference step.

A. *Stedy-state Performance Evaluation*

Fig.4-Fig.6 are the steady-state experimental results for both the conventional FCS-MPC and the proposed control strategy.

Fig.4 shows that the current tracking error of the proposed control strategy is half the error of the conventional FCS-MPC. It reveal a better tracking performance for the proposed control strategy.

Fig.5 depicts the harmonic spectrum of the grid current for the conventional FCS-MPC. The total harmonic distortion(THD) for the conventional FCS-MPC is 6.5%. From Fig.6， the THD for the proposed control strategy is much less than the conventional FCS-MPC, and the measured THD is 2.85%. These results demonstrate the proposed method have improved the steady-state and robustness of the system.

B. *Robustness Comparison between Two Control Strategies*

For studying robustness improvement of the proposed control strategy more exactly, the value of the filter inductance L has decreased 15%. Fig.7-Fig.8 show the robustness comparison between the conventional FCS-MPC and the proposed control strategy.

When the variation occur in the filter inductance, the THD in Fig.7 seems to be much more than that in Fig.5, showing poor robustness. The THD value is 8.7%.But compare Fig.6 and Fig.8, the proposed control strategy show strong robustness. The THD in Fig.8 is 3.45%.

C. *Dynamic Response Tests*

Fig.9 depicts the dynamic response of the conventional FCS-MPC for the grid current with a reference step from 8.5- to 3.5-A peak and vice versa. The results show that 381μs is required to reach a steady-state level in Fig.9 (a) while 251μs is required in Fig.9 (b).

Fig.10 depicts the dynamic response of the proposed control strategy for the grid current with a reference step from 8.5- to 3.5-A peak and vice versa. Compared with the conventional FCS-MPC, the proposed control strategy needs 387μs for the dynamic response in Fig.10 (a) and 243μs in Fig.10 (b), showing the same dynamic response as the conventional FCS-MPC.

V. CONCLUTION

FCS-MPC have attracted attention for it is easy to achieve and can be used in various situation ,simple to incorporate constraints. More importantly ,it shows faster transient response than other control strategies with modulation. But some disadvantages, such as model mismatch and time delay stop the development of FCS-MPC.

For solving both problems and improving robustness of the conventional FCS-MPC, an improved model predictive control based on novel error correction between reference and predicted current has proposed in this paper. The method in this paper introduces novel error correction between reference and predicted current to improve robustness and steady-state performance of the system. More importantly, the control coefficient is calculated by the error of two instants and also limited by the Lyapunov stability theorem. In order to testify the effectiveness of the proposed control strategy, the method is tested under a single-phase voltage source rectifier. The simulated and experimental results present excellent steady-state performance and stronger robustness without sacrificing the transient response. The proposed control strategy is of great importance to be applied in other control strategies based on the model of the system and different topologies.

REFERENCES

[1] C. Buccella, C. Cecati and H. Latafat, "Digital Control of Power Converters—A Survey," in IEEE Transactions on Industrial Informatics, vol. 8, no. 3, pp. 437-447, Aug. 2012.

[2] A. Simon-Muela, Y. El Basri, C. Alonso and J. L. Chaptal, "Review of digital control laws for high-frequency point-of-load converters," 2008 IEEE International Symposium on Circuits and Systems, Seattle, WA, 2008, pp. 2222-2225.

[3] M. P. Kazmierkowski, M. Jasinski and G. Wrona, "DSP-Based Control of Grid-Connected Power Converters Operating Under Grid Distortions," in IEEE Transactions on Industrial Informatics, vol. 7, no. 2, pp. 204-211, May 2011

[4] Y. Zhang, B. Xia, H. Yang and J. Rodriguez, "Overview of model predictive control for induction motor drives," in Chinese Journal of Electrical Engineering, vol. 2, no. 1, pp. 62-76, June 2016

[5] Manfred Morari, Jay H. Lee, Model predictive control: past, present and future, Computers & Chemical Engineering, Volume 23, Issue 4, 1999, Pages 667-682

[6] Rodriguez, J, and P. Cortes. "Predictive Control of a Three-Phase Inverter." Wiley-IEEE Press, 2012:41-63.

[7] H. A. Young, M. A. Perez, J. Rodriguez and H. Abu-Rub, "Assessing Finite-Control-Set Model Predictive Control: A Comparison with a

Linear Current Controller in Two-Level Voltage Source Inverters," in IEEE Industrial Electronics Magazine, vol. 8, no. 1, pp. 44-52, March 2014.

[8] S. Vazquez, J. Rodriguez, M. Rivera, L. G. Franquelo and M. Norambuena, "Model Predictive Control for Power Converters and Drives: Advances and Trends," in IEEE Transactions on Industrial Electronics, vol. 64, no. 2, pp. 935-947, Feb. 2017.

[9] P. Cortes, M. P. Kazmierkowski, R. M. Kennel, D. E. Quevedo and J. Rodriguez, "Predictive Control in Power Electronics and Drives," in IEEE Transactions on Industrial Electronics, vol. 55, no. 12, pp. 4312-4324, Dec. 2008.

[10] S. Vazquez et al., "Model Predictive Control: A Review of Its Applications in Power Electronics," in IEEE Industrial Electronics Magazine, vol. 8, no. 1, pp. 16-31, March 2014.

[11] Belda, Květoslav, and D. Vošmik. "Explicit Generalized Predictive Control of Speed and Position of PMSM Drives." IEEE Transactions on Industrial Electronics 63.6(2016):3889-3896.

[12] M. G. Judewicz, S. A. González, N. I. Echeverría, J. R. Fischer and D. O. Carrica, "Generalized Predictive Current Control (GPCC) for Grid-Tie Three-Phase Inverters," in IEEE Transactions on Industrial Electronics, vol. 63, no. 7, pp. 4475-4484, July 2016.

[13] Mariethoz, Sébastien, and M. Morari. "Explicit Model-Predictive Control of a PWM Inverter With an LCL Filter." IEEE Transactions on Industrial Electronics 56.2(2009):389-399.

[14] Almér, Stefan, S. Mariéthoz, and M. Morari. "Sampled Data Model Predictive Control of a Voltage Source Inverter for Reduced Harmonic Distortion." IEEE Transactions on Control Systems Technology 21.5(2013):1907-1915.

[15] C. S. Lim, E. Levi, M. Jones, N. A. Rahim and W. P. Hew, "FCS-MPC-Based Current Control of a Five-Phase Induction Motor and its Comparison with PI-PWM Control," in IEEE Transactions on Industrial Electronics, vol. 61, no. 1, pp. 149-163, Jan. 2014.

[16] S. M. Muslem Uddin, S. Mekhilef, M. Rivera and J. Rodriguez, "A FCS-MPC of an induction motor fed by indirect matrix converter with unity power factor control," 2013 IEEE 8th Conference on Industrial Electronics and Applications (ICIEA), Melbourne, VIC, 2013, pp. 1769-1774.

[17] R. P. Aguilera, R. Baidya, P. Acuna, S. Vazquez, T. Mouton and V. G. Agelidis, "Model predictive control of cascaded H-bridge inverters based on a fast-optimization algorithm," IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, 2015, pp. 004003-004008.

[18] P. Cortes, J. Rodriguez, D. Quevedo and C. Silva, "Predictive Current Control Strategy with Imposed Load Current Spectrum," 2006 12th International Power Electronics and Motion Control Conference, Portoroz, 2006, pp. 252-257.

[19] Shen, Kun, and J. Zhang. "Modeling error compensation in FCS-MPC of a three-phase inverter." IEEE International Conference on Power Electronics, Drives and Energy Systems IEEE, 2013:1-6.

[20] B. Ding, and B. Huang. "Constrained robust model predictive control for time-delay systems with polytopic description." International Journal of Control 80.4(2007):509-522.

[21] C. Xia, T. Liu, T. Shi and Z. Song, "A Simplified Finite-Control-Set Model-Predictive Control for Power Converters," in IEEE Transactions on Industrial Informatics, vol. 10, no. 2, pp. 991-1002, May 2014.

[22] P. Cortes, J. Rodriguez, C. Silva and A. Flores, "Delay Compensation in Model Predictive Current Control of a Three-Phase Inverter," in IEEE Transactions on Industrial Electronics, vol. 59, no. 2, pp. 1323-1325, Feb. 2012.

[23] V. Léchappé et al., "Delay Estimation and Predictive Control of Uncertain Systems With Input Delay: Application to a DC Motor," in IEEE Transactions on Industrial Electronics, vol. 63, no. 9, pp. 5849-5857, Sept. 2016.

[24] J. Rodriguez et al., "Predictive Current Control of a Voltage Source Inverter," in IEEE Transactions on Industrial Electronics, vol. 54, no. 1, pp. 495-503, Feb. 2007.

[25] Young H A, Perez M A, Rodriguez J. Analysis of finite control set model predictive current control with model parameter mismatch in a three phase inverter[J]. IEEE Transactions on Industrial Electronics, 2016, 63(5):3100-3107.

[26] Xia Changliang, Wang Meng, Song Zhanfeng, “Robust model predictive current control of three-phase voltage source PWM rectifier with online disturbance observation,” IEEE Transactions on Industrial Informatics, vol.8, no.3, pp.459-471, Agu.2012.

[27] Li H, Liu S, “Speed control for PMSM servo system using predictive functional control and extended state observer,” IEEE Transactions on Industrial Electronics, vol.59, no.2, pp.1171-1183, Feb.2012.

[28] J. M. Espi, J. Castello, R. García-Gil, G. Garcera and E. Figueres, "An Adaptive Robust Predictive Current Control for Three-Phase Grid-Connected Inverters," in IEEE Transactions on Industrial Electronics, vol. 58, no. 8, pp. 3537-3546, Aug. 2011.

[29] Kun Shen, Jing Zhang, “Modeling Error Compensation in FCS-MPC of a Three-phase Inverter,” IEEE International Conference on Power Electronics, Drives and Energy Systems, 2012, pp.1-6.

[30] Mohsen Siami, Davood Arab Khaburi, Alireza Abbaszadeh, and Jose Rodríguez, "Robustness Improvement of Predictive Current Control Using Prediction Error Correction for Permanent-Magnet Synchronous Machines," IEEE Transactions on Industrial Electronics, vol.63, no.6, pp.3458-3466, Jun.2016.

[31] H. Komurcugil, N. Altin, S. Ozdemir and I. Sefa, "An Extended Lyapunov-Function-Based Control Strategy for Single-Phase UPS Inverters," in IEEE Transactions on Power Electronics, vol. 30, no. 7, pp. 3976-3983, July 2015.

[32] Kato, T, K. Inoue, and M. Ueda. "Lyapunov-Based Digital Control of a Grid-Connected Inverter With an LCL Filter." Emerging & Selected Topics in Power Electronics IEEE Journal of 2.4(2013):942-948.

[33] Sanders, S. R, and G. C. Verghese. "Lyapunov-based control for switched power converters." Power Electronics IEEE Transactions on 7.1(1990):17-24.

[34] Komurcugil, H, and O. Kukrer. "Lyapunov-based control for three-phase PWM AC/DC voltage-source converters." Power Electronics IEEE Transactions on 13.5(1998):801-813.