IET Smart Grid

Review Article

Comprehensive study of finite control set model predictive control algorithms for power converter control in microgrids

eISSN 2515-2947
Received on 13th October 2018
Revised 7th June 2019
Accepted on 8th August 2019
E-First on 4th February 2020
doi: 10.1049/iet-stg.2018.0237
www.ietdl.org

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Abstract: Advances in power electronics and digital control open a new horizon in the control of power converters. Particularly, model predictive control has been developed for control applications in industrial electronics and power systems. This study presents a comprehensive study on recent achievements of model predictive control algorithms to overcome the challenges in the real-time implementation of power converter control, which is the lowest level control of hierarchical control in microgrids. The study shows that most of these alternate solutions can enhance system reliability, stability, and efficiency. The control platform devices for the real-time implementation of these algorithms are compared. The related issues are discussed and classified, respectively. Finally, a summary is provided, leading to some further research questions and future work.

1 Introduction

Advances in power switches alongside with digital control platforms facilitate a rapid development in the control of power converters. The history of power electronics and control concepts applied to power converters is reviewed in [1]. Power converters are one of the main components of microgrids utilised in distributed generations (DGs), electric vehicles, uninterruptible power supplies, energy storage systems, and electrical drives. The increasing number of such applications at the consumer side imposes new challenges for the setup, control, operation, management, and supervision of microgrids and the main power grid [2–6].

Microgrids can be classified into AC, DC, and hybrid AC–DC network. In recent years, the development of DC technology has empowered the idea of DC network, especially in the fields of high-voltage direct current (HVDC) transmission system and low voltage microgrid. A flexible voltage control strategy, which considers the regulation ability of the distributed energy storage units in DC distribution networks, is discussed in [7] and showed an excellent performance in diminishing the voltage variation of DC buses. On the other hand, a hybrid microgrid reduces the power conversion levels and complexity significantly. As a result, it can improve efficiency, flexibility, and controllability. In the shipboard power system, a flexible power control strategy is proposed for the coordinated operation of the hybrid AC–DC zones [8]. The proposed approach is designed with the operating characteristics of the hybrid system, which enables the distributed energy storage units to respond to the power deviation of both zones. Besides, interlinking power converters between the hybrid grids can realise reasonable mutual power support to improve the power quality and system dynamics while facing short-term high power demands.

Control approaches applied in power converters have been the research focus for years. A power converter in the microgrid is broadly categorised into grid-forming, grid-feeding, and grid supporting converters. The controller in grid-forming power converters is responsible for setting the voltage amplitude and the frequency of the islanded microgrid. Therefore, this converter acts as the reference machine for the other power converters within the islanded microgrid. The controller in grid-feeding and grid-supporting power converters is aimed at meeting the active and reactive power demand and improving the voltage profile of the microgrid in both the islanded and grid-connected operation modes. The primary control structure of these power converters is reviewed in [9–13].

In a three-phase system, power converters can be controlled in natural (*ABC*), stationary ($\alpha\beta$), or synchronous (dq) reference frames. Employment of control algorithms in dq-frame is widely applied in different applications of three-phase systems. Although these schemes bring certain advantages like the proportional–integral (PI) controller, two coordinate transformation stages, decoupled control network, and regulation efforts are essential to assuring the stability and efficiency [14]. Yet, under the unbalanced circumstances, the PI controller is incapable of adjusting the appearing fluctuations in the current [15]. One solution to this downside is the use of two separate PI controllers for each positive and negative sequence currents [16]. An efficient approach is applied with the help of $\alpha\beta$-frame and proportional resonant controller where neither the decoupled control network nor sequence control is required. Nevertheless, both controllers need a complicated synchronisation scheme for a seamless transition between two operation modes in microgrids [17, 18].

On the other hand, with the progress of faster, more accurate and more powerful microprocessors, utilising digital control platforms has revealed a new horizon for more flexible, consistent and effective approaches [19]. A summary of control algorithms applied to power converters is depicted in Fig. 1. A comprehensive study is conducted in [20] on the modulation schemes used for controlling power converters. Over the years, model predictive control (MPC) has gained much attention among researchers as an alternative modern control for power converters in distributed generation applications [21–27].

MPC is a well-established method, and its concepts, operating principles [28], and technology readiness for real-time implementation (RTI) [29] are well studied. MPC techniques can be categorised into two forms: the finite control set (FCS)–MPC and the continuous control set (CCS)–MPC. The main criteria for both types are illustrated in Fig. 2.

In particular, FCS–MPC has been verified to be a very effective substitute for classical control algorithms for power converters, which are based on pulse-width modulation (PWM) techniques [30, 31]. A comparison between FCS–MPC and PWM based algorithms is presented in Table 1. As power electronics applications are commonly controlled by using digital platforms, the system model is fitted in the state space form of the discrete-time domain [32]. The FCS–MPC has been an intuitive and potent digital approach to controlling power converters where no

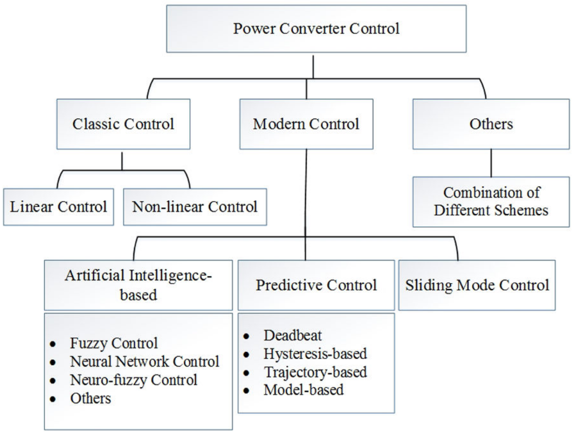


Fig. 1 *Control algorithms for power converters*

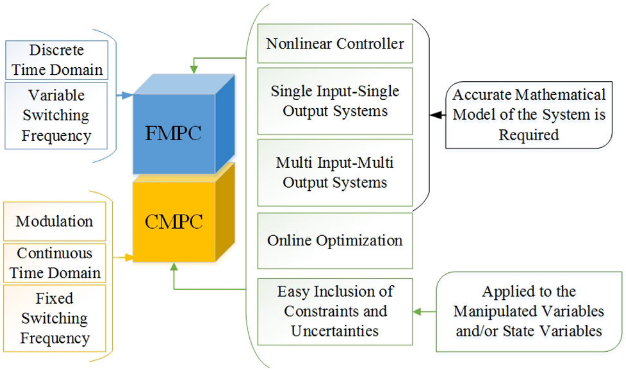


Fig. 2 *Criteria of MPC techniques*

Table 1 FCS–MPC-based versus PWM-based algorithms

Performance criteria	FCS–MPC-based algorithm	PWM-based algorithm
ripples	high	low
switching frequency	variable	fixed
design of weighting factor	empirical (try and error)	not applicable
modulation	not applicable	applicable
adaptation (constraints, uncertainties, and non-linearity)	applicable	not applicable
computation burden and time	low (one-step prediction), high (more than one-step)	low
multi-objectives	applicable	not applicable
online optimisation	applicable	not applicable

modulation stage, decoupled control network, separate sequence control, and complex synchronisation unit are employed to achieve the stable, reliable, and efficient system.

Generally, FCS–MPC solves an optimisation problem over a finite prediction horizon, and then finds the best possibility for the prediction horizon. This searching process is continued with updated estimations and measurements for the next sampling instant [33].

Although MPC is a powerful approach, the algorithm needs to be modified for different purposes due to the difference in the plant characteristics, which poses challenges for the controller design. The issues can be addressed by a combination of MPC and other control methods proposed in different studies [34–39].

The sliding mode control can considerably simplify the resolutions of predictive control difficulties due to parametric uncertainties and disturbances [40–42]. Fuzzy decision-making has also shown good results where multiple objectives and constraints have to be considered [36, 43]. However, implementation complexity, maintenance, and efficiency are some of the factors that need to be assessed. Nevertheless, industrial approval of MPC in power converters and drives has yet to come. In [29], the authors evaluated the technology readiness of MPC with a conclusion that MPC will perform a vital role for the next generation of power converters and electrical drives to operate efficiently.

This study presents a review of recent FCS–MPC algorithms, which addresses different issues involving the control of power converters in microgrid applications. The FCS–MPC principles and converter topologies are discussed in Section 2. A RTI of FCS–MPC through the digital platform is discussed, and a comparison of different platforms is presented in Section 3. Section 4 expresses some main issues associated with FCS–MPC and their alternative solutions. A summary of recent solutions and a discussion with possible solutions to practical problems are addressed in Section 5. Finally, Section 6 is devoted to the conclusions.

2 Finite control set–model predictive control (FCS–MPC)

2.1 FCS–MPC principles

The fundamental operating principle of FCS–MPC is introduced in [1, 21, 28, 32]. In general, FCS–MPC has three fundamental parts: (a) prediction model, which is a mathematical expression of the plant in a discrete state-space form at the step $k + N$

$$\begin{aligned} \boldsymbol{x}_i(k+N) &= f(\boldsymbol{x}_i(k+N-1), \quad \boldsymbol{u}_i(k+N-1)), \\ \boldsymbol{y}_i(k+N) &= g(\boldsymbol{x}_i(k+N)), \end{aligned} \tag{1}$$

where N is the prediction horizon, $\boldsymbol{x}_i(k)$, $\boldsymbol{u}_i(k)$, and $\boldsymbol{y}_i(k)$ are the state, input, and output vector variables at the time instant kT_s, respectively, T_s is the sampling interval, and i is the ith number of possibilities; (b) objective function structure, which can be broad, with the optimisation of various objectives for different purposes; and (c) optimiser in the case of tracking the reference, $\boldsymbol{y}_i^*(k)$, the control problem can be optimised via minimising the following objective function:

$$\begin{aligned} J_i &= \sum_{l=k}^{k+N-1} \| \boldsymbol{y}_{i,\mathrm{Err}}(l+1) \|_2^2 \\ \boldsymbol{y}_{i,\mathrm{Err}}(l+1) &\triangleq \boldsymbol{y}_i^*(l+1) - \boldsymbol{y}_i(l+1) \end{aligned} \tag{2}$$

where $\boldsymbol{y}_{i,\mathrm{Err}}(l+1)$ is the error between the reference and output vector variables.

2.2 Power converter topologies controlled by FCS–MPC in microgrids

FCS–MPC technique has been implemented in various power converter topologies. For an r-level s-phase (rL-sPh) converter, the total number of potential switching possibilities is $m = r^s$. The estimation of the cost function with the m possibilities will lead to m different costs. Since, in each power converter topology, the number of switching possibilities is limited, the minimisation of the objective function can be determined through an exhaustive search.

2.2.1 Two-level voltage source converter: This topology has been broadly used by industry applications at the low-voltage level. The topology of a 2L-3Ph grid-connected voltage source inverter (VSI) is shown in Fig. 3. It is formed by a complementary pair of power switches for each phase and linked to the utility grid through a filter [44].

There are a total number of eight possible converter output voltage vectors for this topology $(m = 2^3 = 8)$ as follows:

$$v_m = \begin{cases} \frac{2}{3}\, \mathrm{e}^{\mathrm{j}(m-1)(\pi/3)}\, V_{\mathrm{DC}}, & m = 1, \ldots, 6 \\ 0, & m = 0, 7 \end{cases} \tag{3}$$

where v_m is the converter output voltage, V_{DC} is the DC-link voltage and m is the number of possibilities for output voltage vectors.

In [45], the FCS–MPC approach is applied to a 2L-3Ph VSI for photovoltaic systems with flexible power tracking as well as switching loss minimisation through direct power control (DPC). A detailed study of DPC strategies is explored in [46]. A simplified FCS–MPC based on direct current control is utilised on a 2L-3Ph voltage source rectifier in [47]. Moreover, this topology is the most common topology chosen for different applications.

2.2.2 Multilevel converters: Multilevel converters, including neutral point diode clamped (NPC), flying-capacitor (FC), and cascaded H-bridge [48], are some of the topologies which have attained immense industrial success for medium voltage applications. A 3L-3Ph NPC topology is illustrated in Fig. 4. There are a total number of 27 possible voltage vectors for this topology $(m = 3^3 = 27)$ which, according to their magnitudes, can be divided into four groups as illustrated in Table 2. For the NPC topology, the neutral point voltage has to be controlled, which is an extra control target besides the main objectives of the application [49]. The output voltage of the inverter in the $\alpha\beta$-frame is described by

$$\begin{aligned} v_m^{\alpha\beta} &= \frac{V_{DC}}{2}\boldsymbol{M}S_m \\ S_m &= \begin{bmatrix} S_{am} & S_{bm} & S_{cm} \end{bmatrix}^{\mathrm{T}} \end{aligned} \quad (4)$$

where $\boldsymbol{M}$ is the Clarke transformation matrix, and S_{am}, S_{bm}, and S_{cm} are phase switching sequences for $m = 0, \ldots, 26$. The mathematical model of 3L-3Ph NPC grid-connected inverter with a resistor–inductor filter can be formulated in the stationary frame via matrix $\boldsymbol{M}$ as

$$v_m^{\alpha\beta} = L\frac{\mathrm{d}i_o^{\alpha\beta}}{\mathrm{d}t} + R \cdot i_o^{\alpha\beta} + v_{\mathrm{grid}}^{\alpha\beta} \quad (5)$$

where i_o is the output current of the inverter, L and R are the inductance and resistance of the filter, respectively, and v_{grid} is the main grid voltage [50].

As for FC converters, the topology is mainly similar to the NPC converter topology, except that, instead of clamping via diodes, the FC converters use clamping capacitors [51–53]. For high power applications, adding more voltage levels to the converter can be practical such as four-level NPC [54, 55] and five-level NPC [56] converters. Furthermore, active power filter (APF) through multilevel converter can compensate the current harmonics imposed through non-linear loads along with adjusting the power factor [57].

2.2.3 Modular multilevel converters (MMCs): The MMC is a prospective power converter used in applications requiring large capacity and high voltage [58], such as HVDC transmission [59] and the static synchronous compensator [60]. For an $(r + 1)$L-sPh MMC, the number of possible switching states is $m = sC_{2r}^{r}$. For instance, if $r = 5$ and 10, the possible voltage vectors are 252 and 184,756, respectively, only for each phase. For controlling MMCs, the voltage balancing and circulating current reduction for the sub-module capacitor are two objectives that must be taken into account [61, 62]. Furthermore, lower harmonic distortion and higher efficiency can be reached due to the high modularity [59, 63–65].

2.2.4 Direct matrix converter (DMC): The conversion from AC to AC can be realised through DMC directly, as depicted in Fig. 5. In this manner, large storage parts and DC-link can be eliminated to increase the system reliability [39]. Another benefit of this topology is that the load frequency can differ from the source frequency [67]. With a matrix converter, different conversions, AC–DC, DC–AC, and DC–DC, can be utilised if needed [66].

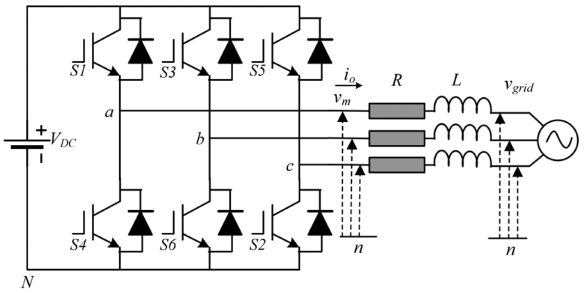


Fig. 3 *2L-3Ph grid-connected inverter [32]*

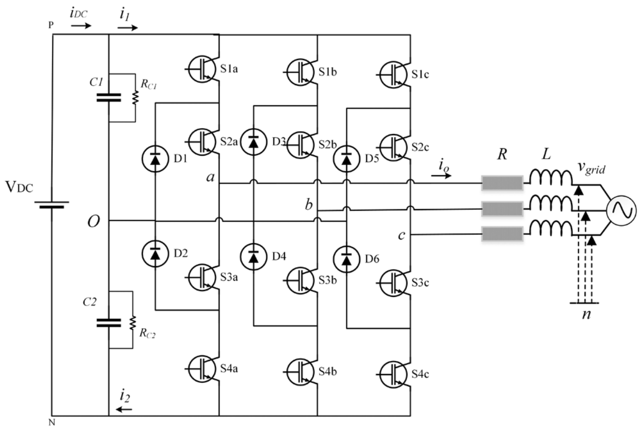


Fig. 4 *3L-3Ph NPC inverter*

Table 2 Voltage vectors of a 3L-3Ph NPC inverter

Voltage vectors	Numbers	Comment
zero vectors	0, 13, 26	no current flows through the neutral point
small vectors	1, 3, 4, 9, 10, 12, 14, 16, 17, 22, 23, 25	the sign for the neutral current at positive vectors does not alter whereas the negative ones change it
medium vectors	5, 7, 11, 15, 19, 21	connect a phase current to the neutral
large vectors	2, 6, 8, 18, 20, 24	no current flows through the neutral point

3 RTI of FCS–MPC algorithm

As digital control is an essential element of modern industrial power converters, hardware and software design procedures and implementation barriers must be investigated. In the presence of robust and high-performance processors, the design procedures are considerably reformed.

Generally, the RTI of FCS–MPC in power converters has five stages, as shown in Fig. 6. Stage I controls the analogue-to-digital conversion of electrical and mechanical measures, such as voltage, current, position, speed etc. Then, in stage II, the measured values are transformed into the two-phase stationary coordinate. The reference and prediction of the state variables are delivered in stage III. In stage IV, the objective function is minimised through an optimisation process, leading to the selection of the best switching states. Finally, stage V contains a register that stores the optimal states [19, 40].

MATLAB Simulink and National Instruments LabVIEW are two commercial tools used to model, simulate, and analyse the real-time systems in different domains. RTI of FCS–MPC algorithm is divided into two groups based on the device used for control: (i) software-based with the aid of digital signal processors (DSPs) such as fixed-point DSPs and floating-point DSPs, and (ii) hardware-based with the assistance of field programmable gate arrays (FPGAs). A comparison in terms of performance, ease of implementation, and device capabilities is summarised in Table 3.

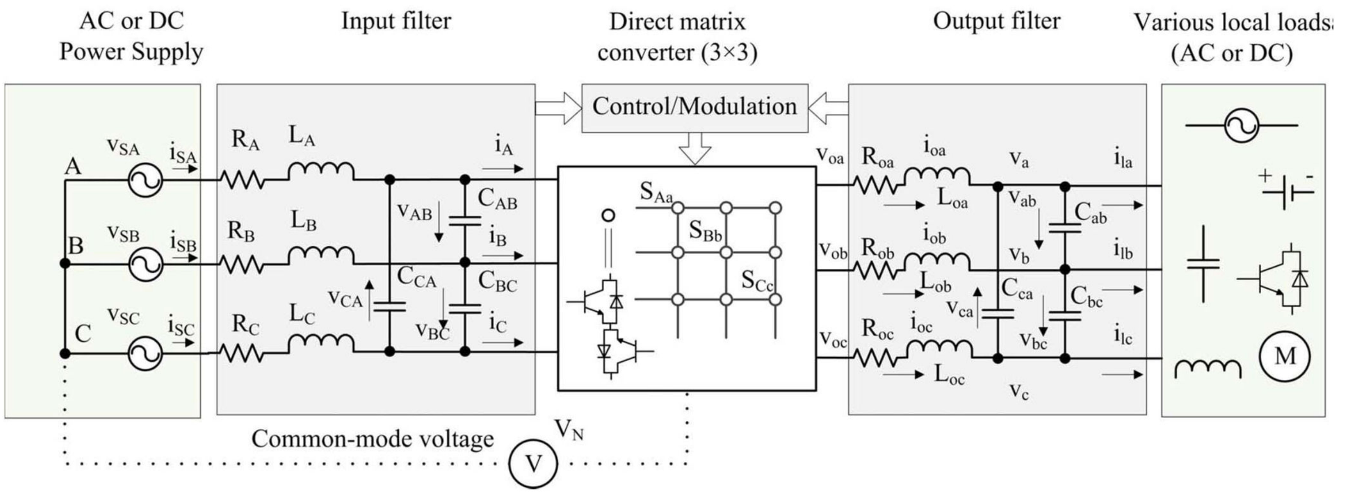
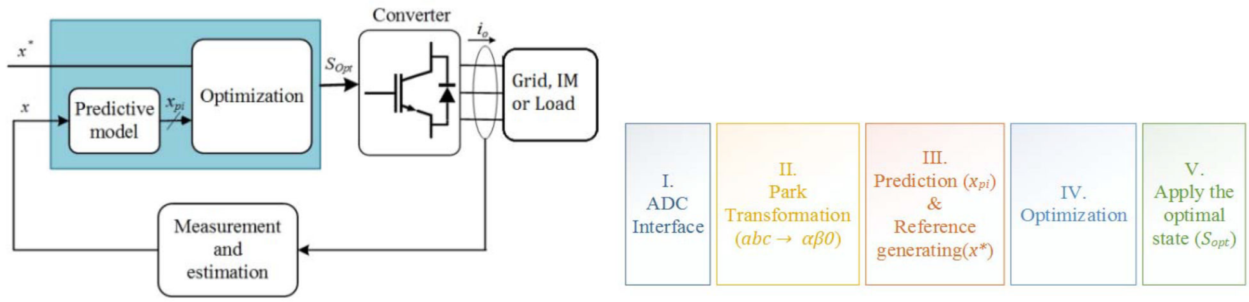


Fig. 5 *DMC topology [66]*



a *b*

Fig. 6 *FCS–MPC*
(a) Block diagram, ***(b)*** Implementation stages

Table 3 Performance comparison among DSPs and FPGA for control of power converters

Criteria	Fixed-point DSP	Floating-point DSP	FPGA
commonly used device	TMS 320F2812	TMS 320F28335	Xilinx XC3S400
performance efficiency	low	high	medium-high
computation capability	low	high	high
ease of implementation	easy	easy	hard
execution time	long	long	short
execution method	sequential	sequential	parallel
sampling frequency	low	low	high
programming language	C	C	Verilog/VHDL
cost	low	low	medium
flexibility	medium	medium	high
reliability	medium	medium	medium
accuracy	low	high	medium

Modern DSPs have now much higher computing power than before. Although the fixed-point DSPs have a good performance, embedding a floating-point processing unit into DSPs can enhance mathematical flexibility, computational performance, and accuracy significantly. DSPs are also restricted to lower sampling frequencies (up to 50 kHz) compared to FPGAs (up to hundreds of kHz).

As FPGAs work with fixed-point numbers, working with them is more complicated compared with floating-point DSPs [30]. Parallel execution of the control algorithm can reduce the computational delay time notably up to, e.g. 3.52 µs [68] and 2.12 µs [67] for three instantaneous objectives.

The RTI of FCS–MPC based on FPGA using high-level synthesis is proposed in [69]. It permits to consider trade-offs between energy, speed, and memory requirements in FPGA, and to deliver advice for optimal synthesis for designers. In [70], multiple-vector direct power FCS–MPC for the grid-tied wind turbine system is implemented with FPGA to enhance the steady-state performance while the sampling frequency is kept similar to DSP. Therefore, it can achieve more advanced objectives and reduce cost.

dSPACE DS1104 R&D Controller Board, together with MATLAB Simulink, is another method aimed at RTI, which has been widely used by researchers to verify their proposed methods [71, 72]. dSPACE has attained much attention among researchers due to its user-friendly interface. For example, TMS320F28335 can execute 150 million instructions per second (MIPS), and Xilinx XC3S400 or the modern dSPACE DS1103 platform can execute 2500 MIPS.

Some researchers propose an integrated control platform built via FPGA and floating-point DSP, which is designed and implemented in [64, 73]. The time associated with the calculation of FCS–MPC algorithms is much more dependent on the converter topology, objectives, and constraints, as shown in Table 4.

4 Issues and alternative FCS–MPC methods

FCS–MPC has proven to be an alternative control approach in power converters and electrical drives. Also, in [77], FCS–MPC is implemented for variable speed drives at the multi-megawatt level. As aforementioned, FCS–MPC is a model-based control method, and thus, developing an accurate and tolerable model of the plant is vital. Although many advantages of using FCS–MPC in power systems are validated by lab-based studies, including a more precise variation of the control variables, constraints, non-linearity, and uncertainties are essential for further analytical and

Table 4 Time associated with the calculation of FCS–MPC algorithms in different scenarios

Converter topology	Application	Objectives	Device	Sampling time, µs	Calculation time, µs
2L-3Ph VSI [45, 74]	grid-tied DGs	power flow control, switching frequency reduction	TMS 320F28335	50	68
2L-3Ph VSI [71]	induction machine	torque and flux control, lower load current THD	dSPACE RTI 1104	25	—
3L-3Ph NPC-VSI [72]	induction machine	torque and flux control, switching frequency reduction, neutral point voltage balancing	dSPACE DS 1104	70	59.15
3L-3Ph NPC-VSI [68]	grid-tied DGs	power flow control, switching frequency reduction	FPGA Spartan XC3S500E	100	sequential: 9.4; parallel: 3.52
MMC N module [75]	HVDC transmission/ motor drive/static synchronous compensator	reference tracking, minimise circulating current, minimise capacitor voltage variation	TMS 320F28335	125	124
MMC 2 module [63]	medium voltage	reference tracking, minimise circulating current, minimise capacitor voltage variation	FPGA	100	9.15
back to back converter [76]	grid-tied DGs	load side current tracking, grid side power tracking, DC-link voltage tracking	FPGA	50	2
DMC [67]	AC–AC conversion	output load current tracking, switching frequency reduction, reduction of reactive power	FPGA	50	2.12

experimental studies. In this section, the issues and their alternative FCS–MPC solutions for power converters in different cases in power systems are discussed.

4.1 Cost function optimisation and design

A Lyapunov-based cost function is suggested for FCS–MPC to guarantee stability and performance (including transient and steady-state error (SSE) performances) in [78–80]. The scheme is implemented through a floating-point DSP and FPGA for a 2L-3Ph inverter and through dSPACE for a 2L-3Ph bidirectional converter in [78, 79], respectively. The simulation and experimental results validate the proposed cost function. However, similar to the linear quadratic programme, there is a trade-off between SSE and the losses in power switches [78]. In [81], the SSE is improved by adding an additional term, integrating the error between the reference and predicted variable within a sampling time, in the cost function. An explicit MPC algorithm to enhance the steady-state performance is proposed in [51], where the optimisation problem can be resolved offline.

Observer-based flexible voltage control by using Lyapunov theory is proposed in [82] for three-phase uninterrupted power supplies. The controller has feedback and a compensating control term to alleviate the system dynamics and estimate the uncertainties, respectively. Under different load scenarios, the proposed control algorithm exposes a better voltage tracking performance with the total harmonic distortion (THD) value of the output voltage declined by almost 49% in all scenarios.

In [83], deadbeat control is proposed to solve the FCS–MPC optimisation problem more effectively. A generalised FCS–MPC structure for the VSI current controller design is proposed in [84] where the Kalman filter is used as an observer. The noise and periodic disturbances for the system output are considered in this model as well. In another approach [85], the control sequence is calculated by CCS–MPC based on the optimal switching sequence model. This method can be used for RTI, where the system constraints are considered.

4.2 Computational burden and time

A notable flaw of the conventional FCS–MPC is that the state switching cost has to be accounted for, which leads to the enormous computational burden and time [86]. For a longer prediction horizon or multilevel converters where the number of switching possibilities is increased considerably, FCS–MPC will face a computational challenge and impracticality for RTI. This drawback leads to the time delay for DSP-based RTI that needs to be considered in the controller design to sustain the system stability and performance [87, 88]. Excluding the redundant voltage vectors and second-step prediction are standard methods to compensate for the computation load or time delay [44, 89]. For example, in a 3L-3Ph NPC inverter, there are eight redundant voltage vectors, which may be ignored. To achieve this, an additional term is added to the objective function [90]. In [81], by dividing the space into sections and considering the candidate voltage vector for each sector, the calculation effort is reduced to seven possibilities for each enumeration. Furthermore, in the optimal switching sequence-based FCS–MPC, by reducing the number of sectors in a 2L-3Ph VSI from 12 to six sectors, the computation time by TMS320F28335 is reduced from 90 to 40 µs [14].

To reduce the computation burden for MMC, an FCS–MPC algorithm based on the sorting method is proposed in [62], where the current polarity of each arm arranges the sub-module capacitor voltages of every arm. Thus, with S modules, the number of possible vectors is reduced to $S + 1$ for each phase. In [91], the optimisation problem is formulated as an integer least squares problem where the branch-and-bound technique of sphere decoding is implemented to calculate the best sequence of the manipulated variable. For a longer horizon (e.g. $N = 10$), the computation load of the mentioned strategy is decreased up to 45% compared with the conventional technique used in the FCS–MPC algorithm.

The computational complexity increases with the number of constraints considered. In general, the results of off-line-based MPC are incorrect as the controller cannot apply the real-time changes. In [92], the proposed optimisation method reduces the computation load about five times less than general approaches. In the proposed method, a set of potential active constraints are maintained and updated. A distributed FCS–MPC is proposed in [93] where a cost function is formulated in a distributed way, helping to reduce the computing time for complex power converters. A typical procedure of this method is depicted in Fig. 7.

4.3 Switching loss

In a hard-switched power converter, the higher the switching frequency is, the higher the switching loss will be, which leads to a lower efficiency [94]. A significant drawback of FCS–MPC is the variable switching frequency, which leads to higher switching losses. To reduce the switching frequency, a two-step prediction algorithm is applied in [45, 95]. In [96], a modulated MPC is proposed to employ a PWM-based modulator to gain a fixed

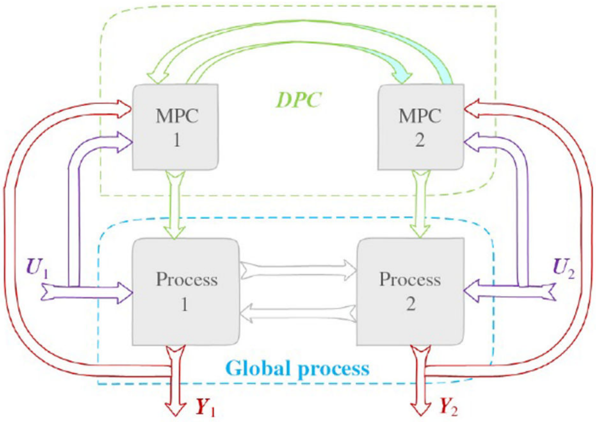


Fig. 7 *Typical block diagram for distributed MPC [93]*

switching frequency. A modified FCS–MPC algorithm is presented in [97] to achieve the lower switching frequency while no additional term is needed in the objective function, just through utilising the available redundant voltage vectors. Therefore, this algorithm can reduce the total possibilities of switching states at each sampling time and provide outstanding reference tracking abilities. In [98], a duty cycle-based direct power FCS–MPC is proposed to achieve a lower average switching frequency, where the modulation stage is by a fuzzy logic modulator.

4.4 Ripple reduction

As the traditional FCS–MPC method applies just one switching state through the entire sampling period, the ripples of the tracking variables are more apparent than the indirect controller with the modulator.

An FCS–MPC algorithm based on the duty cycle control of the power converter shows lower ripples for tracking purposes based on the two-vector [99, 100] and three-vector [14, 86, 99, 101] selections. In [102], an FCS–MPC-based direct torque control (DTC) is proposed to minimise the flux and torque ripples at the steady state by adjusting some parameters of the voltage vector such as magnitude, phase, and time duration. A ripple reduction of 81.43% and 79.65% for flux and torque is obtained, respectively, using this method in comparison with the conventional FCS–MPC based on DTC. Furthermore, fast dynamic responses can be achieved as well by regulating the parameters of voltage vectors in the transient state.

Although this algorithm shows a much better dynamic performance, it increases the computational burden by about 64%. A different approach is proposed in [103] to reduce the torque ripples in permanent magnet synchronous motors. In this case, the voltage vector will be selected accurately through a mathematical calculation where the time duration of the voltage vector varies.

4.5 Harmonic performance

In [104], a dual-stage FCS–MPC for MMC is proposed to improve the harmonic performance as well as reduce the computational burden. For high-power converters working at low switching frequencies, exclusion of low-order harmonics is hugely advantageous [105, 106]. The selective harmonic elimination (SHE) technique is one way to achieve this purpose.

A model predictive switching pattern control with space vector-based SHE for a current source converter is proposed in [107, 108], which can eliminate low-order harmonics effectively in the steady state, and enhance the transient responses. Furthermore, this method mitigates the quantisation errors in the steady state and evades the use of weighting factors. FCS–MPC can improve the transient performance of the space vector-based SHE, and in the steady state, the output PWM waveform can track SHE pattern. In [96], FCS–MPC is modified by introducing a cost function-based modulator, which aims to reduce power losses, ripples, and harmonics. As an example, the THD value of load current with this approach is lessened by three times.

4.6 Mutual interference (MI)

The MI during control is an issue with the cost function involving the sum of two or more terms, where one may affect another, such as active and reactive power control in DG applications. In [109], the objective function is restructured to resolve the MI problem as

$$
\begin{aligned}
cf_{\text{recon}} &= p_{\text{wf}}\left(p^{\text{ref}} - p^{k+2}\right)^2 + q_{\text{wf}}\left(q^{\text{ref}} - q^{k+2}\right)^2 \\
p_{\text{wf}} &= \left[\lambda \left|\frac{q^{\text{ref}} - q^{k+2}}{q_{\text{rated}}}\right| + 1\right] \\
q_{\text{wf}} &= \left[\lambda \left|\frac{p^{\text{ref}} - p^{k+2}}{p_{\text{rated}}}\right| + 1\right]
\end{aligned}
\tag{6}
$$

where p_{wf} and q_{wf} are the weighting factors for regulating the dynamic performance of active and reactive power, and p^{ref} and q^{ref} the active and reactive reference power, respectively. Also, p^{k+2} and q^{k+2} are the active and reactive power at the time instant $(k+2)T_s$, respectively.

4.7 Parametric uncertainties

The FCS–MPC technique deals with the mathematical model of the system, which is dependent on the system parameters. However, the system parameters may be different from their real values because of measurement errors or may vary because of their dependences on the operating conditions. Therefore, parameter uncertainties and model inaccuracy may cause imprecise prediction of the system [110]. In [111], the parameter uncertainties are considered by implementing the feed-forward linearisation for discrete-time inputs to enhance the prediction accuracy for a permanent magnet synchronous motor. A systematic methodology to observe the effect of model parametric uncertainties on the prediction error for FCS–MPC based on current control in a 2L-3Ph inverter with RL load is investigated in [112]. While the inductance mismatch has a significant effect, the pure resistive parametric changes can be neglected. A generalised MPC can reduce the impact of parameter variation by using the transfer function of the system and constraints at the same time [113].

4.8 Weighting factor

Adding control objectives and constraints is a significant feature of FCS–MPC. These additional terms can be incorporated merely into the cost function with their specific weighting factors. Consequently, all the control necessities will be observed by the controller simultaneously. However, the weighting factor tuning is a heuristic process for which there is not a precise or analytical approach.

In [114], the calculation of weighting factors is attained via a non-trivial process based on a ranking approach. By using this method, multiple voltage vectors may have the same average ranking. Although priorities can be allocated for each target to overcome this matter, it remains an open discussion in this approach. Furthermore, it also increases the computational burden up to three times more than the heuristic methods. In [115], the ranking-based algorithms are applied to matrix converters. The main contribution of [116] is the exclusion of weighting factors in the multi-objective function. The algorithm is used on a 3L-1Ph NPC converter as an APF with three control objectives. A combination of an excellent current reference generator and choice of redundant switching states can be used to remove the weighting factors and DC capacitor currents. In [100, 117, 118], a two-vector based model predictive torque control is studied where the weighting factors are removed by normalising all the terms in the objective function. An online fuzzy approach for tuning weighting factors based on Sugeno technique is discussed in [119].

4.9 Longer prediction horizon

In general, implementing the FCS–MPC algorithm is computationally challenging, mostly due to the difficulty in the direct implementation of switching states. Moreover, the type of

Table 5 Summary of recent contributions on FCS–MPC for power converters

Alternate solutions	Pros	Cons
reconfigured objective function	the Lyapunov-based function has shown an improved transient and SSE compared to quadratic-based one	trade-off between steady-state error and switching loss for both functions
longer prediction horizon	delay compensation, lower switching losses, better dynamic performances	increased computation load and complexity
multi-objectives	control several variables simultaneously	weighting factor design, consideration of different nature of the variables
duty cycle control MPC (two/three-vector based)	better steady-state performances, much lower sampling and switching frequency, ripple reduction	increased computation load and time

optimisation problem and the number of manipulated variables may add to the complexity of this method. As a result, a one-step prediction ahead is typically used for reference tracking in power converters to reduce the computational complexity.

However, a longer prediction horizon can lead to better control performance and stability [120–122]. Therefore, the prediction for longer horizons is desired but has to meet the computational constraint and handle the system complexity [33, 123]. Three strategies that can attain longer prediction horizons within acceptable computation levels are investigated, including the extrapolation, move blocking, and event-based horizon strategies [124]. Among these methods, the extrapolation strategy is employed and implemented in practice for power electronic applications frequently [44]. As demonstrated in [120, 123], by adopting the sphere decoding algorithm for optimisation, longer predictions can be achieved with a reduction of the computational burden.

4.10 Filters

Filters play a significant role in the model of the predicted system. The filter is a part of the prediction model, and it imposes some hardships for controlling the power converters that have to be taken into account. Inductor–capacitor–inductor (LCL) filters are broadly used in grid-tied power converters [22, 125–129]. This filter is capable of improving the harmonic attenuation presented by series inductors. However, the control problem becomes complex due to the filter capacitor, which leads to a delay between the grid and power converter as well as resonant frequencies. By utilising the LCL filter, particularly in medium voltage applications, a lower switching frequency can be achieved. In [128], a virtual resistor concept is employed to deal with resonance damping and harmonic attenuation. Longer prediction horizons gain more accurate decisions and improvements. Moreover, in [125], an active damping strategy via a virtual resistor concept is introduced, which can reduce the average switching losses by 17.3% in comparison with carrier-based PWM.

A hysteresis-based MPC is developed in [127] for high power applications, which can possess the average switching frequency within a standard boundary while enhancing the system stability. In some implementations where islanding from the grid is compulsory, inductor–capacitor filters are used for output voltage control [92, 130].

5 Discussions

Employment of the FCS–MPC in power electronics has been increasing in power systems with the analytical approach as well as the RTI experiences. Nevertheless, the RTI of FCS–MPC for different topologies and applications faces new challenges, which give rise to more exploration of MPC approaches.

Although the FCS–MPC has been established and implemented well for constant sampling time to achieve good performance, it is essential to consider variable sampling time, especially in systems with variable main frequencies. In [131], an improved FCS–MPC for a variable grid frequency environment is proposed to get a proper response. In this algorithm, a parameter estimator is employed to obtain the variable sampling time. Therefore, considering variable sampling time in FCS–MPC can enhance the system performance, particularly in networks with a variable frequency deviation range.

As mentioned before, a conventional approach to consider the delay for RTI by DSP-based devices is the two-step or more prediction. However, the delay time differs in RTI for different applications. Therefore, a delayed model, in which the control and input voltage vector sequences are delayed, is used as shown below:

$$\frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}t} = \boldsymbol{D}\boldsymbol{x}(t) + \boldsymbol{F}\boldsymbol{u}(t-\tau) \qquad (7)$$
$$\boldsymbol{y}(\boldsymbol{t}) = \boldsymbol{G}\boldsymbol{x}(\boldsymbol{t})$$

where $\boldsymbol{D}$, $\boldsymbol{F}$, and $\boldsymbol{G}$ are the system matrices derived from the system model and τ is the delay time. The proposed algorithm is discussed in [44], where the performance of the controller is improved along with the stability and power quality.

Another issue that MPC needs to address for improving its performance is the fault ride through (FRT), during the grid abnormal conditions. The grid-connected power converters may experience current oscillations in case of unsymmetrical grid voltage FRT, which considerably disturbs the system reliability. Therefore, it is vital for MPC to be able to implement the flexible power flow and current-limiting control under these circumstances.

Performance indices are an essential part of evaluating the effectiveness of proposed control algorithms. The transient and steady-state response, ripples, THD, and switching frequency are some of the indices that represent system stability and reliability. Table 5 lists the modified FCS–MPC solutions and their advantages and disadvantages in terms of these indices.

6 Conclusions

This study presents a comprehensive study on the latest contributions to the control technique of FCS–MPC to gain an insight into where the state-of-the-art stands today. The issues and challenges for designing more effective and efficient control algorithms are investigated.

Among the control approaches applied to power converters in the microgrid, MPC has been employed vastly. Therefore, the FCS–MPC approach that takes benefit of the limited number of switching states of the power converter has been verified to be a very adequate substitute for traditional control algorithms. As digital control is an essential element of modern industrial power converters, its hardware and software design procedures and implementation barriers are investigated. Although FCS–MPC is well established, the algorithm needs to be modified for different purposes due to the difference in the plant characteristics that pose various challenges for the controller design. Nevertheless, the RTI of FCS–MPC for different topologies and applications faces new challenges, which give rise to more exploration of MPC approaches. Some of the concerns explored in the literature such as cost function design, computational burden, switching loss, harmonic performance, ripple reduction, weighting factor design, filters, and parametric uncertainties are reviewed, and the possible solutions are discussed. Moreover, the flexibility of the FCS–MPC technique has driven solutions for practical issues in this area [63, 71, 76].

In general, it can be concluded that FCS–MPC is a flexible and yet powerful scheme for control of power converters in different applications. Therefore, the widespread implementation of MPC in the future in power electronics and drives will be an essential key for the reliable operation of microgrids.

7 References

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