Recent Advances of Predictive Control in Power Converters

Ricardo Enrique Pérez-Guzmán
Depto. de Ciencias de la Computación
Universidad de Talca
Curicó, Chile
riperez@utalca.cl

Marco Rivera
Facultad de Ingeniería
Universidad de Talca
Curicó, Chile
marcoriv@utalca.cl

Patrick W. Wheeler
Dept. of Electrical and Electronic Engineering
University of Nottingham
Nottingham NG7 2RD U.K.
pat.wheeler@nottingham.ac.uk

***Abstract*—Model-based predictive control (MPC) is an attractive solution for controlling power converters and drives. This research shows the most recent alternatives of predictive control techniques proposed in the literature to solve control problems in power converters. The current trends and future projections for these control strategies, as well as the most used models, topologies, or variables in different scenarios are shown. This allowed us to compare the main strategies, their pros and cons, including some application examples. Predictive control has several advantages that make it suitable for the control of power converters and drives.**

***Index Terms*—power converters, model predictive control, power electronics**

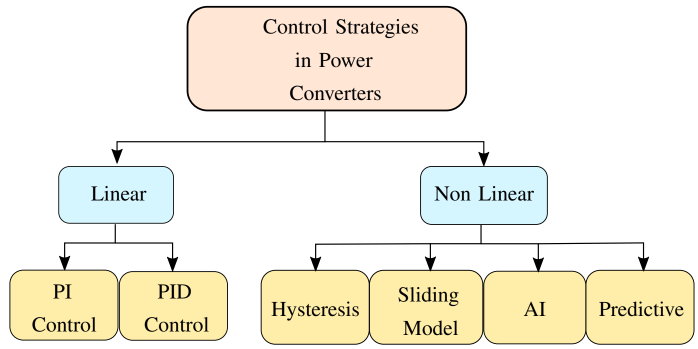

Fig. 1. Control techniques for power converters.

I. Introduction

Power converters and their control techniques have been in constant development over the last years. Its applicability in almost any sphere of social development such as energy, communications, medicine, mining or transportation, encourages new researches on the subject. Specifically, control techniques have been a very active research topic in power electronics field, which covers topologies for low, medium and high voltage applications [1], [2]. Control strategies in power converters can be classified into two groups: linear and non-linear strategies. Within the linear strategies, the proportional controllers (P), integral proportional (PI), proportional integral derivatives (PID) and the linear quadratic controllers (LQ / LQR) stand out among the rest. They are based on one, or several stages of modulation, as a main feature of control. On the other hand, non-linear strategies are characterized by the non-linearity of certain variables, whose magnitude is necessary to know. Some of the most relevant examples are: control based on hysteresis, artificial intelligence (AI) techniques and predictive control. The most commonly used control techniques are summarized in Fig. 1.

In recent years, the appearance of more powerful micro-processors and their processing capability, have allowed an upper evolution of efficient control strategies. In this sense, Model Predictive Control has become one of the most popular control strategies. The main objective of Model-based predictive control (MPC) is to apply mathematical models, to predict the future behavior of the system and select appropriate control actions. The inclusion of several control objectives, constraints and nonlinearities in a single cost function is the main advantage of this popular control strategy, applied in power converters. In this way it is possible to control some typical variables in converters such as current, voltage, power, torque, or flux, through an optimization function. This is achieved by introducing the control objectives into the cost function.

In general, predictive control is a very flexible control technique that allows consider linear and non-linear systems. The control law applies an optimization criterion and it can include more than one variable to predict the desired state of the system. However, this is not an effortless task, as it requires a sufficiently accurate dynamic model of the system and optimization algorithm, which converts in high computational cost. Each term in the control law has a specific weighting factor, which is used to handle its relative effect, comparing to the rest of the objectives. These parameters must be designed properly, in order to achieve the desired performance. Unfortunately, there are no analytical, numerical, or control theories methods to adjust them, and therefore currently determined based on heuristic procedures [3].

The research presented in [4] shows the predictive control strategies in power converters. However, the variability of control possibilities, the application of further efficient optimization techniques and the generation requirements' increase, force researchers to find new predictive control strategies to upsurge efficiency on power systems.

This research summarizes some of the challenges and

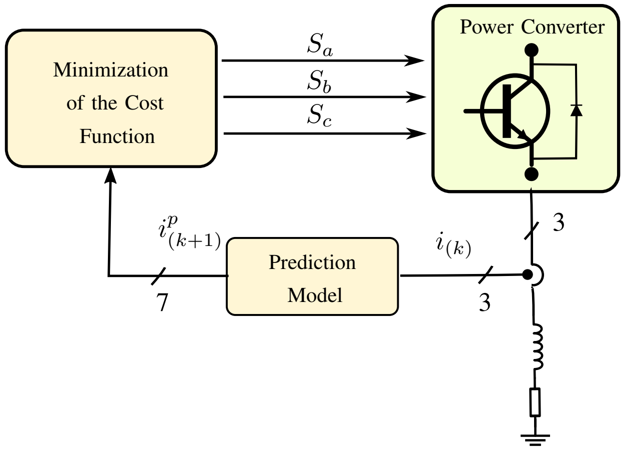

Fig. 2. Block diagram of predictive control for a three-phase load

current trends in predictive control and possible solution alternatives. The main contribution is to show an expanded view on the main strategies of predictive control, some of the most recent researches, as well as the proposal of advantages and disadvantages of each strategy. In addition, this research provides a basis for researchers who initiate their contributions about predictive control.

II. Model-based Predictive Control

Model-based Predictive Control (MPC) has successfully been used for several years in some areas of industry. However, their potential for the control strategy for electrical machines is quite recent and emerging. In general, there are three key components in model-based predictive control: 1) the prediction model, 2) the cost function, 3) the optimization algorithms [3].

In a power converter controlled by FCS-MPC, a finite number of switching states are available to be applied. The system models are used to predict the variable's behavior for each switching state. To select the appropriate switching state a few conditions must be defined. This selection criterion is expressed as a cost function, evaluated for the controlled variables. The prediction of the future values is calculated for each possible switching state. Hence, the switching state that minimizes the cost function [5] is selected. Fig. 2 shows the classic model of the predictive control strategy applied to power converters.

As shown in Fig. 2, the output of the inverter feeds the prediction model and this minimizes the cost function. A cost function can be as complex as the variables or control objectives involved. However, these variables depend only on the application used. In [5] some cost functions applications are summarized. Among them, the functions that consider the current, voltage, torque or the power are emphasized. Other objectives, such as the minimization of voltage ripple, speed and power, can be achieved by including specific variables in the cost function.

In general, the cost function can be written as:

$$g=\sum_{\ell=k+1}^{k=N_\rho}\tilde{x}_\ell^T Q\tilde{x}_\ell+\sum_{\gamma=k}^{k+N_c-1}\mathbf{u}_\gamma^T R\mathbf{u}_\gamma$$

where $\tilde{x}_\ell=\tilde{x}_\ell-\tilde{x}_{\ell^*}$ is a vector in which each component represents the difference between the estimated values $\tilde{x}_{j,\ell}$ and the reference, $\tilde{x}^*_{j,\ell}$, for each variable x_j at instant ℓ. On the other hand, u_γ is a control input vector u_i at instant γ, and N_p and N_c are the prediction and control horizons, respectively [5].

When Q and R are diagonal, then the above equation can be expressed as [5]:

$$g=\sum_{\ell=k+1}^{k+N_\rho}\sum_{\jmath=0}^{m-1}\lambda_\jmath\left(\hat{x}_{j,\ell}-x^*_{\jmath,\ell}\right)^2+\sum_{\gamma=k}^{k+N_c-1}\sum_{\imath=0}^{n-1}\lambda_\imath\left(u_{\imath,\gamma}\right)^2 \quad (1)$$

where $\lambda_\jmath$ and λ_i are the weighting factors associated with the variable x_j and the control action u_i, respectively.

As stated, the complexity of properly cost function selection multiplie with the increase of the control objectives. In this way, the reduction of prediction error is a very important element to consider. Some researchers have shown that this error can be calculated as the equation (2), when the control objectives consider only one variable. On the other hand, if presenting two or more terms, the best results are offered by the square cost function. The square error presents best reference tracking, when additional terms are added to the cost function. The cost function considers the trajectory of the variables between time intervals $t(k)$ and $t(k+1)$. This leads to the minimization of the average error, which implies a more precise tracking. In addition, the selection of the correct cost function is more difficult when several control objectives are included in the optimization problem.

$$g=|x^*-x^p| \qquad or \qquad g=(x^*-x^p)^2 \quad (2)$$

One of the main advantages of MPC, is that the cost function admits some terms that can represent a prediction for another variable of the system, as well as its restrictions. Since these terms can be of a different physical nature (voltage, reactive power, switching losses, torque, flux, among others), their units and magnitudes can also be different. The solution to this problem has been addressed in different ways, although some of them agree to include weight coefficients, or weighting factors λ, for each term of the cost function as shown in the equation (3).

$$g=\lambda_x\left\|x^*-x^p\right\|+\lambda_y\left\|y^*-y^p\right\|...+\lambda_z\left\|z^*-z^p\right\| \quad (3)$$

According to the criteria of some researchers [3], [5], [6], the most used predictive control strategies in power converters are: continuous-control set MPC (CCS-MPC) and finite control set MPC (FCS-MPC). Other forms of control are found within the last alternative such as: modulated MPC, and multi-objective MPC. The following sections describe the latest advances in each of these classifications.

III. Control strategies for MPC

A. Continuous Control Set MPC (CCS-MPC)

The CCS-MPC control strategy assumes a continuous nature of the converter. This means that the commutation states of the semiconductors within the control algorithm are not taken into account. Therefore, a continuous control signal is generated. In this way, a modulator (PWM or SVPWM) [7] is used to generate the switching states, which produces an output with a fixed frequency. The continuous characteristic of this type of modulation gives the name to this control strategy.

One of the most important challenges that affects the performance of any MPC model is the increase of the harmonic content [1]. CCS-MPC has some advantages compared to other forms of control, due to the use of a fixed frequency modulator, which implies a faster dynamic response and lower harmonic content. In addition, larger prediction horizons can be used, without the need to significantly increase the computational cost.

On the other hand, the use of a linear model limits its application to certain operational points. For this reason, if non-linear modeling is required, they should create linear models for different points of operation. The above reasons show that the complexity formulating the model is high and a modulator is required. In order to solve these problems, control strategies are developed as finite control set MPC.

B. Finite Control Set MPC (FCS-MPC)

To find a solution for the complexity of the model and the use of modulators, a finite control set MPC (FCS-MPC) has been developed. To solve the presented drawbacks, FCS-MPC takes into account the discrete nature of the converters, to formulate a less complex algorithm, which does not require modulation. In this way, the state that minimizes the cost function will be selected [8]. Having a finite number of possible states and control actions, this approach is called finite state MPC (FCS-MPC).

The FCS-MPC model is one of the most attractive alternatives nowadays due to its rapid dynamic response, the easy inclusion of non-linearities and restrictions within the prediction model, its simplicity and the absence of modulators or current loops within the control strategy. On the other hand, its development was limited by the high computational cost that this model requires. Even for small electrical systems, a high frequency of computation is needed to reduce the total harmonic distortion (THD). The evolution of programmable devices like FPGA, with more powerful processors, has allowed to solve some of these drawbacks.

The control scheme of this algorithm is shown in Fig. 3. The applications of this control technique are diverse and vary from three-phase inverters [9], inverters of three levels (NPC) [10], matrix converters [11], among others. In each of the above topologies there is a limited number of states to apply MPC.

C. Modulated MPC (M²PC)

To mitigate the insufficiencies of FCS-MPC, referred to the computational increase and the high ripple in the control variables of the algorithm [12], some investigations propose to modify the commutation states of FCS-MPC, to improve the control sequence [13]. Meaning a fixed frequency of conmutation must be taken. This would improve the output of the converter. On the other hand, the use of space vector of modulation (SVM), reduces the ripple of the control variables and allows to increase the forecast horizon [14].

In this way, the purpose of M²PC is to include a modulation scheme within the cost function of the MPC algorithm [15]. Each switching state is calculated from SVM, which implies reducing the harmonics at the output of the converter, produced by the previous modulation stage. In addition, the output states are calculated at a fixed frequency.

The control scheme of this architecture is described in Fig. 4. The modulated MPC block (M²PC) defines a sequence of two voltage vectors $S1$ and $S2$ and two values, $G1$ and $G2$, proportional to their application times. A second stage calculates the final application times using the information of the M²PC block.

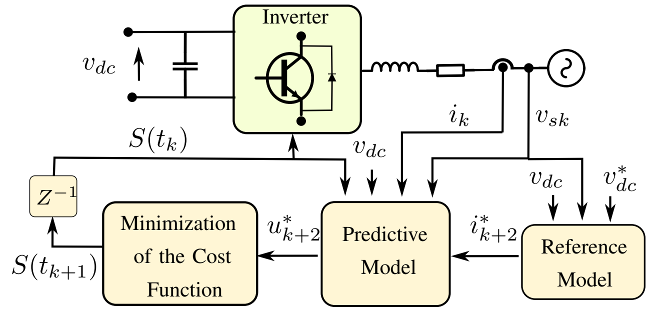

Fig. 3. Control scheme of FCS-MPC.

D. Multi-Objective MPC (MO-MPC)

The main problem with the control strategies described above is the adjustment of the controller parameters (adequate selection of the weighting factors). An interesting solution is to find some mechanisms that do not include the adjustment of these parameters. This is the case of the multi-objective formulation, whose fundamental role is to minimize the cost function, avoiding the adjustment of the weighting factors.

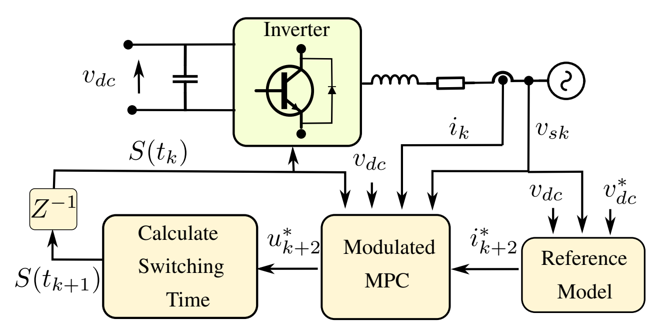

Fig. 4. Control scheme of M^2PC

TABLE I
COMPARISON OF THE DIFFERENT POWER CONVERTER CONTROL TECHNIQUES.

Control strategy	Advantage	Disadvantages	Applications	Ref.
Linear Control	Bandwidth is known. Easy to extend to other topologies. Fixed switching frequency. Widely used in commercial applications.	A modulator (PWM) is required. Lack of stability with non-linear systems. Changes in model constraints can not be included. A coordinate transformation is required.	To reduce the overshoot and steady state error. Can be used for FACTS units. To enhance power flow. To compensate disturbed harmonics.	[16] [17] [18] [19]
Control Based on Hysteresis	No modulator is required. Good dynamic performance. Robust non-linear control. Its design is relatively simple. It is used in commercial applications.	The sampling frequency must be high. It has resonance problems. Complexity to extend it, to other topologies. Variable switching frequency.	Current control is employed for a DC/DC boost converter. Energy storage in electric vehicles. To control charging time for wireless power transfer systems.	[20] [21] [22]
Continuous Control Set (CCS-MPC)	Fixed switching frequency. The dynamic behavior of the system is correctly predicted. Several objectives in a single control law. Extends the prediction horizon without increasing the processing time. The harmonic content is reduced due to the modulation stage.	Incorrect selection of controller elements may worsen. A modulator (PWM) is required. Adapting to changes in the dynamics of the system is not a simple task. Difficulty in including constraints on the control law.	Energy storage applications. To control permanent magnet in synchronous motor applications. Applied to control three-phase rectifier. To control NPC inverter.	[23] [24] [25] [26]
Finite Control Set (FCS-MPC)	Low complexity without a modulator. Multiple objectives at the same time with a single control law. System restrictions are included in the control law. Control strategies widely used in power converters industrial applications.	Problems adjusting switching frequency. Significant output ripple. The ripple is decreased by applying more complex computational strategies. Extending the prediction horizon increases considerably the calculation time. The selection of the driver parameters must be adjusted correctly to allow system performance.	To eliminate the tracking error and in grid connected operation. To reduce the oscillations and remove the steady-state error. Advanced MPC techniques. An adaptive predictive current control for three-phase inverter. Matrix converters.	[27] [28] [29] [30] [31]
Modulated MPC (M^2PC)	The advantages of MPC are maintained in this strategy. It has a good harmonic profile given the modulation stage.	Practical applications require more effort and research. By increasing the prediction horizon, computational time will increase considerably.	To overcome the stability problems caused by a constant power load in cascaded converter system. To control switching frequency in NPC inverter.	[32] [33]
Multi-objective MPC (MO-MPC)	It does not require a modulator, or adjust the controller parameters. The objective function, handles the restrictions in a simple way. The dynamic response is very fast.	A high computational cost is required. Variable switching frequency.	MO-MPC combined with M^2PC for multilevel solid-state transformer. To improve the steady state current tracking performance. To regulate frequency and voltages for islanded agents. Cooperative EMS.	[34] [35] [36] [37]

The multi-objective optimization concept applied to power converters is relatively a new approach. In [38], a cascading strategy of FCS-MPC fuzzy logic controllers is proposed. In a first step, they propose a strategy to reduce the switching frequency and a fuzzy controller to choose the weighting factors in a dynamic way. On the other hand, in [39], a control strategy for double fed induction generators (DFIGs) based on the multi-objective model (MO-MPC) predictive control scheme is presented. The future behavior of the DFIG is predicted using the system model and the possible switching states of the converter. Finally, in [40], a finite state model predictive control (FS-MPC), based on fuzzy logic is used to improve the stability and changes during converter steady state. This proposal has among its objectives, to avoid the problems related to weight adjustments, without affecting the performance of the control strategy.

An important element of this control strategy relies on being based on the same operating principles as FCS-MPC. This implies that the disadvantages with respect to the prediction horizon found in FCS-MPC are present in MO-MPC. Even the optimization algorithm adds computational complexity, so this strategy will require greater computational resources. Thus, some authors consider it practically impossible to implement it in multilevel converters [41]. Table I shows some of the most important elements of the control strategies addressed and applications in power electronics.

IV. DISCUSSION

MPC control strategies are one of the most used control alternatives in power electronics and electrical drives in recent years. However, it is still necessary to investigate some issues such as weighting factors selection, intelligent control strategies, expanding the forecast horizon, or improve the controller's computational performance. For example, to guarantee the stability of a voltage source inverter (VSI), it is necessary to adjust the weighting factors considering even possible changes in the load.

It was possible to verify in the literature that within the MO-MPC strategies the fuzzy logic algorithms stand out, due to the low computational requirements and the good results especially in the selection of weight factors. However, optimization algorithms such as simplified FCS-MPC, multistep FCS-MPC, or hierarchical FSC-MPC are also recent control alternatives, which reduce the computational cost and are described in [5].

The cost function gives flexibility to the control system and allows optimizing parameters such as power, switching frequency, torque or motor control. Its biggest drawback is that it requires an appropriate and previously known mathematical model. Several researchers agree that there are three important elements to consider, when applying MPC and they are: i) decrease in computational cost and the future prediction horizon [42], ii) the adjustment of the weighting factors [43] and iii) the increase in the efficiency of the converter [1].

Alternatives for improving the performance and quality of the steady state system have been proposed using a control technique with a modulation scheme (M^2PC). However, in the cost function, a weighting factor is also required, so the complexity is maintained. On the other hand, the performance of MPC against a broad prediction horizon in steady state, favors the efficiency of the control strategy. Its fundamental limitation continues being to limit the size of the prediction horizon, which increases the computational cost.

Despite the increase of computational capacity of the devices at present, in some cases it is not possible to carry out an adequate predictive control, due to the lack of processing. An example of this is the multi-phase and multi-level converters, where in each sampling time they have to evaluate the prediction model for a large number of switching states.

Finally, the feasibility and interest of the community in predictive control strategies applied to power converters has been demonstrated. However, there are still elements to be addressed in future research.

V. Future works

Predictive control in power converters is a potential researching branch today. Elements such as the reduction of the tracking error of the references, the converter performance on a steady state, or the optimization of the considered variables, should be considered as incipient research areas. The following are the potential topics for future research:

- To improve the steady state response, may be possible to define an extended prediction horizon, combined with a reduction of the switching frequency, can be used to decrease the THD.
- New contributions are needed regarding stability and optimal selection of the weighting factor. There is no established way to demonstrate the stability of predictive control and optimally select the weighting factors [5].
- Several MPC algorithms focus on the application of fixed frequency methods to improve the harmonic content of the controlled signals [44]. This leads to new possibilities in the control strategies, maintaining the advantage of not using a modulator, but applying the optimal switching state during a specific period.
- There are inadequacies in the validation of control algorithms proposed in specific applications, which generally require a high computational performance, such as power generation or electric vehicles.

VI. Conclusions

Model-based Predictive Control (MPC) is a very attractive solution for controlling applications in power electronics. The principle of operation of MPC was addressed, concluding that the implementation of MPC depends on three key elements, i) the prediction model, ii) the cost function and iii) the optimization algorithm. Several aspects related to these topics have been investigated in the literature. The most relevant are the selection of the cost function, the design of the weighting factor, the reduction of the computational cost and the extension of the prediction horizons.

The FCS-MPC control method is one of the most used for its simplicity and control of different magnitudes without requiring additional modulation techniques or internal cascade control loops. However, the most appropriate predictive control strategy will depend on the application and the requirements of the system.

VII. Acknowledgment

This work was supported by the Chilean Government under Projects FONDECYT 1160690 and the National Doctorate Scholarship CONICYT 2019.

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