Chapter 6
Application of Predictive Control in Power Electronics: An AC-DC-AC Converter System

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Abstract This chapter presents an application of predictive control in power electronics. The analyzed application is an energy conversion system from alternate current (AC) to direct current (DC) and to alternate current (AC) again. This example has been carefully selected because a number of predictive control principles can be clearly explained using this topology and later expanded to a wide variety of converter topologies. The chapter includes the mathematical models an a clear presentation of the control strategies. The results show that the use of predictive control introduces a conceptually different solution which allows for the control of electrical energy without using pulse-width modulation and linear controllers.

1 Introduction

After years of development, predictive control has found increasing acceptance, particularly in the process industry [1], being considered as one of the major advances during the last two decades in the field of control theory [2].

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Now, the scientific community is observing an increasing application of predictive control to control and transform electrical energy using power semiconductors.

The main driving forces behind this development are:

The maturity of the control theory

The field of control theory has developed a firm theoretical basis that allows for a good prediction of the behaviour for different physical systems with a high degree of accuracy and certainty.

The existence of very good models in electrical engineering

In the field of electrical engineering there are very good mathematical models to describe the behaviour of all variables of interest. By using these models it is possible to predict very precisely the future behaviour of variables like voltage, current, power, etc.

The same situation is valid for mechanical systems. In addition, the interaction of electrical variables with mechanical variables is also very well known and established trough the theory of electrical machine and drives [3].

The existence of powerful microprocessors

Microprocessors are the tool that allows the calculation of the variables prediction. Today it is possible to find very powerful microprocessors in the market, that can perform a large amount of calculations at very reduced cost. In addition, these calculations can be fast enough to predict the behaviour of variables like electrical currents or voltages in real time without affecting negatively the performance of the system under control .

The attractive features of predictive control

The control community has already established several attractive features of predictive control such as: it is easy to implement and simple to understand, it works in an intuitive and logical way, it can deal very easily with non-linearities and finally, it can easily include sophisticated and diverse control laws.

About the selected example

The major part of electrical energy is generated, transmitted, distributed and finally consumed in the form of three-phase AC voltages and currents. For this reason, the control and transformation of electrical energy from a three-phase source with voltage at fixed amplitude and frequency to a three-phase load with voltages of variable amplitude and frequency is a topic of high interest.

Figure 1 presents the main structure of an indirect conversion system. This system includes the grid side converter which transforms the three-phase alternate voltages of fixed frequency and amplitude into controlled direct voltage when a capacitive DC link is used as shown in the figure. Machine side converter transforms the DC voltage into three-phase alternate voltages of variable amplitude and frequency.

This conversion system has a wide variety of applications in different productive areas like:

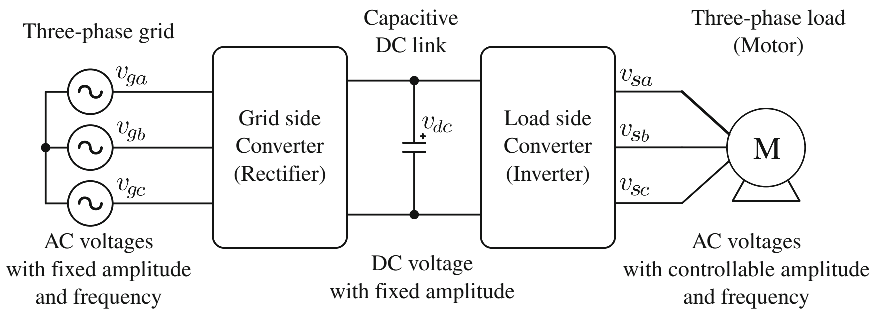

Fig. 1 Basic structure of an AC-DC-AC power converter

Energy	Energy transmission, renewable energies (wind and photovoltaic), etc.
Transportation	Trains, conveyor belts, electric trucks, cars, etc.
General industries	Pumps, shovels, laminators, industrial robots, etc.

This converter system was carefully selected to present the predictive control application due to its very general nature. In effect, the analysis, design procedures and conclusions obtained from this converter can be easily extended and used in a wide variety of different converter topologies.

2 The AC-DC-AC Conversion System

There are different ways to achieve the transformation from alternating current into direct current and to alternating current again. In Figs. 2 and 3 two conversion systems with diode and thyristor bridges respectively as grid side converter are shown.

The grid side converter presented in Fig. 2 allows for power flow exclusively from the AC source to the DC link, in consequence this converter system is suitable for applications where the energy flows only from the three-phase source to the three-phase load. If regenerative braking is required a DC–DC chopper with a resistive load is added to the DC link. In spite of this restriction, this topology is widely used in a number of industrial applications with unidirectional power flow: fans, blowers, pumps, etc. Among its main characteristic are the simple and reliable structure and the fixed, but not controllable, DC voltage. The main disadvantage is the high harmonic content of the input current requiring large input filters or multi-pulse configurations to reduce current harmonics and comply with standards. Additionally, although the fundamental component of the current is in phase with the input voltage the distortion factor produced by the harmonic content reduces the power factor.

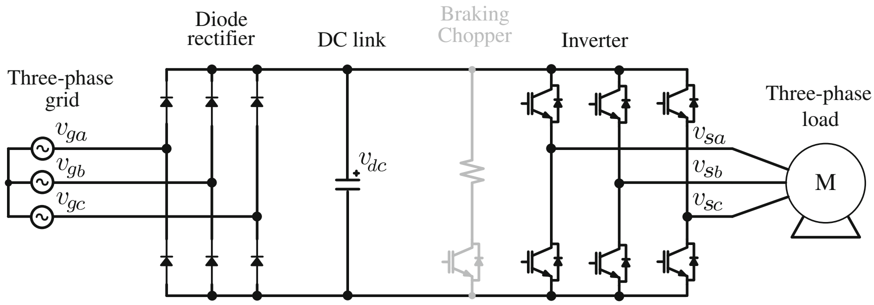

Fig. 2 Topologies for AC-DC-AC conversion: diode rectifier at the input

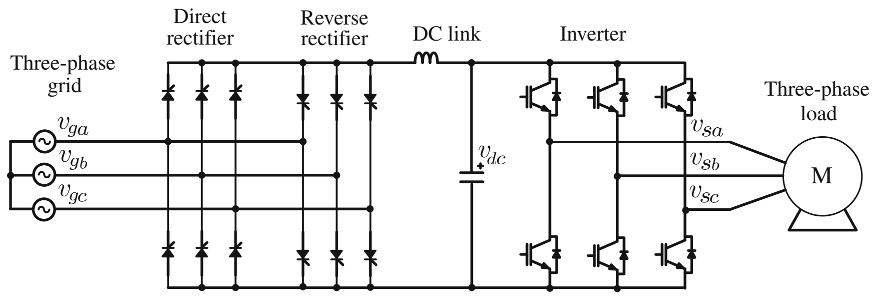

Fig. 3 Topologies for AC-DC-AC conversion: thyristor rectifier at the input

The topology presented in Fig. 3 uses two thyristor rectifiers in anti-parallel connection at the grid side. The direct rectifier transfers energy from the three phase-source to the load, while the reverse rectifier permits the flow of energy from the load to the three-phase source, what is called regenerative operation. This converter topology is suited for loads with regenerative capability such as shovels, trucks, mills, downhill conveyors, etc. This topology is much more complex than the diode bridge and is prone to failure during its operation, particularly in the regenerative mode. The thyristor rectifier provides control over the DC voltage, but the harmonic content is higher than diode bridge. The power factor is usually lower than the diode bridge because the DC voltage control is performed changing the firing angle and consequently modifying the angle between the current and voltage.

2.1 General Description of the Back-to-Back Converter

Although the two grid side topologies shown in the previous section have been used for years in machine drives, a third alternative called back-to-back converter has been increasing its industrial application. This converter has reduced input

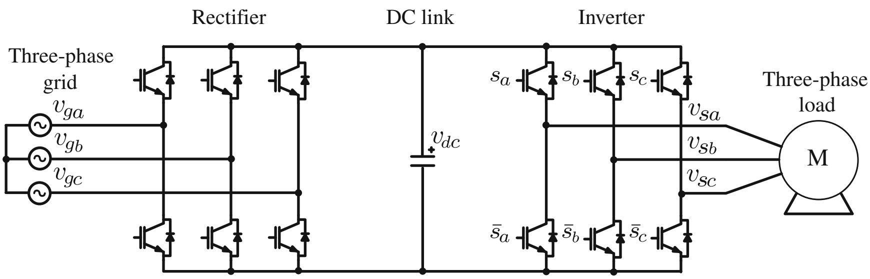

Fig. 4 Back-to-back topology for AC-DC-AC conversion

current harmonics, bidirectional power flow, operation with variable input power factor and controllable DC voltage.

The back to back converter topology is shown in Fig. 4. The output stage is composed, as usual, by a six fully controlled semiconductors arranged to form a three phase bridge but, in this case, the rectifier has the same topology of the inverter resulting in a completely symmetrical topology.

The inverter generates an output voltage whose fundamental component is variable in frequency and amplitude. To provide this output voltage the inverter assumes a regulated DC voltage. The rectifier must provide this regulated DC voltage and take care of the input active and reactive power. The control system must manage all these control objectives.

The predictive control of this back-to-back topology will be presented, analysed and designed in this chapter.

2.2 *Classical Control of Power Converters*

There are several linear control methods to control the back-to-back converter proposed in the literature, where usually the control of the inverter is considered separately from the control of the rectifier. In this section some of the classical methods to control back-to-back converters are reviewed.

2.2.1 Field Oriented Control

The inverter must control the output voltages and currents in terms of amplitude and frequency. When the load is a machine the control objective is the flux and torque and, usually in an external loop, the speed. One of the fundamental methods to control machines is the flux oriented control. In this control scheme, the currents are controlled in a rotating frame aligned with the flux. Therefore, the flux amplitude and torque are decoupled and can be controlled independently by the direct and quadrature current components.

The dynamical equation of the stator of an electrical machine is

$$\mathbf{v}_s = r_s \mathbf{i}_s + \frac{d\boldsymbol{\psi}_s}{dt} \tag{1}$$

The dynamical equation of the rotor of an squirrel cage induction machine is

$$0 = r_r \mathbf{i}_r + \frac{d\boldsymbol{\psi}_r}{dt} \tag{2}$$

The flux linkages are defined as

$$\boldsymbol{\psi}_s = l_s \mathbf{i}_s + l_m \mathbf{i}_r \tag{3}$$

$$\boldsymbol{\psi}_r = l_m \mathbf{i}_s + l_r \mathbf{i}_r \tag{4}$$

Expressing the rotor equation in terms of rotor flux and stator current and using a rotating coordinate transformation, the rotor flux equations can be written as

$$\frac{r_r}{l_r} l_m i_d = \frac{r_r}{l_r} \psi_{rd} - \omega_r \psi_{rq} + \frac{d\psi_{rd}}{dt} \tag{5}$$

Aligning this system with the rotor flux $\psi_{rq} = 0$, $\psi_{rd} = \Psi_r$, the dynamical equation of the rotor flux becomes

$$\frac{d\Psi_r}{dt} + \frac{r_r}{l_r} \Psi_r = \frac{r_r}{l_r} l_m i_d \tag{6}$$

The electromagnetic torque can be expressed as

$$T_e = \frac{p}{2} \frac{l_m}{l_r} \mathbf{i}_s \times \boldsymbol{\psi}_r \tag{7}$$

Expressing the torque equation in the coordinate transformation

$$T_e = \frac{p}{2} \frac{l_m}{l_r} \left(i_q \psi_{rd} - i_d \psi_{rq} \right) \tag{8}$$

Aligning this system to the rotor flux, the torque can be expressed as

$$T_e = \frac{p}{2} \frac{l_m}{l_r} \Psi_r i_q \tag{9}$$

It is clear from expressions (6) and (9) that the flux amplitude can be controlled by the direct component of the stator current i_d and, if the rotor flux dynamics is considered slower than the current, the torque can be controlled by the quadrature component i_q of the same current. Figure 5 shows the FOC scheme where, after a coordinate rotation, the direct and quadrature component of the stator currents are controlled by two independent PI controllers. The reference of the torque (quadrature current component) is given by an external speed controller. The stator voltage reference generated by the current controllers is transformed to the original

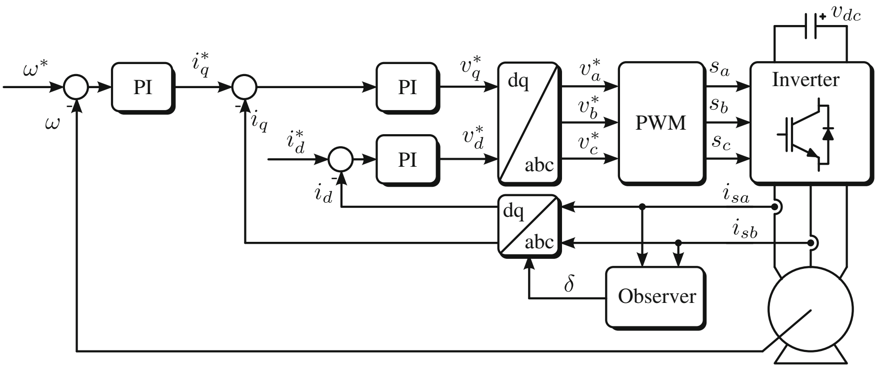

Fig. 5 Classical control of inverters: field oriented control

coordinate system, then they are modulated and sent as gating signals to the inverter. It can be noticed that an observer is required to obtain the angle for the coordinate transformation.

There are two main pulse width modulation (PWM) schemes used in industrial drives: the carrier based modulation and space vector modulation. The carrier based modulation uses a high frequency triangular carrier which is compared to the reference and directly generates the gating signals. The references must be in three-phase coordinates and the frequency of the carrier defines the frequency of the output harmonics. This modulation is very simple to implement both in analogical or digital technology.

The space vector modulation uses a vector representation of the reference voltage and the possible voltages generated by the converter. In each sample time the reference voltage is synthesized by the three nearest vectors the inverter can generate. The time in which each vector must be applied is calculated using geometric relationships between these vectors. The gating signals are generated combining the selected vector and the time each one must be applied in a given sequence. This sequence can be arbitrary defined, for example, to reduce switching frequency or to keep the symmetry of the pulse pattern. This modulation technique is more complex than carried based modulation, requiring digital implementation, but it brings better utilization factor and more control over the pulse pattern.

2.2.2 Direct Torque Control

Another well establish drive control method is direct torque control. This control scheme uses the model of the rotor dynamics Eq. (2), but in this case the rotor equation is expressed in terms of stator flux amplitudes as

$$r_r \frac{l_s \Psi_r}{l_s l_r - l_m^2} + \frac{d\Psi_r}{dt} = r_r \frac{l_m \Psi_s}{l_s l_r - l_m^2} \tag{10}$$

The torque can be expressed in terms of flux amplitudes as

$$T_e = \frac{p}{2} \frac{l_m}{l_s l_r - l_m^2} \Psi_s \Psi_r \sin(\delta) \tag{11}$$

From the previous expressions (10) and (11), the rotor flux amplitude can be controlled by the stator flux amplitude and, considering that rotor flux has slower dynamic than stator flux, the torque can be controlled by the angle of the stator flux vector. From the stator equation, neglecting the stator losses, the stator flux can be approximated in one sample time T_s by

$$\Delta \boldsymbol{\psi}_s \approx \mathbf{v}_s T_s \tag{12}$$

where $\mathbf{v}_s$ is the voltage vector generated by the converter which can have only a finite number a possibilities. Each one of these switching states will have a different effect in both, the amplitude and angle of the stator flux and, therefore, generates a different combination of changes in rotor flux and torque. All these combinations can be listed in a table and, depending on the errors in torque and flux amplitude, and the angle of the rotor flux, they can be addressed to generate the proper switching signals.

The complete scheme of DTC is shown in Fig. 6. To generate the errors of torque and flux hysteresis controllers are used. It is worth to note that torque has a double-band hysteresis block in order to minimize the torque ripple. The torque reference, as well as FOC is generated by an external speed controller. The main advantage of this scheme is that it does not require the parameters of the drive. Its main drawback is the variable switching frequency. However, it is possible to keep the switching frequency in a defined range by changing the width of the hysteresis bands.

2.2.3 Voltage Oriented Control

The rectifier control schemes are closely related to the inverter control schemes. The control must regulate the DC voltage adjusting the input current reference. The active rectifier can provide independent active and reactive power, therefore, this reference must be also modified to control the reactive power. The main difference between the grid side and the load side converter is the operation at constant frequency, which is fixed by the grid voltage.

The model of the grid side converter is

$$\mathbf{v}_g = r_s \mathbf{i}_g + L_s \frac{d\mathbf{i}_g}{dt} + \mathbf{v}_r \tag{13}$$

where $\mathbf{v}_g$ is the grid voltage, $\mathbf{i}_g$ is the grid current and $\mathbf{v}_r$ is the rectifier voltage.

Using a coordinate transformation the dynamic model becomes

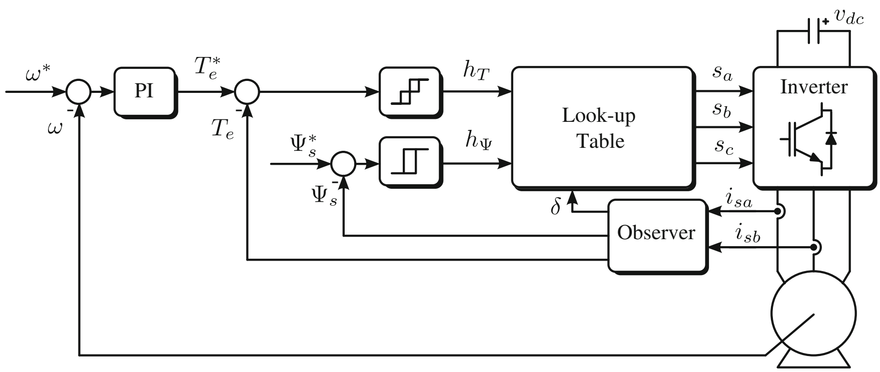

Fig. 6 Classical control of inverters: direct torque control

$$v_{gd} = r_s i_d + L_s \omega_s i_q + L_s \frac{di_d}{dt} + \mathbf{v}_{rd} \tag{14}$$

$$v_{gq} = r_s i_q - L_s \omega_s i_d + L_s \frac{di_q}{dt} + \mathbf{v}_{rq} \tag{15}$$

Since the amplitude and frequency of the input voltage can be considered constant, a compensation of the input voltage and the coupled terms can be added as feed-forward terms, resulting

$$L_s \frac{di_d}{dt} + r_s i_d = -v_{rd} \tag{16}$$

$$L_s \frac{di_q}{dt} + r_s i_q = -v_{rq} \tag{17}$$

The instantaneous active and reactive power in the rotating frame can be written as

$$p_s = v_{gd} i_d + v_{gq} i_q \tag{18}$$

$$q_s = v_{gd} i_q - v_{gq} i_d \tag{19}$$

Considering the coordinate transformation aligned with the input voltage $v_{gd} = V_g$ and $v_{gq} = 0$ these powers can be written

$$p_s = V_g i_d \tag{20}$$

$$q_s = V_g i_q \tag{21}$$

Therefore, from the previous expressions, the active and reactive power can be controlled by the direct and quadrature components of the grid current. This control technique is called VOC and can be seen that is very similar to FOC, where each current component controls one output variable - torque and flux in FOC and

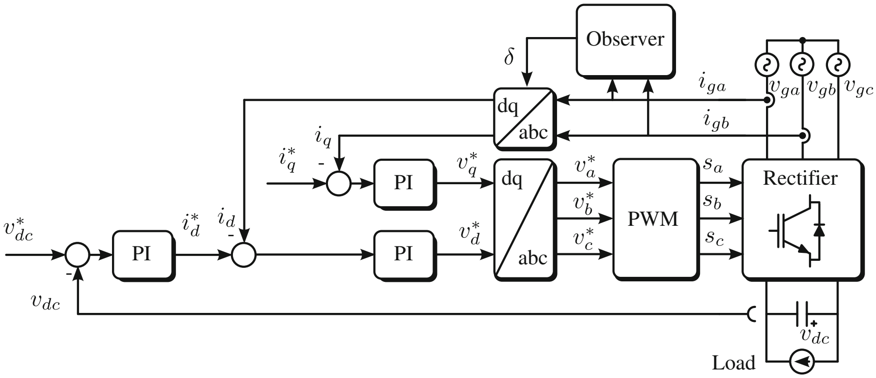

Fig. 7 Classical control of rectifiers: voltage oriented control

active and reactive power in VOC. The control scheme is shown in Fig. 7 and it can be seen that two PI controllers manage the active and reactive power generating the rectifier voltage reference which is modulated using any of the previously presented modulations schemes. The reference of reactive power can be adjusted as required and the reference of the active power comes from an external PI controller which manages the DC voltage.

It is possible to work with the integral value of the input voltage. This control technique is called virtual flux and is equivalent to flux controllers in the machine side. The main advantage of this method is the use of an estimator to obtain this virtual flux, avoiding to measure the input voltages.

2.3 Direct Power Control

Considering the active and reactive power defined as

$$p_s = \mathbf{v}_g^T \mathbf{i}_g \tag{22}$$

$$q_s = \mathbf{v}_g^T \mathbf{J} \mathbf{i}_g \tag{23}$$

where $\mathbf{v}_g^T$ is the transpose of the source voltage vector and $\mathbf{J}$ is a matrix used to calculate the cross product. Deriving these equations, replacing the model of the current and considering balanced input voltages $\frac{d\mathbf{v}_g^T}{dt} = -\omega \mathbf{v}_g^T \mathbf{J}$, gives

$$L_s \frac{dp_s}{dt} = -L_s \omega_s \mathbf{v}_g^T \mathbf{J} \mathbf{i}_g + \mathbf{v}_g^T \mathbf{v}_s - r_s \mathbf{v}_g^T \mathbf{i}_g - \mathbf{v}_g^T \mathbf{v}_r \tag{24}$$

$$L_s \frac{dq_s}{dt} = L_s \omega_s \mathbf{v}_g^T i_g - r_s \mathbf{v}_g^T \mathbf{J} \mathbf{i}_g - \mathbf{v}_g^T \mathbf{J} \mathbf{v}_r \tag{25}$$

replacing with the definition of active and reactive power

$$L_s \frac{dp_s}{dt} + r_s p_s + L_s \omega_s q_s = \mathbf{v}_g^T \mathbf{v}_g - \mathbf{v}_g^T \mathbf{v}_r \tag{26}$$

$$L_s \frac{dq_s}{dt} + r_s q_s - L_s \omega_s p_s = -\mathbf{v}_g^T \mathbf{J} \mathbf{v}_r \tag{27}$$

Applying a compensation of the input voltage and coupled terms and writing in terms of amplitudes gives

$$L_s \frac{dp_s}{dt} + r_s p_s = -V_g V_r \cos(\delta) \tag{28}$$

$$L_s \frac{dq_s}{dt} + r_s q_s = -V_g V_r \sin(\delta) \tag{29}$$

From the previous expressions it is possible to note that both active and reactive power change depending on the angle between the input voltage and the rectifier voltage. The rectifier can generate only a finite number of voltages, and each voltage has a different effect on both powers. In this case, just like in DTC, it is possible to store all the switching states in a table and, depending on the error in active and reactive power, to apply the switching state that makes the power to follow the references. This method is called Direct Power Control (DPC) [4] and is very similar to DTC as shown in Fig. 8. The active and reactive power errors are obtained by hysteresis blocks. The active power reference, as well as in VOC, is obtained from an external DC voltage PI controller. An observer is required to obtain the angle reference to perform the coordinate transformation.

3 Principle of Predictive Control in Power Electronics

Model predictive control has several advantages when it is applied in power electronics applications. The well known models, the finite number of the converter states and the flexibility of the cost function, make this control strategy very well suited for power electronics.

In this section the predictive control principle, its algorithm and how to include it into the converter control scheme will be explained.

3.1 The Basic Idea

The basic idea behind predictive control is to predict the behaviour of the complete drive using a mathematical model of it. The predicted variables are calculated for each one of the possible switching states of the converter and evaluated in a cost

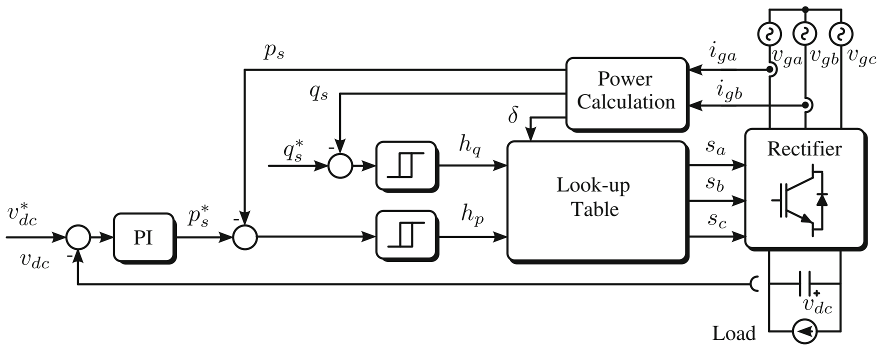

Fig. 8 Classical control of rectifiers: direct power control

function which describes the control objectives. The switching state that minimize this cost function is selected and applied to the converter in the next sample time.

Predictive control can be used to control inner variables such as currents, directly replacing the linear or hysteresis controllers as shown in Fig. 9. In the next sections this example will be developed and more advanced predictive control schemes will be discussed.

3.2 Why Predictive Control is Suitable for Power Electronics

As stated in the introduction, predictive control has been already used in the process industry. However its introduction to power electronics, although recent, seems to have high impact. There are several reasons for this effect:

Established and well known models

The models in power electronics are basically electrical machines (induction, synchronous, permanent magnets, etc.) whose physical models have been widely studied. Other loads correspond to combinations of resistive, inductive and capacitive elements.

Finite set of input variables

Power converters are composed by semiconductors operating in short-circuit and open-circuit. Therefore, it always exists a finite number of possible combination of these switching states. This characteristic greatly simplifies the application of predictive control because a direct evaluation is used instead of continuous optimization.

Cost function definition

The cost function directly represents the control objective of the system, which is usually to follow the currents, voltages, power, torque, flux or another reference. However, additional aspects such as commutation losses, common mode voltages,

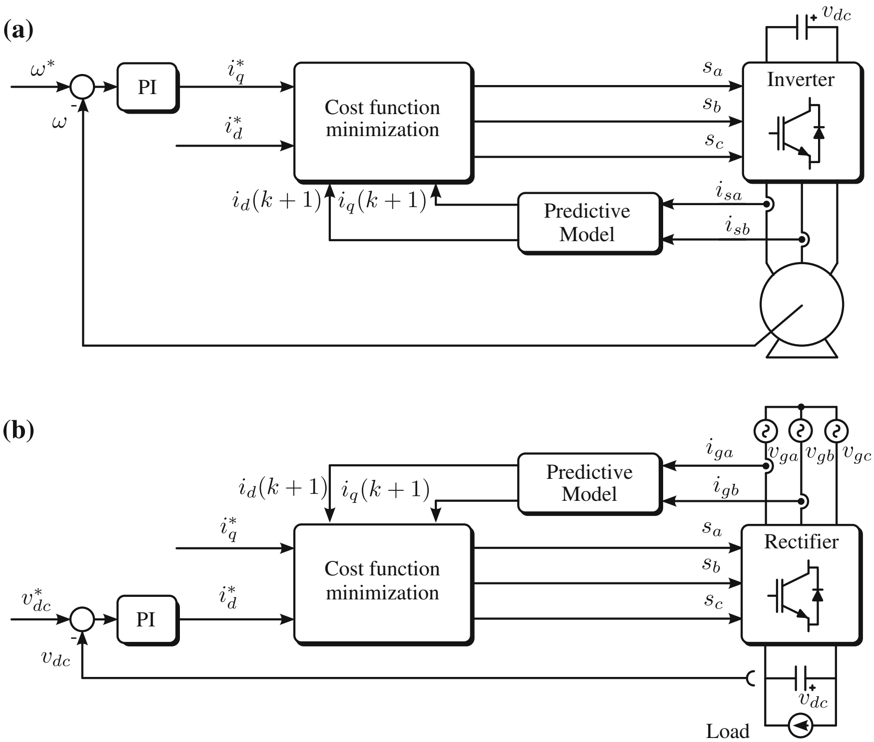

Fig. 9 Model predictive control **a** Inverter, **b** Rectifier

switching frequency and others, can be included. Furthermore, non-linear operation, such as restrictions can be easily added.

Processing capability

New digital processors have increased their calculation capability to afford high demanding tasks such as video processing. This huge calculation capability allows the implementation of sophisticated control strategies such as predictive control, without any negative effect on the performance.

3.3 Predictive Algorithm

The algorithm of predictive control is shown in Fig. 10. This algorithm is the same in all the predictive control schemes, because if the plant changes only the model must be adjusted, if the converter changes, just the switching states evaluation must be adjusted and, if the control objective changes, only the cost function must be modified accordingly.

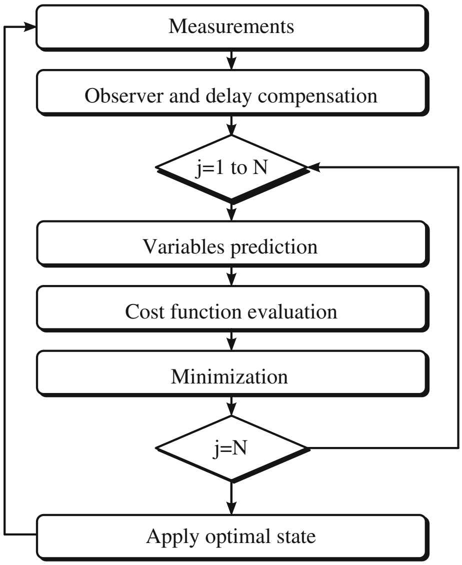

Fig. 10 Model Predictive Control algorithm

The algorithm starts with the measurements of variables at the beginning of the sampling time. Then, if it necessary, delay compensation and observers to obtain non measured variables are implemented. Once all the variables are available, the model is evaluated for the first switching state. The predicted variables are used in the cost function whose resulting value is kept if it is minimum or dropped if not. The loop is repeated for all the switching states. Once all the switching states were evaluated the optimal one is selected and applied to the load. This implementation is well suited for processors that work sequentially. If the hardware is capable of parallel processing, the model evaluation, cost function and minimization can be performed in parallel.

4 Mathematical Models for Predictive Control

The majority of the models used in predictive control are based on physical phenomena with well developed mathematical models. Among the variables used in predictive control can be mentioned electrical and mechanical variables such as electrical charges, magnetic fluxes, currents, voltages, power, torque, speed, heat and temperature.

In this section, different models to control the back-to-back converter by means of predictive algorithm will be presented.

4.1 Load Side Model

From the stator Eq. (1), neglecting the derivative of the rotor current and using the coordinate transformation, the dynamic equation of the stator current is given by

$$l_s \frac{d\mathbf{i}_s}{dt} + r_s \mathbf{i}_s + \omega l_s \mathbf{J}_{dq} \mathbf{i}_s = \mathbf{v}_s \tag{30}$$

From the rotor flux expression, the dynamic behaviour of the rotor flux is

$$\frac{d\Psi_r}{dt} + \frac{r_r}{l_r}\Psi_r = \frac{r_r}{l_r} l_m i_{sd} \tag{31}$$

and the torque is

$$T_e = \frac{p}{2}\frac{l_m}{l_r}\Psi_r i_{sq} \tag{32}$$

Using a forward Euler discretization gives

$$i_{sd}(k+1) = \left(1 - T_s \frac{r_s}{l_s}\right) i_{sd}(k) - T_s \omega(k) i_{sq}(k) + \frac{T_s}{l_s} v_{sd}(k) \tag{33}$$

$$i_{sq}(k+1) = \left(1 - T_s \frac{r_s}{l_s}\right) i_{sq}(k) + T_s \omega(k) i_{sd}(k) + \frac{T_s}{l_s} v_{sq}(k) \tag{34}$$

$$\Psi_r(k+1) = \left(1 - \frac{r_r}{l_r} T_s\right) \Psi_r(k) + T_s \frac{r_r}{l_r} l_m i_{sd}(k+1) \tag{35}$$

$$T_e(k+1) = \frac{p}{2}\frac{l_m}{l_r}\Psi_r(k+1) i_{sq}(k+1) \tag{36}$$

These four last discrete equations are used to model the complete drive. The first two equations predict the stator current requiring the measurement of the actual current. The third equation calculates the prediction of the rotor flux. It is worth to note that this prediction requires an observer of the rotor flux. The last equation is the evaluation of the torque prediction.

4.2 Grid Side Model

The active and reactive instantaneous power are calculated as

$$p_s = \mathbf{v}_g^T \mathbf{i}_g \tag{37}$$

$$q_s = \mathbf{v}_g^T \mathbf{J} \mathbf{i}_g \tag{38}$$

This calculation can be performed in three-phase stationary frame, as well as, in the rotating frame. The matrix used to calculated the cross product must be modified accordingly. The dynamic model of the current is

$$L_s \frac{d\mathbf{i}_g}{dt} + r_s \mathbf{i}_g = \mathbf{v}_g - \mathbf{M}\mathbf{s}v_{dc} \tag{39}$$

where $\mathbf{M}$ is a matrix used to calculate the common mode voltage generated by the rectifier. Using a forward Euler discretization gives

$$\mathbf{i}_g(k+1) = \left(1 - T_s \frac{r_s}{L_s}\right)\mathbf{i}_g(k) + \frac{T_s}{L_s}\left(\mathbf{v}_g(k) - \mathbf{M}\mathbf{s}(k)v_{dc}\right) \tag{40}$$

$$p_s(k+1) = \mathbf{v}_g^T(k)\mathbf{i}_g(k+1) \tag{41}$$

$$q_s(k+1) = \mathbf{v}_g^T(k)\,\mathbf{J}\,\mathbf{i}_g(k+1) \tag{42}$$

From the first equation, the current prediction is calculated. The last two equations calculate the predictions of the powers.

4.3 Power Converter Model

The converter structure will influence the calculation of the predictive algorithm defining the switching states in which the model must be evaluated.

This is one of the most attractive characteristics of model predictive control because, if in a given application the converter is changed, the model is still the same but it must be now evaluated in the switching states the new converter generates. No matter how complex the converter could be, always there will be a finite number of switching states associated with it.

The back-to-back converter is composed by two three-phase two-level converters which have the switching states given in the Table 1. From this table it is possible to obtain the converter voltages applied to the AC side v_{ra}, v_{rb} and v_{rc} and the converter current injected to the DC side i_{r} The predictive models of load side and grid side obtained in the previous sections must be evaluated at these switching states.

5 Control Objectives

There are several control objectives in the back-to-back converter depending on the control implementation. For example, if the predictive control is designed to replace the linear controllers, current error minimization will be the control objective. However, if the model of the torque and flux are directly included in the

Table 1 Switching states of three-phase two-level converters

Switching state	s_a	s_b	s_c	v_{ra}	v_{rb}	v_{rc}	v_O	i_r
s_0	0	0	0	0	0	0	$v_{\underline{0}}$	0
s_1	0	0	1	0	0	v_{dc}	v_1	i_{sc}
s_2	0	1	0	0	v_{dc}	0	v_2	i_{sb}
s_3	0	1	1	0	v_{dc}	v_{dc}	v_3	$i_{sb} + i_{sc}$
s_4	1	0	0	v_{dc}	0	0	v_4	i_{sa}
s_5	1	0	1	v_{dc}	0	v_{dc}	v_5	$i_{sa} + i_{sc}$
s_6	1	1	0	v_{dc}	v_{dc}	0	v_6	$i_{sa} + i_{sb}$
s_7	1	1	1	v_{dc}	v_{dc}	v_{dc}	v_7	$i_{sa} + i_{sb} + i_{sc}$

control strategy, then the control objective will be the error minimization of these two variables. Moreover, if the speed is modelled, then the speed error and the current-to-torque ratio must be minimized.

The cost function in predictive control can contain not only the main control objective, but other operational aspects can be included. For example, to minimize the common mode voltage, to reduce or to fix the switching frequency, to minimize the losses, to reduce THD, etc., giving a high flexibility in this aspect.

In this section a comprehensive review of different control objectives applied in the back to back converter are shown.

5.1 Machine Current Controllers

The simplest form to include predictive control in machine drives is to control the stator currents. The model of currents is a first order model and, if no compensation is required, it does not require observers. The cost function to reach this control objective is

$$G = \left(i_{d,\text{pred}} - i_{d,\text{ref}}\right)^2 + \left(i_{q,\text{pred}} - i_{q,\text{ref}}\right)^2 \tag{43}$$

where $i_{d,\text{pred}}$ is the predicted value of i_d.

5.2 Torque and Flux Controllers

If predictive control is used to control the torque and flux, the cost function is

$$G = \left(T_{\text{pred}} - T_{\text{ref}}\right)^2 + \lambda_\psi \left(\psi_{\text{pred}} - \psi_{\text{ref}}\right)^2 \tag{44}$$

where λ_ψ is a weighting factor used to give relative importance to one of the error terms. This weighting factor is a design parameter.

5.3 Grid Current Controllers

In the rectifier, just as the inverter, predictive control can be used to replace the current controllers using the following cost function

$$G = \left(i_{d,\text{pred}} - i_{d,\text{ref}}\right)^2 + \left(i_{q,\text{pred}} - i_{q,\text{ref}}\right)^2 \tag{45}$$

It can be noticed that this equation has the same structure of the machine current controller cost function.

5.4 Direct Power Controllers

To control the instantaneous input active and reactive power the following cost function can be used

$$G = \left(p_{s,\text{pred}} - p_{s,\text{ref}}\right)^2 + \left(q_{s,\text{pred}} - q_{s,\text{ref}}\right)^2 \tag{46}$$

5.5 DC Voltage Controllers

The DC voltage can be also included in the predictive algorithm using the cost function

$$G = \left(p_{s,\text{pred}} - p_{s,\text{ref}}\right)^2 + \left(q_{s,\text{pred}} - q_{s,\text{ref}}\right)^2 + \lambda_{dc}\left(v_{dc,\text{pred}} - v_{dc,\text{ref}}\right)^2 \tag{47}$$

In this expression the terms associated with the DC voltage and the active active power are heavily related. Therefore, an internal algorithm to adjust the required active power reference must be included [5].

5.6 Restrictions and Constraints

One of the aspects where predictive control shows its flexibility is in the inclusion of non linear elements in it. For example, restrictions can be added simply by using a logical function as

$$G = \lambda_{lim}\left(i_{d,\text{pred}} > i_{\text{lim}}\right) \tag{48}$$

The value of λ_{lim} must be large enough to avoid the minimization algorithm to select the state if it is higher than the limit.

5.7 Advanced Control Objectives

In predictive control it is possible to include other operational issues which are not directly related to the main control objective, but could improve another features. This is possible due to the optimization stage in which no matter what the structure is and the number of terms of the cost function, the algorithm always find the optimum value.

For example, the common mode voltage can be minimized if a suitable model of it is included and the respective term is added to the cost function [6] as

$$G = \left(v_{cm,\mathrm{pred}}\right)^2 \tag{49}$$

with

$$v_{cm,\mathrm{pred}} = \frac{v_{sa} + v_{sb} + v_{sc}}{3} \tag{50}$$

Also the switching frequency can be controlled using [7] the following term in the cost function

$$G = \left(i_{de,\mathrm{pred}}\right)^2 + \left(i_{qe,\mathrm{pred}}\right)^2 \tag{51}$$

where $i_{de,\mathrm{pred}}$ and $i_{qe,\mathrm{pred}}$ are the filtered value of the currents.

Finally, it is possible to add to the cost function a term related with the total harmonic distortion, eliminating or mitigating the harmonic content [8].

$$G = \sum_{i=0}^{N} \lambda_i \mathrm{SDFT}\left|\left(v_{s,\mathrm{pred}} - v_{s,\mathrm{ref}}\right)\right| \tag{52}$$

where the function SDFT() is the Sliding Discrete Fourier Transform, calculated for each one of the harmonics that will be minimized. It is important to note that the harmonics are not simply minimized, but they are assigned with a fixed value. In this way the switching frequency is not heavily increased and the converter still comply with harmonics regulations.

5.8 Predictive Control Results

The results of a back-to-back system with an inverter using Predictive Torque Control and a rectifier using Predictive Power Control are shown in Fig. 11. The initial condition of the inverter is a speed reference of 1,500 RPM with a nominal torque of $+100$ Nm and a nominal output frequency of 50 Hz. At $t = 0.05$ s the speed reference is changed from 1,500 to $-1,500$ RPM. The PI controller generates a negative reference torque which is saturated at -220 Nm. At $t = 0.25$ s the speed is completely reversed and the torque is set at -100 Nm. During the complete operation

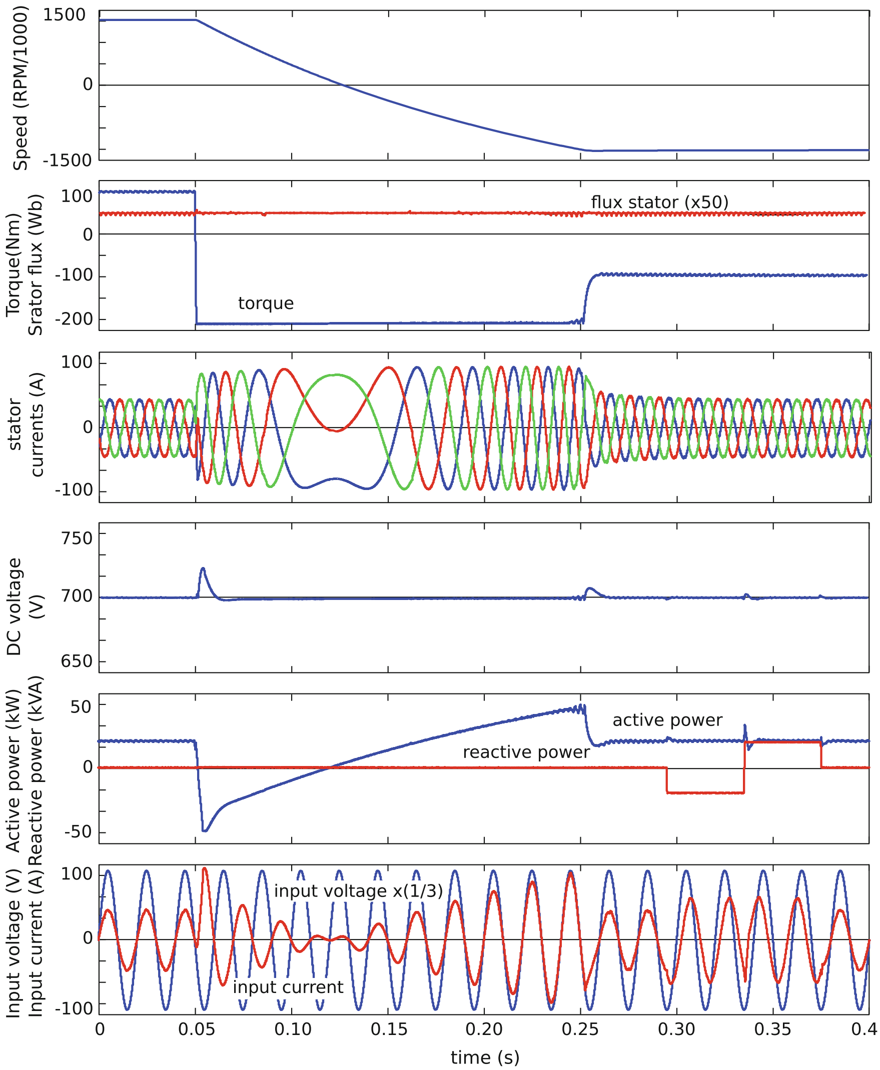

Fig. 11 Model predictive control of the inverter and the rectifier

the flux is kept constant. The DC voltage has small disturbances when the speed change starts and ends however it is kept fixed at its reference value of 700 V. The rectifier delivers initially +25 kW nominal at unity power factor. At t = 0.05 , when the machine is breaking, the power is reversed reaching a peak of −50 kW. When the machine is accelerated in the reverse direction, the power reach a positive peak of +50 kW. When the reversal speed is set the power is set again at the +25 kW. During the entire operation the reactive power reference is zero keeping the current in phase with the voltage. At t = 0.295 s the reactive power reference is set at −25 kVAr displacing the current in a lagging angle. At $t = 0.335$ s the reactive power reference is changed to $+25$ kVAr and the current is accordingly displaced to a leading angle.

6 Digital Implementation

Digital processors are used for control purposes from the early 1980s where the digital signal processors (DSP) and field programmable gate array (FPGA) appear. Their capabilities also includes analogical to digital signal conversion, digital filter implementation, sequential and parallel processing making use of an ever increasing number of mathematical and logical functions. In industrial power electronics converters, digital controllers are steadily used from the 1990s. They are in charge of tasks such as handling of signal acquisition, carrier generation and modulation, filtering and control algorithm implementation. The control algorithm includes PI controller, observers and estimators which are usually digital implementations of their linear counterpart. Nowadays, digital processors are designed to develop intense calculation tasks, such as, audio, image and video processing. Therefore, there exists a large processing capability gap between processor calculation capability and the requirements of power electronics applications. This increasing processing capability has pushed the development and implementation of more complex controller structures, such as fuzzy logic, genetic algorithms and model predictive control.

6.1 Delay Time Compensation

From the algorithm description it is clear that the optimization is performed with the variables measured in time k, but the controller sends the gating signal at time $k + 1$. This can be neglected when the dynamics of the variables are slower compared to the sample time. Unfortunately, electric variables such as currents and voltages are fast compared to the currently available processors, therefore a compensation of the time delay must be included.

This delay compensation consists on making an estimation of the predicted variables at the next sample time $k + 1$ using the switching state applied in that moment. With these estimated values the prediction is now evaluated in time $k + 2$, therefore, the optimization will give a result valid for the time in which it will be applied [9].

6.2 Forward Prediction

It is possible to perform the prediction of the states using an extended prediction horizon in order to improve the dynamic response, but more important to improve the steady state response, in particular the steady state error [10].

7 Conclusions

The advances in modern control theory and in microprocessors have made it possible to apply MPC in power electronics and drives in a natural and simple way. The results shown in this chapter demonstrate that, in principle, MPC allows for high quality control of AC-DC-AC converters. This method shows a behaviour similar to well established linear controllers. However, there are a number of aspects that must be clarified in the near future in order to bring MPC to industrial application in drives. First, a rigorous comparison with the existing techniques must be done in order to assess the possible advantages of MPC in terms of performance and simplicity. In addition, the design procedure for MPC must be improved to a more simple and systematic form, as other standard control strategies typically are. In particular, a simpler and more systematic procedure must be found to calculate the weighting factors used in the cost functions. With the research results obtained so far, MPC has proved to be a modern, attractive and competitive alternative for the control of electrical energy using power semiconductors.

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References

1. M. Morari, J.H. Lee, Model predictive control: past, present and future. Comput. Chem. Eng. **23**, 667–682 (1999)
2. J.H. Lee, Model predictive control: review of the three decades of development. Int. J. Control Autom. Syst. **9**(3), 415–424 (2011)
3. E. Fuentes, R. Kennel, Finite-set model predictive control of the two-mass-system, in *2011 Workshop on Predictive Control of Electrical Drives and Power Electronics (PRECEDE)*, pp. 82–87 (2011)
4. M. Malinowski, M. Kazmierkowski, S. Hansen, F. Blaabjerg, G. Marques, Virtual-fluxbased direct power control of three-phase pwm rectifiers. IEEE Trans. Ind. Appl. **37**(4), 1019–1027 (2001)
5. D. Quevedo, R. Aguilera, M. Perez, P. Cortes, R. Lizana, Model predictive control of an afe rectifier with dynamic references. IEEE Trans. Power Electron. **27**(7), 3128–3136 (2012)
6. R. Vargas, U. Ammann, J. Rodriguez, J. Pontt, Predictive strategy to control commonmode voltage in loads fed by matrix converters. IEEE Trans. Ind. Electron. **55**(12), 4372–4380 (2008)
7. P. Cortes, J. Rodriguez, D. Quevedo, C. Silva, Predictive current control strategy with imposed load current spectrum. IEEE Trans. Power Electron. **23**(2), 612–618 (2008)
8. H. Aggrawal, J. Leon, L. Franquelo, S. Kouro, P. Garg, J. Rodriguez, Model predictive control based selective harmonic mitigation technique for multilevel cascaded h-bridge converters. in *IECON 2011—37th Annual Conference on IEEE Industrial Electronics Society*, pp. 4427–4432 (2011)
9. P. Cortes, J. Rodriguez, C. Silva, A. Flores, Delay compensation in model predictive current control of a three-phase inverter. IEEE Trans. Ind. Electron. **59**(2), 1323–1325 (2012)
10. T. Geyer, Model predictive direct current control: formulation of the stator current bounds and the concept of the switching horizon. IEEE Ind. Appl. Mag. **18**(2), 47–59 (2012)