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REVIEW ARTICLE

A Review of Model-Based Predictive Control and its Applications

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ABSTRACT

In technologies including power semiconductors, converter topologies, automatic control, analog and digital electronics, technical development has been achieved and industrial applications are influenced and driven by the evolution of power electronics and its control. The important reason is that, although Model-based Predictive Control (MPC) presents high computational load, it can handle multivariable cases, system constraints and nonlinearities easily in a very intuitive way. Taking advantage of these factors, model-based predictive control has been successfully employed for diverse uses such as in power converters, active front end connected to RL loads, uninterruptible supplies of power and high performance drive for induction machines. In this review, a brief summary of the new developments and recent trends in the MPC theoretical study area and applications are given. It points out that the MPC study for large scale systems, quick dynamic systems, less cost systems and nonlinear systems will be important for the further growth of MPC theory and broadening of MPC application fields. In short, this paper delivers a review of the model-based predictive control and its applications focussing on power electronics and drives.

Keywords: Power semiconductors, Power converter, Dynamic systems, RL loads, Predictive control.

1. INTRODUCTION

In recent years, the field of power electronics and drives has received vital attention and popularity. In 1970s MPC was used usually in industries and applications of procedure control as described in [1]. The fundamental concept of all predictive control methods is that the decision of the controller is not centred on the past system state but on the predicted behaviour of the state variables and the controlled variables are properly selected either offline or online. MPC is also mentioned as receding horizon control. The recent developments and new trends in MPC theoretical study and applications are summarized in [2]. In power electronics, many approaches in conventional control are based on controllers of proportional-plus integral type by giving continuous input signals to a modulator, which manages the conversion to discrete positions for switching. Through MPC [3], instead of combining the current control and the problem of modulation into a single problem, powerful change to conventional controllers of PI is provided. With direct model based predictive control, manipulated variables are the switch positions, which lie in a separate and limited set, giving an escalation to the switched system. In power electronics, these problems of optimization are solved frequently by obtaining the complete details of all the potential solutions which grow exponentially with the prediction horizon [4].

In contrast to common formulations [5] where the frequency of switching is indirectly controlled via penalization of the input switches over the controller horizon, the dynamics of systems are augmented to estimate the switching frequency directly. Our preparations allow the designer to set the desired switching frequency on a priority basis and the deviations are estimated and penalized. Therefore, the function tuning cost can be achieved effortlessly other than the method

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stated in [6] and [7] where, in spans of tuning parameter and the entire range of frequency with no instinctive is connected to the preferred frequency. To address the long prediction horizon computational issues, the problem of tracking as a regulation is expressed by supplementing the dynamics state and casted in the Approximate Dynamic Programming (ADP) framework [8]. Using the approach in [9] and [10], a Semi Definite Program (SDP) is solved in [11] at offline conditions which approximates the cost of infinite horizon tail. This allows the shortening of the horizon of the controller by applying the estimated tail cost to the last stage and to hold onto good control performance. Figure B1 illustrates [12] the converters for grid connection. Scholars have paid extra attention to high performance drive applications.

This review analyses the MPC use for the four foremost categories of PWM power converter applications that can be found in [13]. They contain inverters with RL output load, grid connected converters, LC filter output inverters and high performance drives. Primary problems of established MPC algorithms are obtained for these applications and novel MPC control challenges of drives and power converters are described.

2. APPLICATION OF MPC IN POWER CONVERTERS AND DRIVES

Applicability of MPC in power converters has intensified due to the development in digital microcontrollers [14, 15]. This technique of control needs a non-negligible sum of calculations during low sampling times when applied to regulating drives and power converters. There are numerous approaches to face the problem of computational burden. In a few cases, it is possible to solve the problem of optimization in offline conditions by programming in multi-parametric state. Thus the execution is decreased to fewer calculations in a look-up-table [16]. The other method is based on using predictive techniques such as Generalized Predictive Control (GPC). An online solution for the optimization problem is provided by the GPC and facilitates long prediction horizons at reasonable costs [17, 18]. In the case of power electronics systems, it should be noticed that GPC does not consider power switching semiconductors. Thus GPC gives an appropriate solution to the approximate optimization problem. For finding an exclusive solution this procedure can be applied. However the result will be an unconstrained problem, but it can measure the reference of inverter output voltage. PWM-SVM is responsible for such a voltage generation. Thus the technique of GPC takes the PWM-SVM knowledge into consideration for optimizing a few power converter system aspects [19].

At last, the power converter's discrete nature can be considered for the strategies used in MPC control implementation. In this way, finding the solution to the problem of optimization can be withheld to assess the system behaviour prediction of the cost function only for the power converter. As evaluated, this technique is called Finite Control Set - MPC (FCS-MPC). Due to the finite number of switching states presented, this method has been extensively implemented in power converters.

3. TECHNIQUES OF POWER ELECTRONICS

Based on the dissimilarities in drive electronics and power sources, the actuation methodologies discussed earlier are categorized into two classes viz the shape and thermal memory actuators. The basic requirement is that they operate under current mode, thereby necessitating high current and low voltage. Piezoelectric, electrostatic and actuators of dielectric elastomers on the contrary operates in voltage mode, which needs high voltage and low current.

3.1. Current mode actuator

Electro-thermal cantilever micro actuator finds their use generally in electronic devices such as MAVs, projectors, scanners etc. As per details given in [20], an inverted-connected metal line based CMOS thermal actuator designed on a bimorph platform was considered for the study. The driving voltage was found to be in the range of 0-3V for a thermal actuator. At this range the test structure attains a vertical displacement of 48μm at 3Vdc. The calculated power remains at 139mW. [21] explains an electro-thermal cantilever micro actuator associated with a high vertical motion at low voltage. With an applied voltage of 0.5V, the electro-thermal actuator holds a quality cantilever and generates big perpendicular deflection and creates a 42.9μm vertical displacement.

Finally, it is designed, fabricated and characterized into thermal micro tweezers actuator with three various driving configurations as in [22]. This explains the displacement at the simulated tip of the micro tweezers at an applied range of 0V~1.2V. Inspite of all these factors, there are fluctuations in driving voltage, in the 0V to 3V range. A way for converting the battery voltage to the predictable value is to implement an n-stage cascaded conventional converter connected with an active switch. One of the significant advantages of these converters is its high gain. A disadvantage is that the total efficiency may be negligible for the increased number of stages, as switching loss affects the power losses. The process requires an active switch and 2n-1 passive switches. These type of converter classes are applicable only when the number of stages required are less. Otherwise the efficiency will get worsened. Figure B2 shows the topology of an n-stage cascade buck converter [23].

Figure B3 shows the possible topology named as selected inductor buck converter which is given in [23]. From the mentioned figure, output voltage to drive thermal actuator is achieved by changing the input voltage of lithium polymer batteries.

4. NETWORK CONNECTED CONVERTERS IN MODEL-BASED PREDICTIVE CONTROL

Numerous applications use network connected converters as one of their important components. This application contains Active Front End (AFE) for high performance drives, rectifiers, network incorporation of renewable energies like wind, energy storage systems and FACTS devices [24, 25].

4.1. Principle of Finite Control System – Model Predictive Control (FCS-MPC)

Figure B4 shows the FCS-MPC control block diagram. Here a generic converter is made to provide the load. The converter grants J diverse switching states. The objective states that variable x should follow the reference -x. As analysed in [12] it will be comfortable to do the prediction in two time steps. For mitigating the delay effects the implementation of FCS-MPC in the digital platform is introduced.

Another way to accomplish the predictive controller for AFE is the P-DPC. Figure B5 presents the block diagram of the P-DPC strategy for AFE.

The algorithm of P-DPC uses an external modulator in relation with FCS-MPC resulting in the achievement of constant switching frequency. This can be an added advantage, more particularly in the application of AFE. The connected converter grids include high demanding codes which enforce stringent limits on the low order harmonics where the injection of grids takes place. [26] FCS-MPC grants a variable switching frequency. Thus a widespread harmonic spectrum is given by the current network. PDPC provides a constant switching frequency thereby focussing on the current network harmonic spectrum around the switching frequency. A decrease in the cost of output L filter is noticed. The experimental results obtained by the usage of the P-DPC strategy for a STATCOM application, are shown in figure B5.

It should be noted that the outer control loop which is used to control the dc-link capacitor voltage is resolved using a conventional PI controller. However, the PI controller can be substituted in MPC by suitable methods.

5. CONTROL STRATEGY

A dual-stage methodology is used for converter control. Rather than finding the solution using a hybrid method, a two-step method is used. At first the MPC continuous problem is solved, by measuring the continuous voltage values provided by the converters. Next the PWM modulation is carried out. The use of this modulation is to assign different values (ON/OFF) of the switches to the LC filter. These switches are responsible for producing the required input voltage. The control strategy needed for the first step makes use of the system constraints and tries to represent the fall as a quadratic function that penalizes both the error of voltage tracking and the attempt of control. This is completed using the typical MPC cost function as shown in equation (5.1).

$$J = \sum_{j=1}^{N} (\hat{y}(t+j|t) - w(t+j))^2 + \sum_{j=1}^{N_U} (\lambda(j)(\Delta u(t+j-1))^2) \quad (5.1)$$

where $\hat{y}$= predicted output

w= references to be tracked

u= control action and

λ= factor for control weighting

[14] derived an explicit solution for the dynamic optimization problem. An MPC

formulation for the input-output processes has been done. Hence, a separate input-output system model as described in the previous sections has been found. Even though in this case, constraints are not taken into consideration, this approach is also applicable for the constraints case too. Restrictions apply to amplitude of the controlled voltage, slew-rate, switching frequency, THD, inverter output current and other performance factors [27, 28]. The addition of obliges represents the on-line solution of a problem for Quadratic Program (QP). For short control horizons the solution can be obtained on-line for long prediction horizons [29].

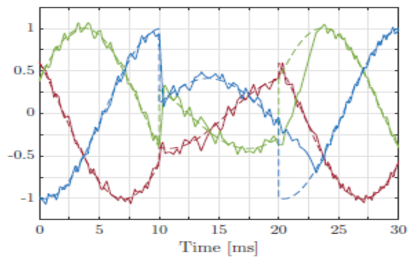
6. STRUCTURE FOR EVALUATION OF PERFORMANCE

The simulations run on a model of a neutral point clamped voltage inverter source associated with a medium-voltage induction machine and a constant mechanical load. As an example for characteristic medium-voltage induction machine, the same model as in [30] uses 3.3kW and 60Hz, squirrel-cage induction machine valued at 3MVA with 0.35pu total leakage inductance. On the inverter side, it is assumed that the voltage of dc-link V_{dc} = 5.2 kV is constant. The base quantities of the per unit (pu) system are the following: V_B = $\sqrt{2/3}V_{rat}$ =2694V, $I_B = \sqrt{2}\, I_{rat}$ = 503.5A and f_B = f_{rat} = 50 Hz. Quantities V_{rat}, I_{rat} and f_{rat} denote the rated voltage, current and frequency respectively. Table A1 shows all the parameters. Frequency ranges between 200 and 350 Hz are of specific importance for medium-voltage inverters [30]. For the current model, the state of the art methods reach THDs between 7 and 4%.

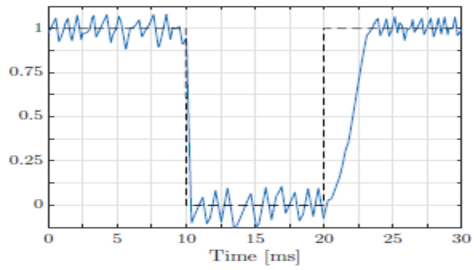
Using an idealized model, the semiconductors are switched instantaneously and the simulations are functioned to run in MATLAB. This is inspired by the fact that, previous simulations [31] are almost similar to the experimental results in [32]. As such, effects of second-order factors like dead times, controller delays, measurement noise, observer error, magnetic material saturation of device and variations of the parameters should be ignored, without losing the result values. Further, all simulations were completed at rated torque, nominal speed, fundamental frequency of 50 Hz and valued current. The infinite horizon estimation SDP [33] is formulated in MATLAB using YALMIP [34] and solved offline using MOSEK [35].

6.1. Transient response performance

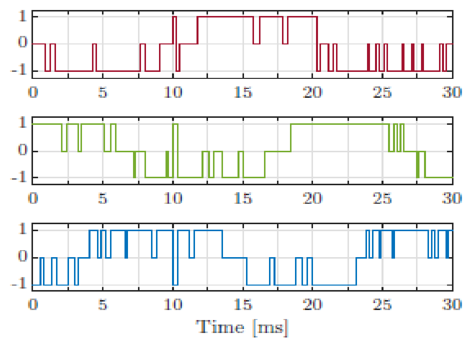
The response of rapid transient is one of the main advantages of direct MPC. It is simulated by the system with the parameters of similar tuning as in the benchmarks for steady state. At nominal speed, the steps for reference torque are imposed, which is seen in figure 1 [36]. As shown in figure 1, these steps are translated into dissimilar references of current to track, while the schematic shows the calculated inputs. As shown in figure 1, [36] it is explained that, during the second switching at 20 ms, the final two phase inputs fill to values +1 and -1 respectively for the transient values providing the maximum existing voltage that could steer the current to the particular direction.



(a) Three-phase stator current with their dashed lines.



(b) Solid line and dashed line torque.



(c) Inputs for three-phase switching position. Adapted from [36]

Figure 1.Steps for the direct model predictive controller produced by the reference torque with horizon N = 1

This review also simulates the transient responses for horizon N = 10 obtaining almost identical settling times. This is because the advantage of longer prediction obtained by extending the horizon or accepting costs of powerful final stage is reduced by the input saturation during the transients. As a final point, the review of the proposed approach presents far greater performance than offline approaches for computations of open-loop switch sequence like Optimized Pulse Patterns (OPPs). Even though these methods are especially suited for operation of steady state, they perform poorly in terms of robustness and settling time for torque transients. In the past, OPPs had been combined with a modulator driven by a very slow control loop to overcome this problem [37]. Some current contributions on OPPs [38–40] are managed to decrease the settling times, even if it is not matched with the direct current MPC performance.

7. MPC CHALLENGES

One of the significant challenges, the MPC faces is that they always require an accurate system model. The realization of such a model is not a simple task in highly dynamic systems. However, in the recent years, complex electrical system modelling has been seriously improved resulting in addressing these challenges properly. Extensive research is being carried out in recognising the applicability of MPC applications to power converters. In these applications modified state observers are used to evade the system parameter uncertainties [41-43].

If the prediction horizon is longer than 1 the computational load grows exponentially resulting in a drawback of the MPC strategy. In the FCS-MPC case, the number of studied switching states (J) is high. If it was in the past this detail would have been crucial. But now, high-speed processors can carry out these calculations and the methods of FCS-MPC can be carried out with sampling times in the range of multiple micro seconds [44]. Even in current scearios, finding algorithms for effective computational control is an open issue. Generally, the technique of FCS-MPC evades using a modulation stage, which is considered as an advantage. Though, this usually leads to spread output waveforms harmonic spectra, this can be resolved taking into account the function of cost [45] or by using a stage for carrying out the modulation process and applying the FCS-MPC by taking into account all the possible combinations of the converter switching states [46].

Another concern for MPC is the efficient cost function design and the weighting factors tuning. It can be assured that a best tuning method for designing the cost function with the weighting factors is still missing. However, some works have been described in the first method for solving the problem facilitating the work of electrical engineers design [47, 48]. Lastly, it should be observed that there is lack of tools for analytical models to estimate MPC performance for drives and power converters without performing widespread simulations or experiments. Hence, it is predictable that future research would be more oriented towards tools development.

8. CONCULSION

In industries, Model Predictive Control (MPC) appeared as a nominal means to deal with multivariable forced control problems. It is a well-known approach to attain an operation resulting in high performance in a wide range of applications. It is established that predictive control is a very flexible and powerful concept of designing controllers. Since decades it has been successfully applied to chemical processes with little requirements of sampling. Complex challenges such as the model accuracy, high rates of sampling and high cost in computations have been overcome due to incessant microprocessors technology evolution. The final modifications of MPC are presently being carried out at various research laboratories and this control method has been attracted to different companies. Hopefully just one step in advance, the MPC will be widely applied to control intricate electrical systems. It put forwards multiple advantages that make it apt for use in power converters and drives control. The use of all existing evidences in the system to choose the optimal actuation, results in achievement of very fast dynamics by the inclusion of the system nonlinearities and restrictions and avoiding the cascaded structure. It also has a potential to take advantage of the distinct nature of the power converters and selection capability from the potential states for switching the optimal solution according to the predefined cost function minimization.

Model Predictive Control (MPC) has been useful for a very wide systems range and it is open for novel applications and topologies for converters. However, the best suited MPC type will depend on the system application and necessities. Model predictive control strategies will continue their key strategic roles in the evolution of new high-performance power electronics and drive systems and will offer novel and interesting viewpoints for the forthcoming research in the concerned fields.

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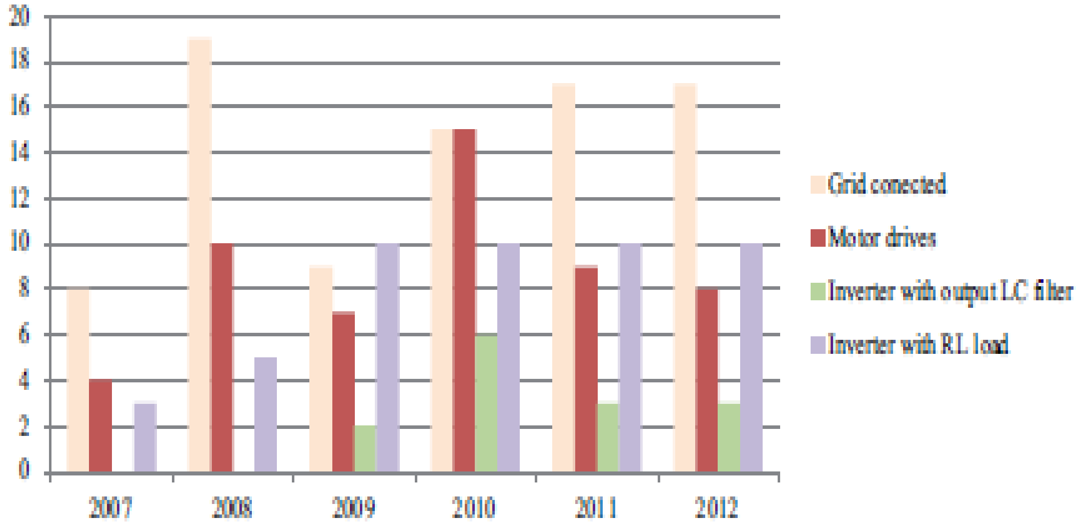
APPENDIX A

Adapted from [36]

Table A1.Rated values and drive parameters

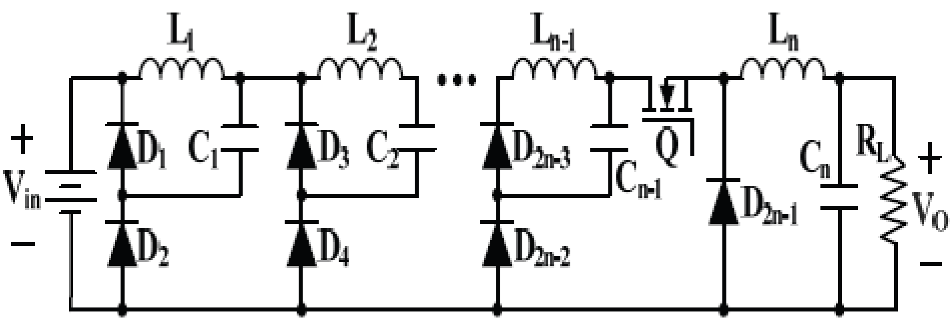
Inductor Motor				Inverter	
Voltage	3300 V	r_s	0.0108 pu	V_{dc}	1.930 pu
Current	356 A	r_r	0.0091 pu	x_c	11.769 pu
Real power	1.587MW	x_{l_s}	0.1493 pu		
Apparent	2.035MWA	x_{l_r}	0.1104 pu		
Frequency	50 Hz	x_{l_m}	2.3489 pu		
Rotational speed	596 rpm				

APPENDIX B



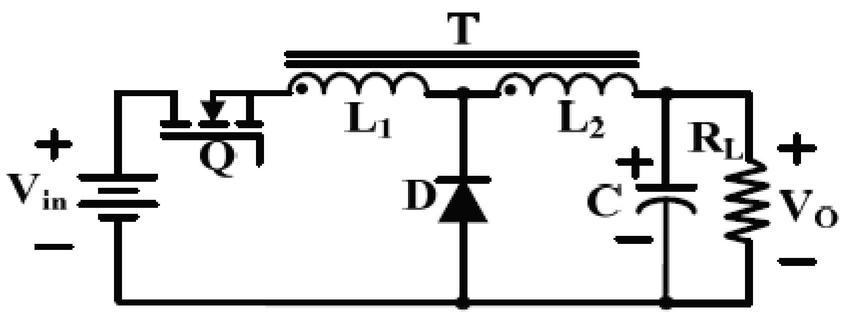
Adapted from [12]

Figure B1. MPC for PWM power converters



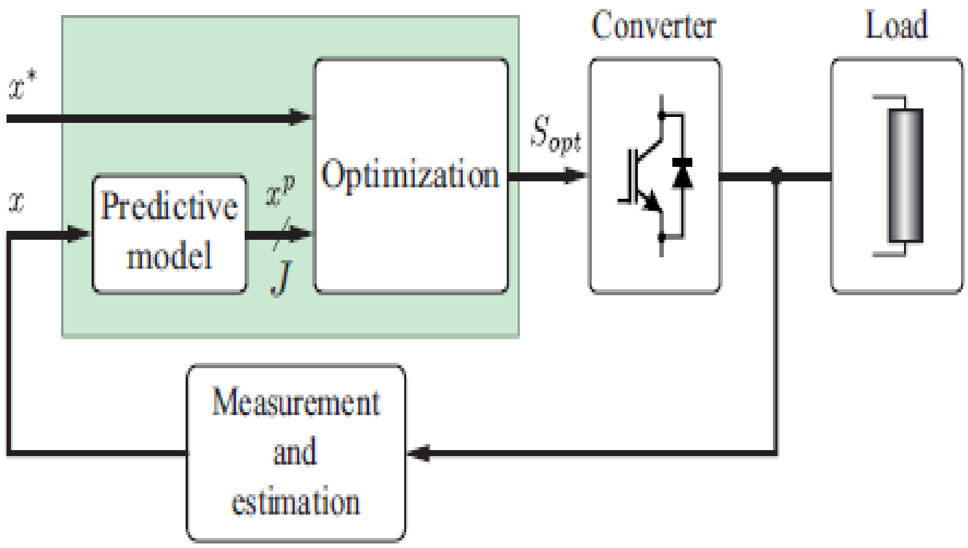
Adapted from [23]

Figure B2.N-stage cascaded buck converter



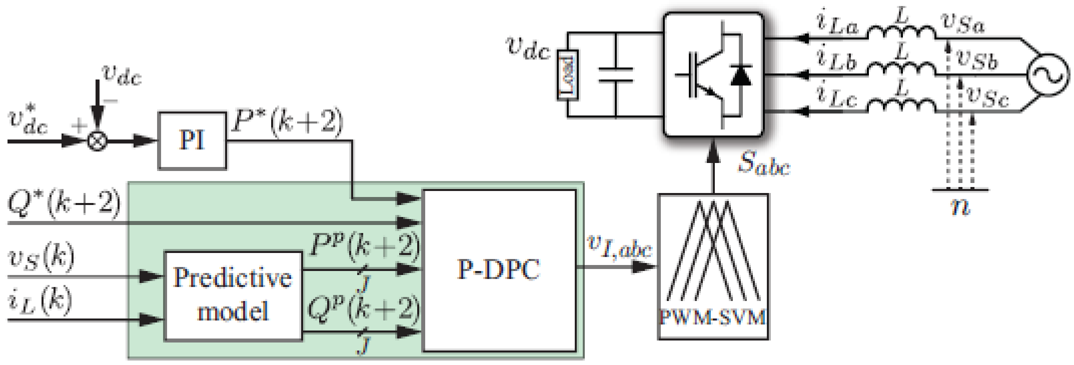
Adapted from [23]

Figure B3.Tapped inductor buck converter



Adapted from [12]

Figure B4.Block diagram of FCS-MPC



Adapted from [12]

Figure B5.P-DPC control strategy block diagram for AFE