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Review

Predictive Control Applied to Matrix Converters: A Systematic Literature Review

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Abstract: Power electronic devices play an important role in energy conversion. Among the options, matrix converters, in combination with predictive control, represent a good alternative for the power conversion stage. Although several reviews have been undertaken on this topic, they have been conducted in a non-systematic manner, without indicating how the studies considered were chosen. This paper presents results from a systematic literature review on predictive control applied to matrix converters that included 142 primary papers, which were selected after applying a defined protocol with clear inclusion and exclusion criteria. The study provides a detailed classification of predictive control methods and strategies applied to different matrix converter topologies. Research findings require to be understood in combination to develop a common understanding of the topic and ensure that future research effort is based on solid premises. In light of this, this study identifies and characterizes different predictive control techniques and matrix converter topologies through systematic literature review. The results of the review indicate that interest in the area is increasing. A number of open questions in the field are discussed.

Keywords: control strategies; matrix converters; predictive control strategies; review protocol; systematic literature review; types of matrix converters

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1. Introduction

Worldwide energy consumption has been increasing steadily year by year. Even with a slight drop due to the global COVID-19 pandemic, predictions suggest that sustained growth in global consumption will continue into early 2023 [1]. In addition, the harmful effects on the environment of fossil fuels mean it is necessary to develop new generation systems to replace harmful energy sources. In this context, renewable energy sources (RES) have emerged as a good alternative. An important aspect of RES applications is the conversion of the power generated by such sources to another form suitable for normal use [2]. Power converters constitute an intermediate stage between the energy source and the end-users or load (e.g., consumers in residential or industrial spaces). Among the options for power converter topologies, matrix converters (MCs) have attracted particular attention because of several advantages, including reduced size, high efficiency and significant improvement in overall system reliability by elimination of failure-prone dc-link electrolytic capacitors [3]. Similarly, model predictive control represents a good alternative for the control of power electronic devices, with the advantages that it is easy and simple to implement, can be applied to a great variety of systems, offers simple treatment of constraints, and can deal with multi-variable systems and non-linearities [4]. Because of the growing interest in these research areas—the application of matrix converters as a power conversion stage, and the use of predictive control strategies to control them—there have been several surveys published that have evaluated the state-of-the-art and provided criteria to guide the design of new predictive control alternatives applied to matrix converters and their topological variants [5–7].

However, none of these reports has presented a systematic methodology for the selection of studies to be considered or the criteria by which they were selected. In this paper a systematic literature review (SLR) is reported that utilized a novel protocol for selecting the studies to be considered, avoiding biases and specifying the criteria for inclusion and exclusion of studies to address the research questions posed. The main aim of this paper is to present the state of the art regarding predictive control applied to matrix converters to produce reliable data that can provide a basis for new research topics.

The remainder of the paper is structured as follows: Section 2 presents the necessary background for understanding the basic problems. Section 3 explains the methodology for conducting the literature review. In Section 4, research findings on predictive control techniques applied to matrix converters are briefly described. Section 5 presents the matrix converter topologies identified in this review process. In Section 6, new trends in predictive control techniques are summarised that enable the identification of potential new research topics. Finally, the conclusions are presented.

2. Background

Owing to the well-known impact of the use of fossil fuels on the environment, global interest in relation to power generation systems has turned towards renewable energy sources (RES) and distributed generation systems (DG). Energy production from renewable sources is expected to increase due to the low operating costs and preferential access to many energy systems [8]. Moreover, the use of electrical energy, for example, in automotive and aerospace applications, has increased to reduce pollution [9,10]. Power electronics represent an essential part of the system by controlling the generated power in a suitable form for use for a specific application. Traditionally, the most used topology for ac-ac conversion has been the back-to-back (BTB) converter. However, this converter has the disadvantage that it requires a bulky and expensive dc link stage, making it unsuitable for applications where small size is required, such as for automotive and aircraft applications [11]. The MC has emerged as a good alternative, since it does not require a dc stage for ac-ac conversion and, hence, utilizes smaller power converters [12]. Amongst control strategies described in the literature, model-based predictive control (MPC) is a non-linear control strategy that has been successfully implemented to control several types of power electronic system.

Key goals of using MPC with MC can include: (i) creation of a simple control technique that significantly reduces the complexity of existing MC methods, (ii) taking into account of various control objectives (such as output, input reactive power minimization, source current control, etc.) and constraints when controlling the MCs, (iii) achieving high controller bandwidth and shorter control cycle times, and (iv) achieving fast and accurate performance in both transient and stable states. To contribute to some of these areas, it is necessary to know the state of the art to identify niches. Although it is possible to find reviews related to the subject, such as [5–7], these have been carried out in an unsystematic way and have not followed a reproducible methodology for evaluating the quality of the articles or otherwise followed specific defined rules. To avoid possible biases or trends, this review has been approached in a structured way. To ensure an objective approach, an SLR protocol was used, which is described in the following section.

3. The Systematic Literature Review Method

A specialised study process devised to compile and assess the information that is relevant to a certain topic is referred to as a systematic literature review (SLR) [13,14]. An SLR is constructed, as the term indicates, in a formal and methodical manner, in contrast to the typical process of literature review, which is pursued unsystematically at the outset of a particular research project. A systematic approach to the research review process implies following an artificially generated protocol that is clearly defined and which follows a fixed sequence of methodological steps. The approach is built around a fundamental topic that serves as the focus of the research and is expressed using particular concepts and terminology that must be employed to gather data for a specific, predefined, focused, and structured question. In order that other professionals can follow the same protocol and assess the suitability of the standards selected for the case, the methodological processes, evidence-retrieval techniques, and the question's focus are all clearly specified [15]. The SLR procedure used is summarised [16] in Figure 1.

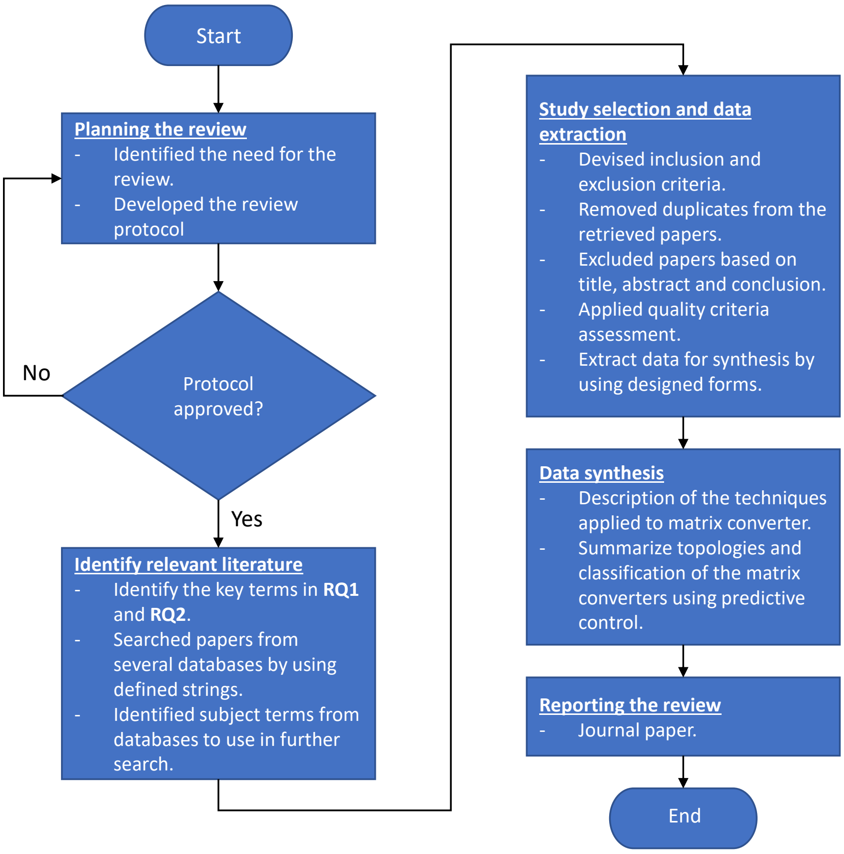

Figure 1. Systematic literature review procedure flowchart.

3.1. Scope of the Review

To develop an SLR, one of the first steps is to state the research question. Here, the aim was to collect information regarding predictive control techniques that have been applied to matrix converters to identify the possibilities of applying new techniques that may be used in other converters but which have not yet been tested in matrix converters, in general, or in any topology in particular. For this reason, it is necessary to know which techniques have been implemented and for which matrix converter topology. To obtain this information, the following research questions were posed:

- **RQ1:** *Which variants of model-based predictive control are used with matrix converters?*
- **RQ2:** *What matrix converter topologies handle predictive control?*

To address these questions, a protocol for conducting the SLR was developed. The following section describes how the primary studies were selected.

3.2. Search for Primary Studies

First, the keywords for search to identify studies pertinent to the research questions need to be defined. In this particular case, and based on the proposed questions, the keywords were:

- Matrix converter.
- Predictive control.

Then, it is necessary to look for all possible synonyms of the mentioned words. A summary of synonyms is shown in Table 1. To search primary studies, search strings were generated using the steps described in Algorithm 1 based on the keywords shown in Table 1.

Table 1. Keywords and their synonyms.

	string1	**string2**
1	Matrix Converter	Predictive Control
2	Cycloconverter	MPC
3	Direct ac	

To locate studies published in established conference proceedings and journals, a search was carried out using editorial and academic databases. In the case of journals, it was necessary to narrow down the search. Therefore, it was proposed to use quartile scores. In this case, the Scientific Journal Ranking (SJR) developed by *Scimago Lab* that provides yearly rankings of social science and science journals in the applicable subject areas for the publication (there may be more than one) was used. Based on the quartile of the impact factor (IF) distribution each journal fell into for each of its subject categories, quartile rankings were determined. The top 25 percent of the IF distribution was represented by Q1, the middle-high position by Q2 (between the top 50 percent and the top 25 percent), the middle-low position by Q3 (between the top 75 percent and the top 50 percent), and the bottom 25 percent by Q4. Here, the primary areas of interest were the Q1 and Q2 categories. The following databases were considered when looking for primary studies:

- IEEE Xplore (http://ieeexplore.ieee.org/), accessed on 13 July 2020,
- SCOPUS (https://www.scopus.com/), accessed on 13 July 2020,
- IET Digital Library (http://digital-library.theiet.org/), accessed on 13 July 2020, and
- Web of Knowledge (http://www.webofknowledge.com), accessed on 13 July 2020.

A search was also carried out in the databases of the following editorials:

- Science Direct (http://www.sciencedirect.com/), accessed on 13 July 2020,
- Wiley InterScience (http://onlinelibrary.wiley.com/), accessed on 13 July 2020, and
- Springer link (http://link.springer.com/), accessed on 13 July 2020.

Each of the strings generated by Algorithm 1 was used in the above databases to identify primary studies. The search process yielded 2858 results from all the databases. Once all the results were stored, the next step consisted of selecting the most suitable studies for answering the research questions.

Algorithm 1: Search strings generation

```
input  : An array of keywords
output : A sequence of search strings
k ← 1;
for i ← 1 to 3 do
    for j ← 1 to 2 do
        sentence_k = string1_i AND string2_j;
        k ← k + 1;
    end
end
```

3.3. Study Selection and Data Extraction

In this section, the selection criteria used are defined, based on experience. The following inclusion and exclusion criteria were defined:

3.3.1. Inclusion Criteria

- **IC1:** The study is published in Q1/Q2 Journals or in peer-reviewed conference proceedings.
- **IC2:** The study is written in English.

3.3.2. Exclusion Criteria

- **EC1:** Duplicate studies found in different databases are excluded (i.e., just one is considered).
- **EC2:** Only primary studies are considered; if the study is a review, it is excluded.
- **EC3:** The title explicitly mentions that the topic is not related to matrix converter or predictive control.
- **EC4:** The study's lack of consideration of predictive control in a matrix converter is made clear in the abstract.
- **EC5:** If there are different iterations of the same study, the less thorough are disregarded.
- **EC6:** Full text read reveals the study does not refer to predictive control applied to a matrix converter.

After applying the inclusion and exclusion criteria, 417 primary studies remained for the next step of the procedure.

3.3.3. Quality Assessment

To quantify the quality of the paper (**QA**), these points were evaluated:

a. How the results are presented:
    - Experimental results (0.6 pts).
    - Simulation results (0.4 pts).
    - Not presented (0 pts).
b. Clarity in the topology. For a good level of clarity, the article should describe:
    - Power circuit (0.5 pts).
    - Knowledge of the valid states (0.2 pts)
    - Relationship between input and output (0.3 pts)

   A totally clear topology will be assigned 1 pt.
c. Accuracy in predictive control description. For complete clarity of predictive control application, the study must include:
    - Control scheme (0.2 pts).
    - Prediction model (0.5 pts).
    - Cost function (0.3 pts).

Using the weighted system presented above, all studies were assessed in such a way that the higher the score for a study, the greater its contribution to answering the research questions. The selection thresholds were set to **QA** $>$ 2.1 out 3. Finally, 142 primary studies which were highly related to the defined research questions were considered.

3.3.4. Data Extraction

The selected studies were analysed by filling in a corresponding form. The following data was entered for each primary study: ID, title, author, year of publication, publication type (journal/conference), topology, application, technique, cost function and sampling time. This form was used to condense all the information from the selected studies. Once all the forms were filled, the data synthesis process was initiated.

3.4. Synthesis of the Extracted Data

The data synthesis consisted of summarising the extracted data in an effective and understandable format. The data extraction forms were used for data extraction so that data analysis could be performed. The next section describes the most important information extracted in the present review, which focused on the predictive control techniques used for matrix converter topologies and to which topologies predictive control was applied. In the last section, the topics of research interest and identified trends are presented.

4. Model Predictive Control Applied to Matrix Converters

This section primarily addresses **RQ1** by offering an overview of predictive control methods utilized with MCs. Although both predictive control and matrix converters appeared in the literature around the 1980's, the first study identified in this review was published in 1997 [17]. Figure 2 shows the studies per year. It is noticeable that, after 1997, MPC applied to MC did not appear until 2007, since when its popularity has been increasing, reaching a peak in 2017, with a significant number of publications on the topic subsequently up to July 2020.

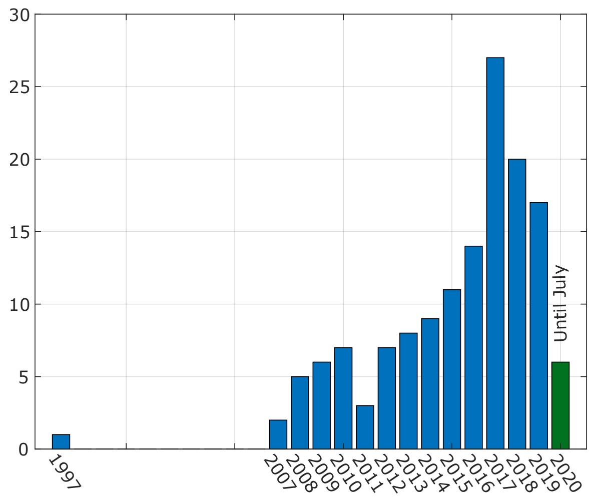

Figure 2. Number of studies published per year on the topic.

There has been increased interest by researchers, aided by growth in the computational capability of new-generation microprocessors, making the implementation of this control technique more feasible every day. In the following section, the predictive control techniques that have been applied to matrix converters for different applications to accomplish a wide number of control outcomes are briefly described to illustrate the scope of the techniques for this power converter topology.

4.1. Basic Principles of MPC

The MPC control strategy is based on the following principles:

- The system's discretized model is used to predict how the variables of interest will behave in the future up to a given horizon. The system's discretized state-space equations, for instance, could be used as follows:

$$\mathbf{x}(k+1) = \mathbf{\Phi}\mathbf{x}(k) + \mathbf{\Gamma}\mathbf{u}(k) \tag{1}$$

$$\mathbf{y}(k) = \mathbf{H}\mathbf{x}(k) + \mathbf{J}\mathbf{u}(k) \tag{2}$$

  where $\mathbf{x}$, $\mathbf{u}$, and $\mathbf{y}$ stand for the state variables, inputs, and outputs, respectively.
- The intended control performance is then used to define a cost function, g. The reference and predicted values of the control variables are included in this cost function, together with the actuation.

$$g = f(\mathbf{x}(k), \mathbf{u}(k), \ldots, \mathbf{u}(k+N)) \tag{3}$$

- Finally, optimal actuation is obtained to solve the optimisation problem; the result that minimises g is applied by the controller.

With respect to the MC as a conversion stage, numerous control techniques have been proposed. Predictive current control with several variations to improve particular characteristics stands out. The different techniques are shown in Figure 3. There are six main techniques based on the variable to be controlled with the technique, and then secondary targets of the control strategy. For instance, in a conversion system, the main goal is to control the output current, but it is also feasible to add other variables to control, such as reactive power or switching losses, leading to predictive current control with minimal reactive power and reduced switching losses. In the following section, the control strategies identified are described.

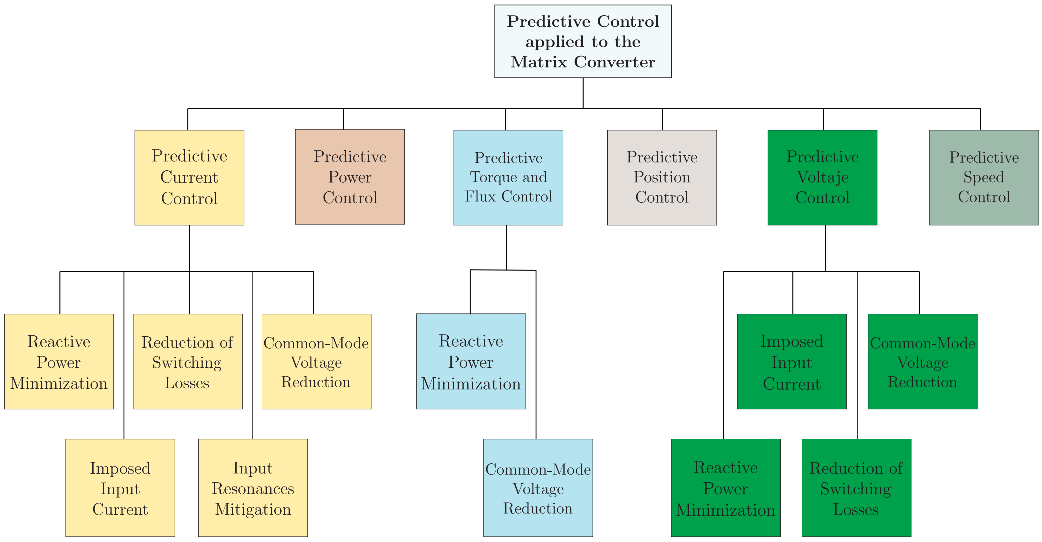

Figure 3. Predictive control techniques applied to matrix converters.

4.2. Predictive Current Control

Predictive current control (PCC) is the technique most applied to the matrix converter. Figure 4 shows the basic stages in the implementation of the technique. They include the use of the model of the load, grid or machine to determine the future current for every valid state and selection of the one that best fits the desired current for that part of the system [17–46]. A particular example of implementation of this technique for a three-phase direct matrix converter feeding an RL load, as shown in Figure 5, is detailed below.

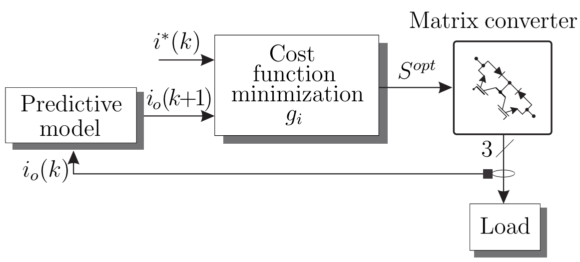

Figure 4. Predictive current control block diagram.

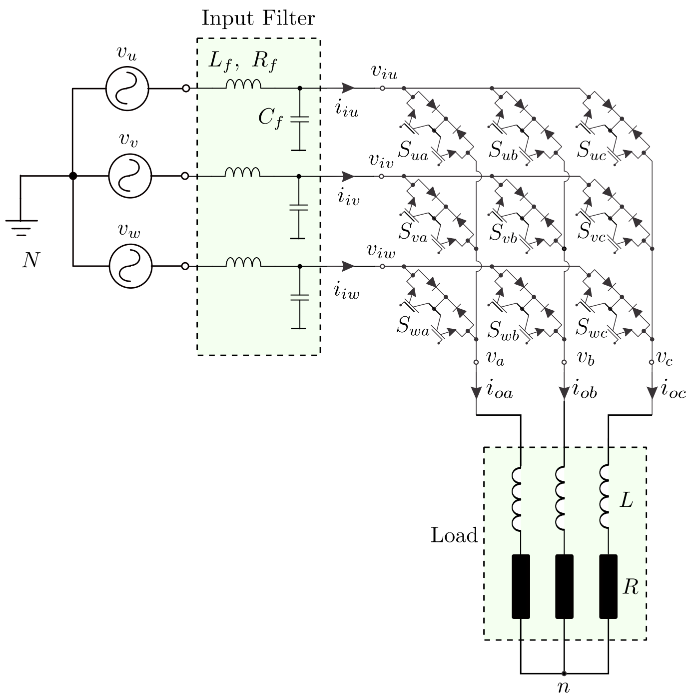

Figure 5. Three-phase direct matrix converter feeding an *RL* load.

As was described in Section 4.1, the first step is to obtain a discrete model of the system. In this case, a model that relates the input of the converter to its output is required at the outset. As can be seen in Figure 5, the three-phase input is directly connected to a three-phase load via a set of bidirectional switches. The relationship between input and output voltages is given by:

$$\mathbf{v}_o = \mathbf{S}\,\mathbf{v}_i \tag{4}$$

being

$$\mathbf{v}_o = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}, \quad \mathbf{v}_i = \begin{bmatrix} v_{iu} \\ v_{iv} \\ v_{iw} \end{bmatrix} \quad \text{and} \quad \mathbf{S} = \begin{bmatrix} S_{ua} & S_{va} & S_{wa} \\ S_{ub} & S_{vb} & S_{wb} \\ S_{uc} & S_{vc} & S_{wc} \end{bmatrix}$$

The relationship between the input and output currents is, in turn, given by:

$$\mathbf{i}_i = \mathbf{S}^T\,\mathbf{i}_o. \tag{5}$$

where

$$\mathbf{i}_i = \begin{bmatrix} i_{iu} \\ i_{iv} \\ i_{iw} \end{bmatrix} \quad \text{and} \quad \mathbf{i}_o = \begin{bmatrix} i_{oa} \\ i_{ob} \\ i_{oc} \end{bmatrix}$$

S being the transfer matrix ; the S_{xy} element has a binary value, corresponding to the state of the single switch. To avoid short circuits and over-voltages, there are only 27 valid states for **S**. This condition can be written as:

$$S_{ui} + S_{vi} + S_{wi} = 1, \quad \forall i \in \{a, b, c\}. \tag{6}$$

Once a model of the converter is defined, a prediction model for the load can be defined. A discretization method must be used to obtain a discrete time model. Given that first-order systems are straightforward, it is useful to approximate the derivatives using the Euler forward approach, which involves:

$$\frac{dx}{dt} = \frac{x(k+1) - x(k)}{T_s} \tag{7}$$

where T_s represents the sampling period. Since this method introduces a considerable amount of inaccuracy for higher-order systems, the discrete time models derived using Euler are not as good when the system's order is higher. It is necessary to utilize the exact discretization for higher-order systems.

Thus, considering the RL load, the continuous model of the system can be given by:

$$\frac{d\mathbf{i}_o}{dt} = -\frac{R}{L}\mathbf{i}_o + \frac{1}{L}(\mathbf{v}_o - \mathbf{v}_{nN}), \tag{8}$$

where v_{nN} is the approximated voltage between the load common neutral point and the source neutral point determined using the following equation:

$$v_{nN} = \frac{1}{3}(v_{aN} + v_{bN} + v_{cN}). \tag{9}$$

and applying Equation (7), the discrete model of the system is:

$$\mathbf{i}_o(k+1) = \left(1 - \frac{RT_s}{L}\right)\mathbf{i}_o(k) + \frac{T_s}{L}(\mathbf{v}_o(k) - \mathbf{v}_{nN}(k)), \tag{10}$$

The cost function g is derived in terms of a comparison between the desired current $\mathbf{i}^*(k+1)$ and the predicted output current of the converter $\mathbf{i}_o(k+1)$ in the α-β or d-q frame:

$$g_i = |i^*(k+1) - i_o(k+1)| \tag{11}$$

Finally, in every sampling period, the cost function has to be evaluated for every valid switching state of the converter; that which minimizes g_i is selected and applied in the next sampling period.

An example is shown as Algorithm 2.

Algorithm 2: Predictive current control in DMC

1. Initialize $g_i^{opt} := \infty$,
2. Measure $\mathbf{v}_i$, $\mathbf{i}_o$,
3. **From** j = 1 **to** 27
4. Calculate $\mathbf{v}_o$ using $\mathbf{S}_j$ (Equation (4))
5. Calculate the predicted current $\mathbf{i}_o^{k+1}$ using Equation (10)
6. Calculate the cost function g_i using Equation (11)
7. **if** $g_i < g^{opt}$ **then**
8. $g^{opt} \leftarrow g_i$, $\mathbf{S}^{opt} \leftarrow \mathbf{S}_j$,
9. **end if**
10. **end for**
11. Apply the optimal state $\mathbf{S}^{opt}$

The main difference between the example and the studies using predictive current control are the topologies used, the application and the conditions of the experiment (e.g., under unbalanced source or fault conditions), but the main idea is always the same. Some variations are shown in subsequent sections.

4.2.1. Predictive Current Control with Reactive Power Minimization

One of the main advantages of MPC is that it allows multi-objective control to develop. This means that it is possible to control several variables at a time. Regarding basic PCC, a major drawback consists of input currents that are highly distorted. As can be seen in Figure 5, the MC is connected to the three-phase source through the input filter, which has two main purposes: (i) to prevent the generation of over-voltages caused by the power supply's short circuit impedance, and (ii) to eliminate the input currents' high frequency harmonics. A model of the input filter is generally used to predict the input currents and to control it using predictive control in a similar form to the load to control the output current.

To attain the unity power factor and enhance the source current response, another term is added to the cost function [47–73]:

$$g_Q = |Q^* - Q| \tag{12}$$

with Q^* representing the desired reactive power (i.e., zero for the unity power factor); the reactive power at the input Q is given by:

$$Q = v_{s\alpha} i_{s\beta} - v_{s\beta} i_{s\alpha} \tag{13}$$

where v_s and i_s are the input voltage and current, respectively. Then the cost function for PCC with reactive power minimization is:

$$g = \lambda_1 g_i + \lambda_2 g_Q \tag{14}$$

where g_i is given by Equation (11) and g_Q by Equation (12). The descriptive blocks of this technique are shown in Figure 6. It is important to note that, when the cost function consists of more than one term, weighting factors are required to establish which term is more significant compared to the others; in this case λ_i and λ_Q are the weighting factors for the current and reactive power, respectively. The selection of these factors is a major challenge and requires fine-tuning to achieve optimal results. This issue is addressed in Section 6.

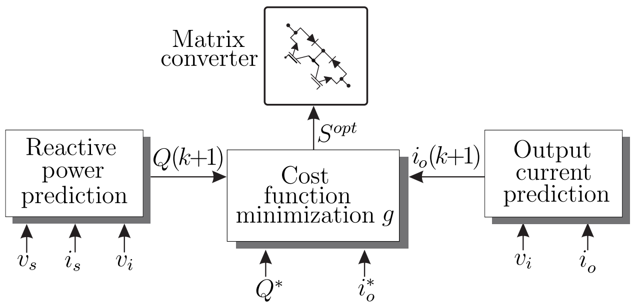

Figure 6. Predictive current control with reactive power minimization block diagram.

4.2.2. Predictive Current Control with Imposed Input Current

In contrast to the previously described technique, the term used in this proposal to force the source currents to follow a sinusoidal reference is replaced by a term that directly controls the source currents, as can be seen in Figure 7, no matter how much distortion there is on the input side [74–84]. The input current references are given by:

$$i_{sA}^* = I_s \sin(\omega_s t + \theta) \tag{15}$$

$$i_{sB}^* = I_s \sin\left(\omega_s t - \tfrac{2\pi}{3} + \theta\right) \tag{16}$$

$$i_{sC}^* = I_s \sin\left(\omega_s t + \tfrac{2\pi}{3} + \theta\right) \tag{17}$$

being $\theta = 0$ for the unity power factor and the amplitude given by:

$$I_s = \frac{V_s k_1 - \sqrt{V_s^2 k_2 + I_o^{*2} k_3}}{k_4} \tag{18}$$

where

$$k_1 = 8\pi^2 f_s^2 L_f C_f - 1, \quad k_2 = k_1^2$$
$$k_3 = 4\eta^{-1} R_L R_f k_1, \quad k_4 = 2R_f k_1$$

L_f, C_f and R_f are the inductance, capacitance and leakage resistance of the input filter. V_s and f_s are the voltage amplitude and the frequency of the source, and η is the efficiency of the converter [85]. Finally the cost function defined for this approach is:

$$g_{im} = |i_{s\alpha}^* - i_{s\alpha}| + |i_{s\beta}^* - i_{s\beta}| \tag{19}$$

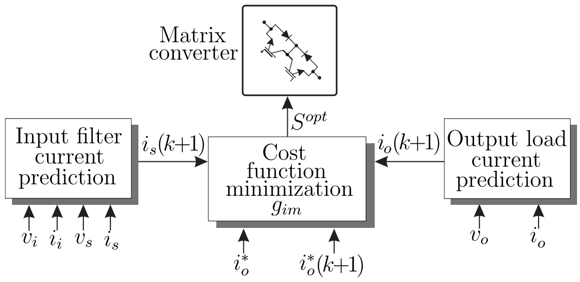

Figure 7. Predictive current control with imposed input current block diagram.

4.2.3. Predictive Current Control with Input Resonances Mitigation

With the use of active damping, the system resonance can be reduced without having an impact on the efficiency converter. The logic behind the method relies on simulating a resistor in parallel with the input filter capacitors to reduce the system harmonics while leaving the fundamental component unaffected [86–89]. The formula for the current through the damping resistor is:

$$\mathbf{i}_d = \frac{\mathbf{v}_c}{R_d} \tag{20}$$

where $\mathbf{i}_d$ is the converter's internal current extraction to simulate the damping resistance and v_c is the input filter capacitor voltage. Figure 8 shows the control diagram for this technique; Figure 9 shows the current reference generation blocks for the control. A detailed explanation of this can be found in [88].

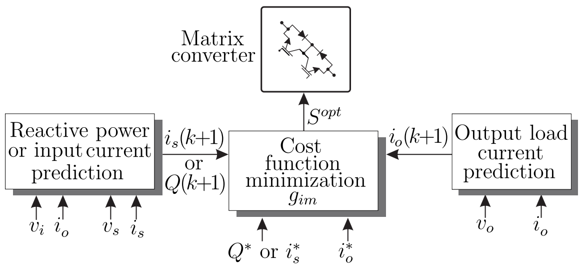

Figure 8. Predictive current control with input resonances mitigation block diagram.

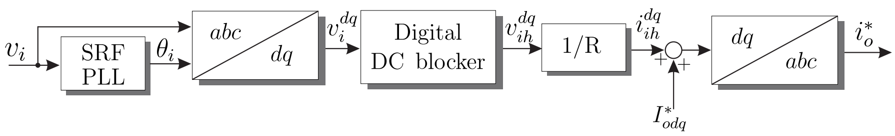

Figure 9. Output current reference generation for active damping approach.

4.2.4. Predictive Current Control with Common-Mode Voltage

Electric motors may sustain damage as a result of shaft voltage, leakage current, and bearing current damage caused by common-mode voltage (CMV), which also lowers the overall reliability of motor drive systems. The primary cause of motor failures is reportedly CMV and its high electrostatic-coupled discharge or displacement [90]. Predictive current control with zero CMV voltage or CMV reduction techniques have been successfully implemented in matrix converters [90–92]. Figure 10 shows a diagram of this strategy.

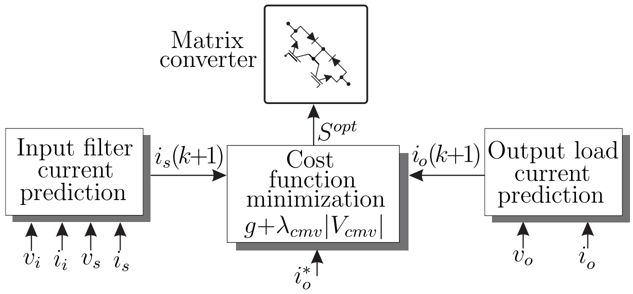

Figure 10. Predictive current control with common-mode voltage block diagram.

4.2.5. Predictive Current Control with Switching Losses Reduction

Switching losses are significant since they rise with switching frequency and the performance of the MPC is enhanced when higher frequencies are taken into account. A basic technique for reducing the switching losses involves decreasing the number of commutations of switches using the following term in the cost function [93]:

$$g_{Sw} = |S(k+1) - S(k)| \tag{21}$$

where $S(k+1)$ is the predicted switching state to be applied and $S(k)$ is the actual switching state. A proposal for calculating the predicted energy losses and to minimize the energy, including the term in the cost function, is presented in [94].

4.3. Predictive Torque and Flux Control

The following studies, among others, have proposed this control method [95–103]. To minimize the cost function, the PTC system requires selection of the best actuation from all feasible MC voltage vectors at each sample time. In this instance, a discrete mathematical model of the motor is used to anticipate the stator flux ψs and the electromagnetic torque T_e for the approaching sampling period. The electromagnetic torque reference value T_e^* is often produced using a proportional-integral control strategy. The cost function for the technique includes the variances between the expected flux and torque values and the reference values:

$$g_{T\Psi} = \lambda_T|T_e^* - T_e^p| + \lambda_\psi|\psi^* - \psi^p| \tag{22}$$

where T_e^* is the reference for the electromagnetic torque and T_e^p is predicted by means of the motor model. ψ^* is the flux reference and ψ^p is the predicted value. Figure 11 shows the scheme for the PTC. PCC, predictive torque and flux control have been applied with other terms to reach more than one control target. They have been used with reactive power minimization [104–115] and CMV reduction [116] schemes.

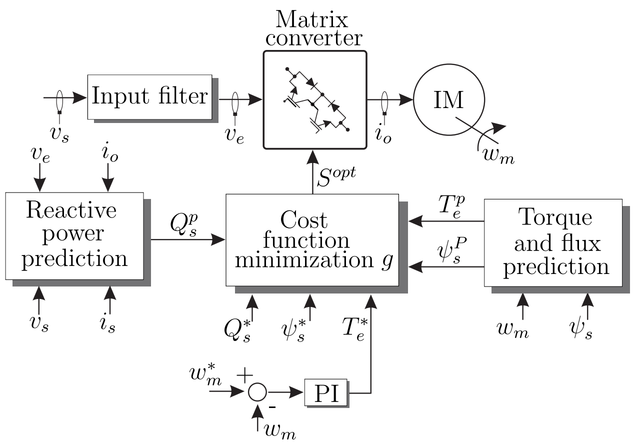

Figure 11. Predictive torque and flux control block diagram.

4.4. Predictive Voltage Control

Numerous papers have reported successfully implemented predictive voltage control, both in its basic form [117,118] and combined with other behaviors to achieve reactive power minimization [119–123], CMV reduction, switching loss reduction [124] and imposed input current control [125,126]. Figure 12 shows an example for the PVC. For this control, the model of the output filter is used to calculate the voltage at the filter capacitor v_o and the cost function is given by:

$$g_v = |v_o^* - v_o^p| \tag{23}$$

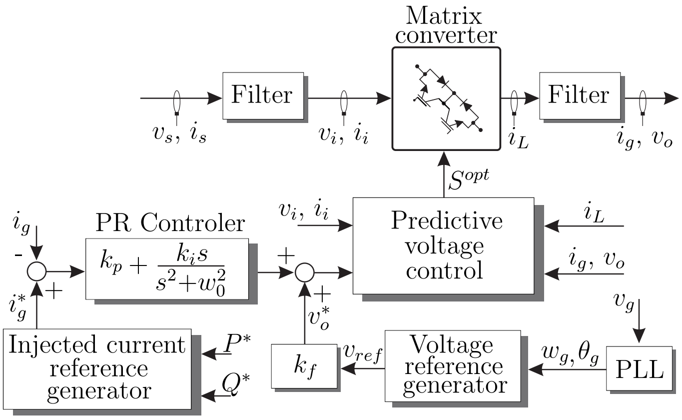

Figure 12. Predictive voltage control block diagram.

4.5. Predictive Power Control

Controlling the active and reactive power output of a generation stage that incorporates a matrix converter is known as predictive power control. It is typically used for grid-connected systems with distributed generation frames. Several references [127–129] deal with the subject. Figure 13 shows the diagram for this technique.

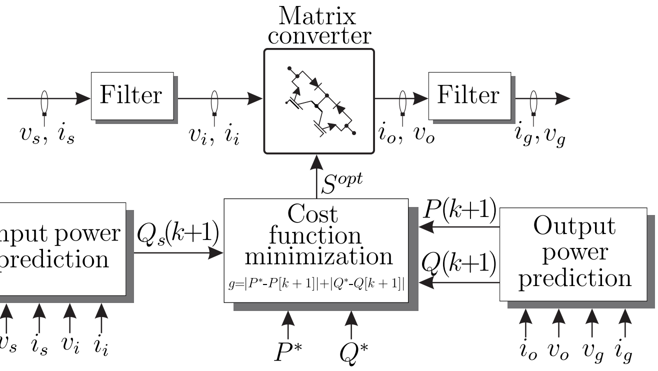

Figure 13. Predictive power control block diagram.

4.6. Predictive Position and Speed Control

These techniques use the model of the system driven by a matrix converter to calculate the future behaviour of the position of the axis [130] or the speed [131] directly without a PID external loop. Figure 14 shows the scheme for the position control.

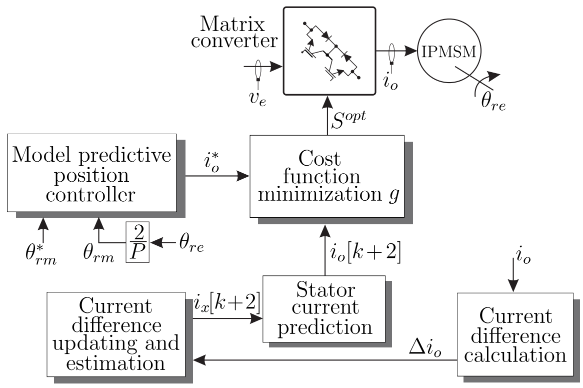

Figure 14. Predictive position and speed control block diagram.

5. Matrix Converter Topologies Using Model Predictive Control

In this section, different topologies of matrix converters which have been identified that apply MPC are listed and briefly described in terms of the power stage. The detailed features can be found in every primary study cited here. Figure 15 shows the MC topology classification. Answering **RQ2**, all the topologies in which predictive control have been applied are shown there. The direct matrix converter (DMC) and the indirect matrix converter (IMC) are the two primary topologies. All the others are derivations of these two main topologies. In the next sections, all the topologies which were identified are described.

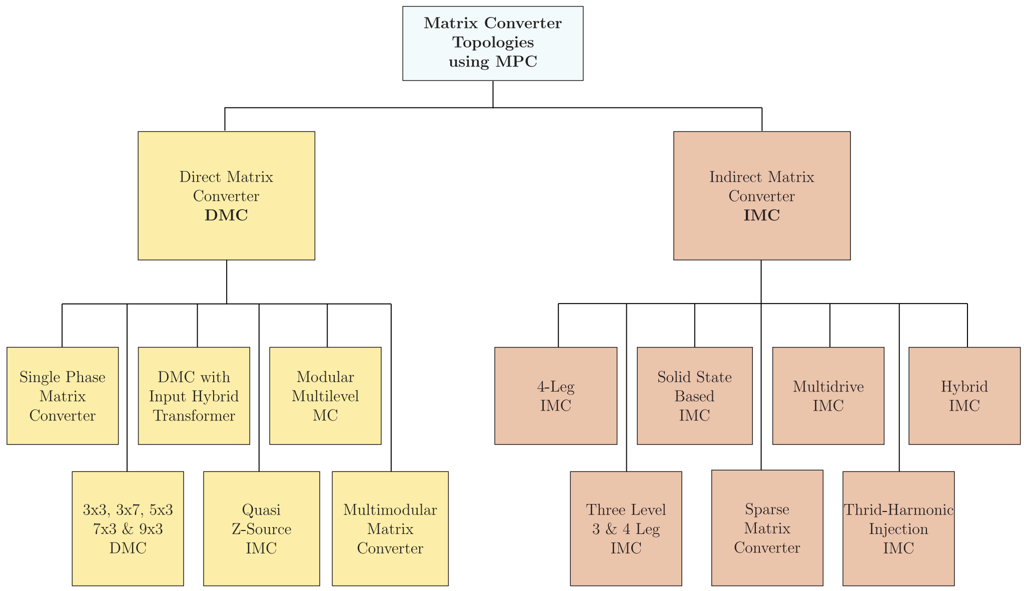

Figure 15. Classification of matrix converters.

5.1. Direct Matrix Converter and Its Derivations

Without the use of a dc-link or other significant energy storage components, the direct matrix converter (DMC) connects the power supply directly to the load or grid using an array of $m \times n$ bidirectional switches, where m represents the number of input phases and n represents the number of output phases.

Among the configurations, three-to-three DMC is the most popular topology and this power stage is shown in Figure 5. The input and output are directly connected through nine all-silicon bidirectional switches. This converter has been used in several applications; Table 2 presents a summary. Predictive control has been successfully applied in a three-to-three DMC; the control strategies are shown in Table 3. In addition, an interesting combination of this topology with a hybrid transformer was used as an active filter applying predictive voltage control to improve the behaviour of the supplied power [119,120].

Table 2. DMC applications.

	Application	Citations
1	Motor drive	[51,104,132]
2	Isolated load feeder	[31,86,90,133,134]
3	Grid connected generation systems	[117]
4	Active filter	[33]
5	Non-linear load feeder	[122]

Table 3. Predictive control strategies applied to DMCs.

	Application	Citations
1	Current control	[18,90,135]
2	Torque and flux control	[101,102,114]
3	Voltage control	[117]
4	Position control	[130]
5	Power control	[128]

The articles cited above highlight the importance and significant interest of researchers in the study of this topology in conjunction with predictive control techniques. Next, the topologies derived from the direct matrix converter in which predictive control has been applied are presented.

5.1.1. Single-Phase Matrix Converter

This is the simplest topology of the MC. It has three input phases and supplies a mono-phase load, as can be seen in Figure 16. An implementation of PCC in this converter can be found in [21].

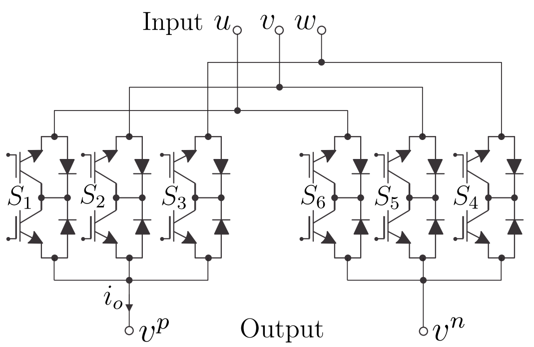

Figure 16. A single-phase matrix converter.

5.1.2. Multi-Phase Direct Matrix Converters

Multi-phase systems have become a research topic in which there is much interest. Several MC configurations have been proposed as the power stage on multi-phase systems applying predictive control. Figure 17 shows a generalized m-to-n matrix converter topology. A simple current control strategy with a three-to-seven DMC to supply a RL load is presented in [77]. A five-to-three DMC is used for a motor drive in [95]. Moreover, predictive control implementation in multi-phase wind generation systems is a topic addressed where DMC is used. In [78], a five-to-three DMC is used to feed an RL load from a five-phase permanent magnet synchronous machine (PMSM) of a wind turbine. In the same way, seven-to-three [75] and nine-to-three [79] topologies have also been studied.

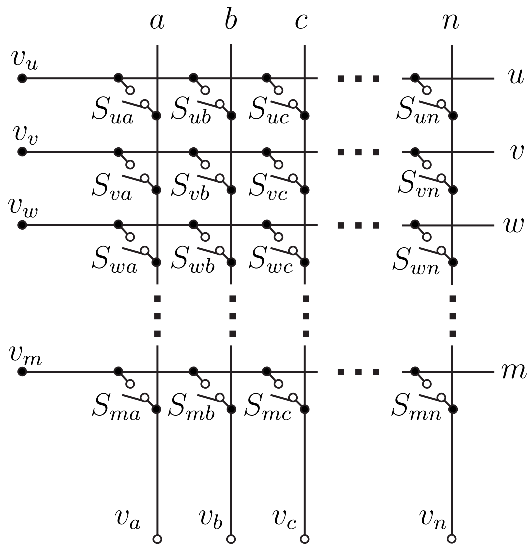

Figure 17. An $m \times n$ direct matrix converter.

5.1.3. Quasi-Z-Source Matrix Converter

A quasi-Z-source matrix converter (qZS-MC) was proposed to extend the voltage gain of a traditional MC, while compensating for the three-phase side low-frequency ripple power. The qZS network incorporated a filtering and boosting function, avoiding an additional input filter or step-up transformer, to reduce the size and component count [129]. The electronic circuit for this topology is shown in Figure 18.

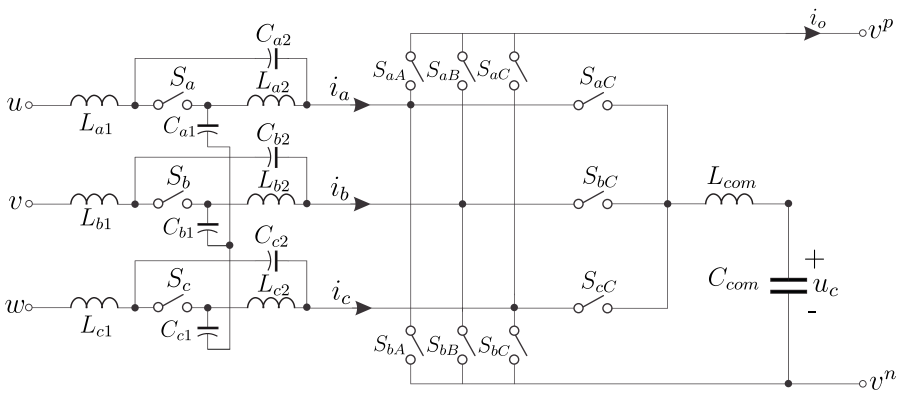

Figure 18. qZSMC topology.

5.1.4. Multi-Modular Matrix Converter

The multi-modular matrix converter consists of a modular combination of three-to-three DMC applied to six-phase systems, as shown in Figure 19. For six-phase generation systems, ref. [45] proposed a predictive current control with reactive power minimization. In [41], predictive current control was used to inject energy to the main grid, and, in [118], predictive voltage control was used for inner loop control of injected active and reactive power to the grid.

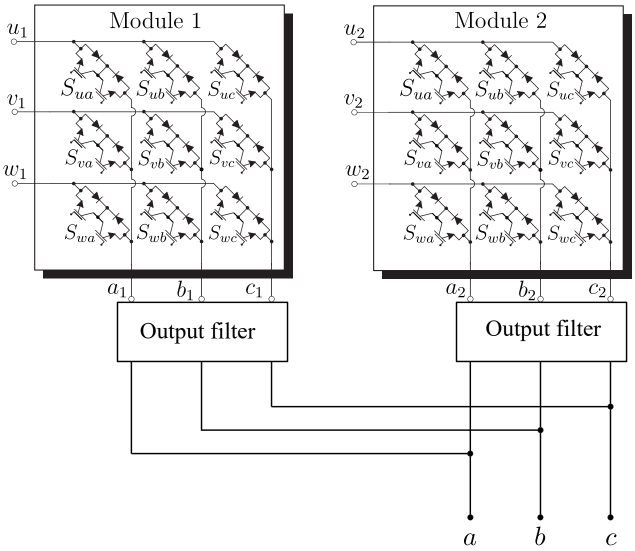

Figure 19. Multi-modular matrix converter.

5.1.5. Modular Multilevel Matrix Converter

Figure 20 shows the detailed circuit configuration of a modular multilevel converter (MMC) or M3C. This converter consists of three star-connected sub-converters, each of which has three branches. The branch B_{xy} connects the phase of $y \in \{a, b, c\}$. Each branch is the series connection of one input phase of the system $x \in \{r, s, t\}$ with one output n with H-bridge-based cells and an ac inductor. The cell dc capacitor voltages can charge-discharge during normal operation of the converter because they are not connected by external power sources. Therefore, the capacitor voltages have to be controlled. A predictive control strategy to control this interesting topology is presented in [37].

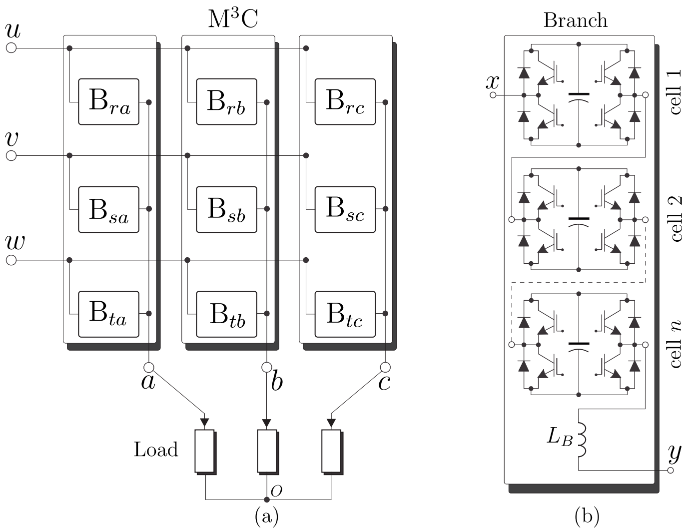

Figure 20. Modular multilevel matrix converter. (**a**) Generic M^{3}C, (**b**) Branch composed by one inductor L_B and n full-bridges.

5.2. Indirect Matrix Converter and Its Derivatives

The indirect matrix converter (IMC) topology consists of a three-stage power semiconductor array, very similar to the ac/dc/ac back-to-back (B2B) converter but with no physical storage units, as shown in Figure 21. By choosing a switching state in the rectifier that connects one phase to point P and the other phase to point N, the converter creates a positive voltage in the virtual dc-link.

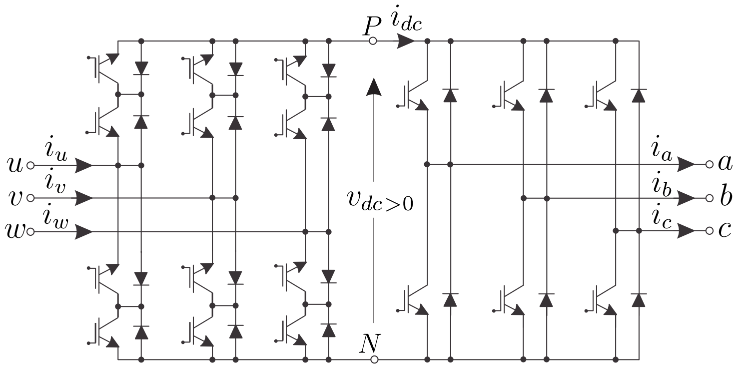

Figure 21. Power stage of an indirect matrix converter.

Several studies have dealt with this topology and predictive control for motor drive applications [96,105], RL load supply [62,136,137] and grid-connected systems [58]. The main advantage of this topology compared with the direct one is that all the previous techniques using the typical B2B converter can be applied with non-significant effort. The following paragraphs describe the variations of this converter.

5.2.1. A Four-Leg IMC

Figure 22 shows a four-leg indirect matrix converter topology. The converter's rectification stage, which consists of six bidirectional switches on the input side, serves as the principal conduit for sinusoidal input currents and the supply of positive dc-link voltage to the inversion stage, which includes eight switches. The large storage capacitor has been eliminated, allowing for direct connections between the rectifier and inverter stages. When using a four-leg IMC, it is possible to effectively decouple the control of the input current and output voltage. This allows the output voltage to be generated independently of the input and the input current phase to be regulated regardless of the output voltage. Simple current control [19,20,29] and reactive power minimization [49,64] predictive techniques have been successfully applied to this converter.

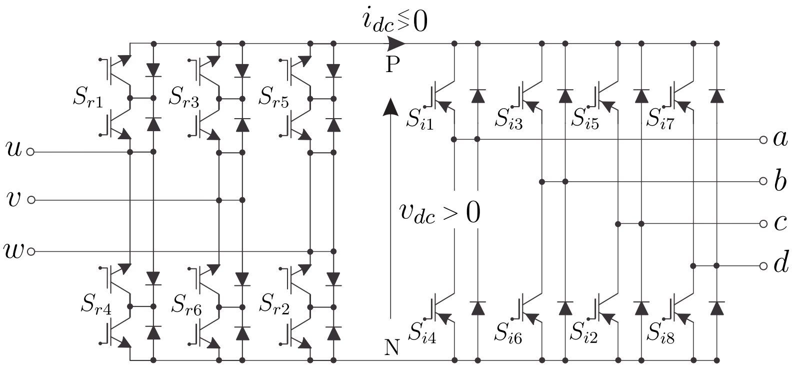

Figure 22. Four-Leg indirect matrix converter.

5.2.2. Three-Level Indirect Matrix Converter (3L-IMC)

Based on adding a dual-buck circuit, this topology enables the generation of three voltage levels at the inverter output side. This converter is available in two topologies, and three-leg [52] and four-leg [54] configurations. Figure 23 shows the three-leg configuration.

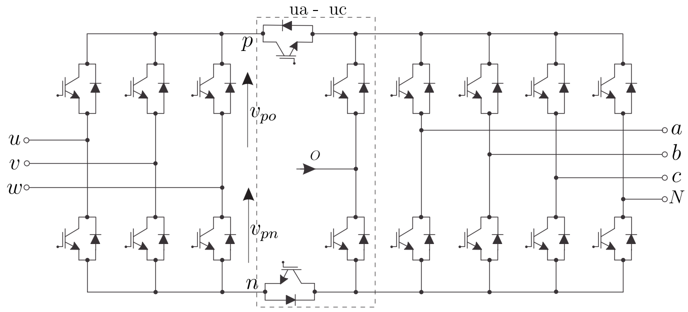

Figure 23. Three-level indirect matrix converter.

5.2.3. Third-Harmonic Injection Two-Stage Matrix Converter

The third-harmonic injection two-stage matrix converter (3TSMC) adopts a hybrid front-end rectifier. It combines the advantages of passive and active front-end rectification [27]. The topology of the 3TSMC is shown in Figure 24. It can be seen that the rectifier has six dynamic switches and the inverter has six insulated-bipolar transistors (IGBT), both associated by an imaginary dc-link. The critical part is the active third-harmonic current injection circuit, which consists of three bidirectional injection switches and a buck circuit. In addition, a clamp circuit, made up of a film capacitor and a quick recovery diode, is included.

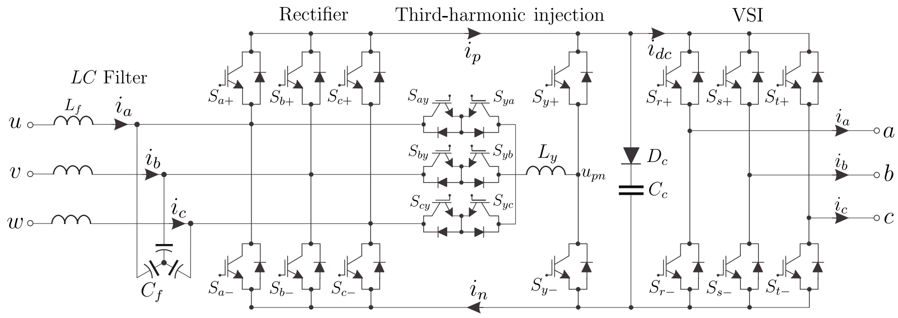

Figure 24. Two-stage matrix converter with third-harmonic injection.

5.2.4. Sparse Matrix Converter

The family of sparse matrix converters is equivalent to the standard circuitous network converter but has a decreased number of switches. They can be classified according to the number of switches as sparse matrix converters (SMCs), very sparse matrix converters (VSMCs), and ultra-sparse network converters (USMCs). The three-phase sparse matrix converter employs twelve IGBTs and thirty diodes, as shown in Figure 25. A basic implementation of predictive current control for this topology can be found in [44].

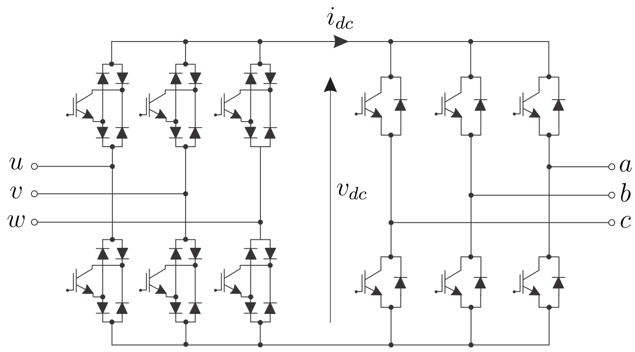

Figure 25. Sparse matrix converter.

5.2.5. Matrix-Converter-Based Solid State Transformer

Figure 26 shows this topology. Two three-to-single-phase MCs are back-to-back connected through an $n:1$ HF transformer. This type of solid state solution fulfils single-stage bidirectional ac-ac power conversion. A basic PCC for this topology is presented in [60] for motor drive applications, isolated load feeder [36] and grid interconnected systems [32].

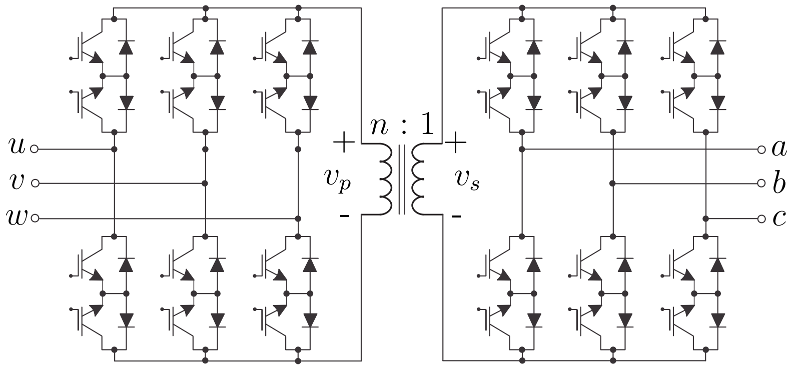

Figure 26. Solid-state-transformer-based matrix converter.

5.2.6. Hybrid Indirect Matrix Converter

The MC topology output voltage is limited (86% of the entry), this being a major drawback. The authors of [138] propose a hybrid IMC (Figure 27), which adds an auxiliary voltage source to the dc-link. This empowers the unity voltage exchange proportion to be accomplished depending on the effect of strong changes within the input voltage.

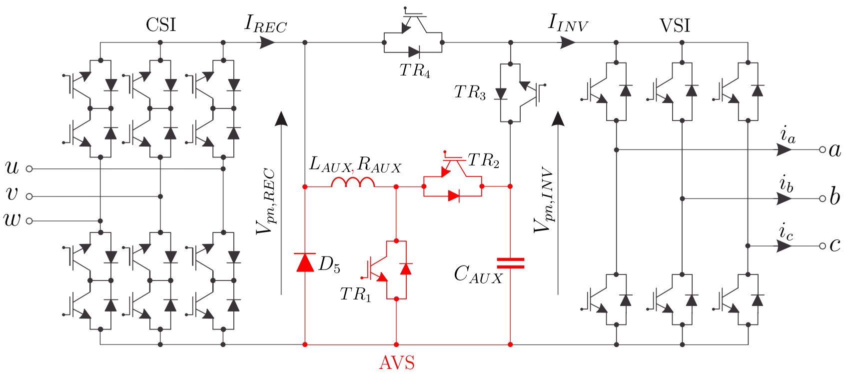

Figure 27. Hybrid indirect matrix converter.

5.2.7. Multi-Drive Indirect Matrix Converter

To reduce implementation costs in systems that require two or more machines to work together, but which require complex, multi-objective and reliable control schemes, multi-drive power converters have been developed. There are two topologies that have the capability to drive multiple systems at the same time. The first configuration is referred to as dual output IMC [47,97]; the power circuit is shown in Figure 28. Another proposal for a multi-drive IMC can be seen in Figure 29, where the basic idea is to connect the factitious dc-link after the rectifier stage to several (in this proposal, two) inverters driving different machines.

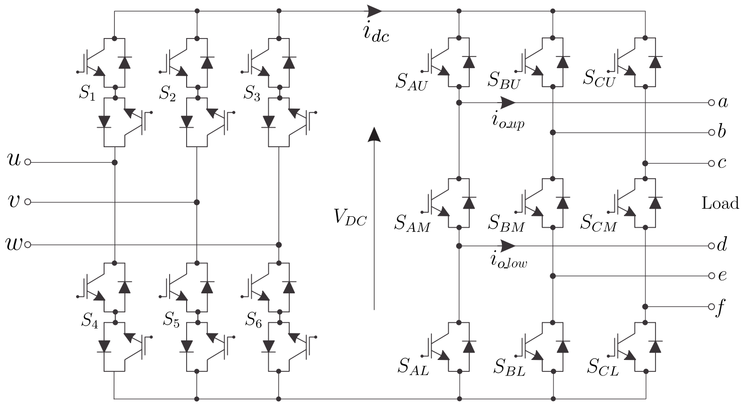

Figure 28. Indirect matrix converter with dual output.

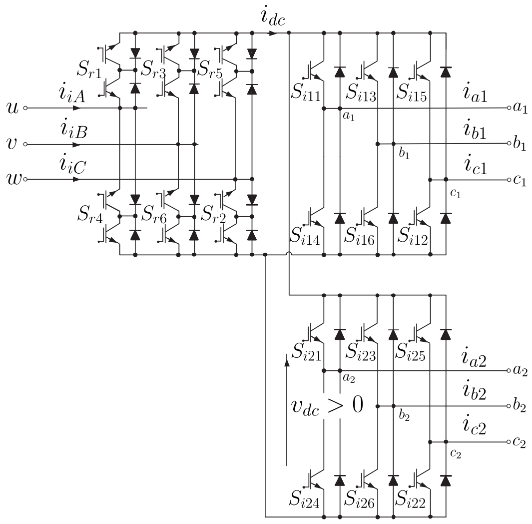

Figure 29. Multi-drive indirect matrix converter.

The topologies mentioned are those that were identified that applied predictive control for different targets. The next section is dedicated to establishing what are currently the most interesting trends in the topics relating to predictive control applied to matrix converters.

6. New Trends on Model Predictive Control Applied to Matrix Converters

Despite the advantages of model predictive control and matrix converters described, these systems have some drawbacks. Some of the solutions proposed are presented below. The main issues are: (i) the inconvenience of variable switching frequency, (ii) avoidance of the use of weighting factors or novel tune techniques, (iii) reduction in the computational burden, and (iv) providing the ability to act during faults. In the following sections, new proposals which seek to address these issues are briefly described.

6.1. Variable Switching Frequency

The absence of a modulation stage in the MPC strategy creates the problem of unfixed switching frequency. Since a single voltage vector is chosen and applied at each sampling instant, the switching frequency presents a very disperse spectrum, causing unwanted ripple components to be generated. To solve this problem, different strategies have been proposed—most consist of including a modulator in the control stage. For several applications, modulated predictive control techniques have been proposed, including current control [40,132,139], current control with active damping for several typologies [133,140–144] or with imposed sinusoidal input current [136,145,146], reactive power minimisation [57,137,147] and torque and flux control [148]. The main benefit of these proposals is provision of a modulation technique inside the predictive control to concentrate, in turn, the spectra of the switching frequency by defining a sequential application of three or more vectors, instead of only one, using a predefined application pattern. An interesting feature of these investigations is the avoidance of weighting factors for multi-objective controls.

6.2. Avoiding the Use of Weighting Factors

At the point of implementing a multi-objective predictive control (i.e., various terms in the cost function), the selection process of weighting factors is not trivial and it is not always feasible to calculate the optimal values for success with expectations of control. Several proposals that avoid using weighting factors can be found in the literature. Some modulation techniques have been presented, including [57]. Some studies that have considered the tuning process have proposed self-tuning methods [48] or fuzzy logic [56,149]. An interesting approach is presented in [112], where a multi-objective ranking-based approach is proposed to evaluate, for each feasible voltage vector, every term of the cost function. Each cost function generates values that are ranked separately, then a rank value is assigned to each value. A lower rank is assigned to voltage vectors with a lower value, while a higher rank is assigned to voltage vectors with a higher value. To decide which voltage vector should be applied, the sum of the ranks of these two cost functions for each voltage vector is used. The voltage vector that minimizes this value is selected. A similar approach is called sequential predictive control [150] in which every objective is represented for a cost function, then, depending on the priority, the first cost function is evaluated for every valid state. The best n solutions are pre-selected and used to evaluate the second cost function. The best m ($m < n$) solutions are used to evaluate the next cost function, and so on, until all the cost functions are evaluated. Finally, the optimal vector is selected. The control strategies described are variations of MPC that avoid the use of a weighting factor.

6.3. Reducing Computational Burden

Simplified predictive control uses the α-β framework to perform a spatial distribution of the matrix converter active voltage vectors. Eighteen active vectors are generated by the matrix converter in six different directions. The magnitude of the vectors depends on the instantaneous value of the input voltages of the matrix converter, keeping the direction of each vector constant [151–153]. Pre-calculation of the sector of the desired output is proposed to reduce evaluations of the cost function at only the valid vector in the sector, reducing the calculation time. Some studies have reported a reduction of around 50% by applying this technique [154].

6.4. Fault Detection Using MPC

An interesting approach to improving the capabilities of the MPC in a direct matrix converter is presented in [155]. A technique to detect faults in the switches is used to avoid the application of unavailable states and the cost function is evaluated using only available switching combinations when a switch is damaged. Another proposal is presented in [55] in which a term depending on open-phase fault is added to the conventional current control with reactive power minimisation.

There has been significant work proposing improving MPC strategy for the MC. Considering the input and output circuit as a complete system, the proposed MPC is based on an accurate prediction model. The accurate prediction model is obtained by discretizing the integral equation of the state space of the entire MC system, considering the interaction. Each valid switching state corresponds to a set of matrices of the precise prediction model. The separate prediction models used in the conventional MPC approach are replaced by an accurate prediction model that has the same eigenvalues as the continuous model of the entire MC system [82].

In Table 4, a comparison between new trends on predictive control and classical approaches is shown in terms of weighting factor use, the need for a modulation stage, and application of variable or fixed switching frequency. As previously mentioned, the tuning of weighting factors is not trivial and sometimes the whole performance of the controller is defined for selection of these factors. As can be seen in the table, using a modulation-based technique, in general, avoids the use of weighting factors, but including this modulator adds complexity in the implementation of the controller compared with a classical approach for which the implementation is simpler. The inclusion of modulation avoids the variable switching frequency making the design of input filters more straightforward, avoiding undesirable resonances. Ranking-based and sequential predictive control are interesting variations that enable weighting factors to be avoided. However, the sequential predictive control approach can result in sub-optimal solutions as, in the first stage of the control, some vectors are eliminated from the set of feasible commutation states.

Table 4. Comparison of new trends based on predictive control and classical approaches.

Technique	Weight Factor	Modulation	Switching Frequency
Basic predictive control [17–46]	Not needed	Not needed	Variable
Predictive control with reactive power minimization [47–73]	Needed	Not needed	Variable
Predictive control with imposed input current	Needed	Not needed	Variable
Modulated predictive control [40,132,139]	Not needed	Needed	Fixed
Modulated predictive control with input reactive power minimization [57,137,147]	Not needed	Needed	Fixed
Modulated predictive control with imposed sinusoidal input current [136,145,146]	Not needed	Needed	Fixed
Multi-objective ranking-based predictive control [112]	Not needed	Not needed	Variable
Sequential predictive control [150]	Not needed	Not Needed	Variable

7. Conclusions

A systematic literature review was conducted to answer two predefined research questions. The methodology involved the definition of a strict protocol to carry out the literature review to provide a set of studies that addressed our initial questions. With respect to predictive control applied to matrix converters, a complete summary of the state of the art of topologies and predictive control techniques developed was presented. Initially, 2858 publications were identified using the search strings in the selected databases. A total of 142 studies were finally selected by applying the methodology described above (i.e., applying the inclusion and exclusion criteria), with the aim of providing sufficient information to answer the research questions. Once the data extraction, data synthesis and report of the data were completed, it was evident that there were some open problems. These included weighting factor selection, reducing computational burden, and variable switching frequency. However, it should be noted that there is increasing interest in the field from researchers. The increasing implementation of predictive control in matrix converters can be attributed to the development of new microcomputers with high processing capability. Predictive control and matrix converters represent valid alternatives in power management and motor drive systems.

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