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Review

Review of Model Predictive Control of Distributed Energy Resources in Microgrids

Darioush Razmi [1], Oluleke Babayomi [1], Alireza Davari [2], Tohid Rahimi [3], Yuntao Miao [4] and Zhenbin Zhang [1,*]

[1] School of Electrical Engineering, Shandong University, Jinan 250061, China
[2] Department of Electrical Engineering, Shahid Rajaee Teacher Training University, Tehran 16788-15811, Iran
[3] Department of Electronics, Carleton University, 1125 Colonel by Drive, Ottawa, ON K1S 5B6, Canada
[4] CRRC Shandong Wind Power Co., Ltd., Jinan 250104, China
* Correspondence: zbz@sdu.edu.cn

Abstract: In recent years, in response to increasing environmental concerns, advances in renewable energy technology and reduced costs have caused a significant increase in the penetration of distributed generation resources in distribution networks. Nonetheless, the connection of distributed generation resources to distribution networks has created new challenges in the control, operation, and management of network reliability. This article is a review on the model predictive control (MPC) for distributed energy resources (DER) in microgrids. The solutions of MPC for energy conversion of solar photovoltaic, wind, and energy storage systems are covered in detail. MPC's applications for increasing reliability of grid-connected converters under (a)symmetrical grid faults are also discussed. The promising potentials of the applications of MPC to the stable multi-variable control performance of DERs are highlighted. This work reflects strong symmetry on MPC control strategies and provides guidance map for readers to facilitate future research works in these exciting fields.

Keywords: microgrid; model predictive control; distributed generation sources; reliability; symmetry

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1. Introduction

Today, power grids around the world face problems such as the gradual depletion of fossil fuel resources, low energy efficiency, and environmental pollution, which has recently led to the local generation of power from renewable energy sources at the distribution and high voltage distribution levels. This type of power generation at low voltage levels is distributed generation (DG) and its sources are known as distributed energy resources (DERs) [1]. According to the definition provided in the IEEE standard no. 1547.2-2011, "Any distributed generation can consist of a power generator and an energy storage system" [2]. From the Electric Power Research Institute (EPRI) point of view, the term DG can be used to refer to "small-scale energy production to meet local needs that has a production capacity in the range of 100 kW to 10 MW" [3]. According to the US Department of Energy, DGs are small generators that can be combined with energy storage systems and operated grid-connected or island mode to improve power system performance and meet local needs. Following the expansion of the use of DGs in the power system, today distribution networks have changed from passive mode with one-way power flow to active distribution networks with two-way power flow. In passive networks, the power distribution is one-way and from the transmission network to the distribution network, while the presence of distributed generation sources has caused two-way power distribution in the power networks. On the other hand, the presence of DGs in the power system has made the control of these networks a major challenge. Control of the DG systems in a modern distribution network requires the use of intelligent control methods as well as changes in the structure of distribution networks, such as the integration of distributed generation resources and energy resource management [4]. These changes led to the creation of microgrids in active distribution networks, opening up a major research field comprising sustainability, energy management, reliability, power quality, and market participation.

Microgrids can structurally be divided into three types: AC, DC, and hybrid AC-DC microgrids. The energy sources used in microgrids, which are connected to the grid by power electronic converters, include photovoltaic (PV), wind energy, fuel cells, and energy storage systems. The roles of the interfacing converter are to inject the output power of the source into the electrical network, and precisely control the active and reactive powers from the distributed source. Although DGs have numerous advantages, as previously mentioned, the interface converters introduce new challenges, which require innovative solutions. For instance, they decrease the inertia of the microgrid, increasing vulnerabilities to frequency instability [5]. The MPC approach in asymmetric systems is not discussed and few studies have been conducted with conventional methods [6]. So far, few analytical studies have been conducted on the MPC approach in the presence of power converters with asymmetric topology and switching [7], which require further studies to simplify and functionalize the MPC approach.

2. Overview of DG Sources in Microgrids

Increasing numbers of distributed energy sources are connected to the distribution network and the evolving smart grid. It is possible to integrate DERs to the grid through microgrids. Microgrids provide a coordinated method to facilitate the penetration of DGs into the power system and increase its reliability. Microgrids can operate in two modes: independently, or connected to the grid. They usually work in parallel with the grid, but there are cases where the microgrid is intentionally or unintentionally disconnected from the main grid and acts as an island. In order to reconnect an islanded microgrid to the grid, a synchronization procedure is necessary. DGs have less generation capacity and are operated at lower cost than large centralized generators, which power the conventional grid. The connection of DGs to low voltage networks have benefits, which include: reducing environmental pollution, increasing the efficiency of electricity generation, improving power quality of electricity supplied to customers, reducing losses in distribution networks, improving feeder voltage profiles, and releasing network capacity [8].

2.1. Low Voltage AC Networks

Distributed generation units are usually connected to the main grid via power electronic converters. For example, a wind turbine produces AC output power that can either be connected directly or via AC/DC/AC converters to the main grid. The low voltage AC networks can be connected to wide area networks through transformers and AC loads can also be connected directly to the network. However, DC loads require power electronic converters to connect to the AC network. On the other hand, solar photovoltaic arrays have DC output power and are connected to AC networks through inverters. Figure 1 shows multiple DG units connected to a low voltage AC network [8].

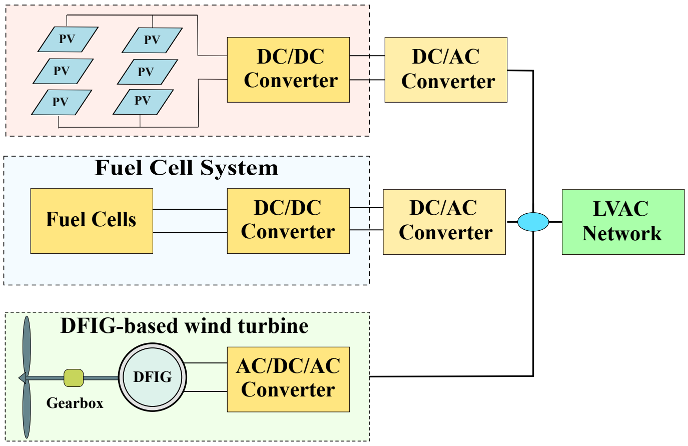

Figure 1. DG units connected to a low voltage AC network [8].

2.2. Low Voltage DC Networks

Low voltage DC (LVDC) microgrids are being increasingly deployed for electricity supply to industries and and commercial buildings. In the future, it is expected that DC distribution systems will be operated in alongside the AC systems to feed all DC electrical appliances and machines. The operation of these parallel systems will be optimally controlled by an energy management system (EMS). Solar PV systems deployed in modular scale are beneficial for DC power generation. In addition, where the primary energy source to the LVDC network is an AC generator, AC/DC converters become essential. Additional elements in the LVDC network include energy storage and DC loads. Figure 2 shows a view of a LVDC network. Features that make LVDC attractive for a higher scale of application are its simplicity and high system efficiency; for this reason, LVDC is expected to increase in popularity [8].

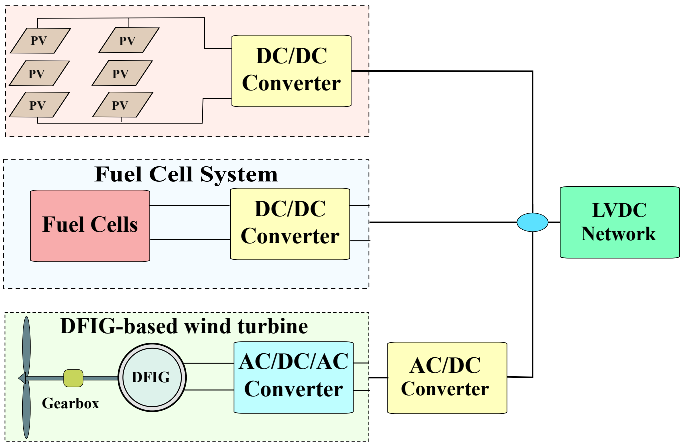

Figure 2. LVDC Network [8].

2.3. Wind Turbines

Wind energy is one of the oldest renewable sources that has gained acceptability in more recent years. The efficiency of energy conversion in wind turbines is improved through maximum power-point tracking control methods. Recent research topics in wind energy conversion include fault identification and isolation, fault-tolerant control, and fault-ride through operation. The older types of wind turbines are fixed-speed devices. They work with squirrel cage induction generators, and require a soft starter to prevent inrush currents. However, modern wind turbines are variable speed equipment, whose real-time operation is more stable and spread over low to high wind speed operations. This is facilitated by power electronics driven by smart control algorithms that convert variable-frequency generator output to grid-compliant frequency [9].

2.4. Photovoltaic (PV) Units

A photovoltaic cell, commonly called a solar cell, is a transducer for the direct production of electricity from solar radiation. When sunlight shines on a PV cell, a potential difference occurs between the negative and positive electrodes, causing current to flow between them. Several PV cells, arranged in series and parallel, make up solar panels or arrays [10].

PV systems are commonly applied in home, commercial, public, and agricultural electrical systems. These systems can serve as independent energy sources or grid-connected systems. As the higher numbers of PV systems are connected to distribution lines, they can provide grid ancillary services. In grid-connected mode, electrical power from the PV system is injected into the main grid through inverters, which match the voltage amplitude and frequency of the PV system with grid voltage. Photovoltaic power plants are connected to the main grid in a centralized or decentralized manner and support the grid by preventing voltage drop of the distribution network. In the stand-alone mode, offgrid locations can be conveniently electrified [11,12].

2.5. Energy Storage Systems

Due to the fact that the production capacity of renewable energy sources is a function of atmospheric and climatic conditions, the proper performance of a microgrid depends on the correct operation of energy storage equipment. These systems play an important role in balancing power supply and demand, and also support the stability of microgrids. The surplus energy produced by renewable sources is stored in energy storage systems and used when there is a shortage of production. Integration with renewable energy sources to increase power efficiency is one of the most important goals of using energy storage systems in grid-connected microgrids. However, in island microgrids, energy storage systems are used to improve power quality and increase reliability. The energy storage control system regulates charge and discharge cycles according to the microgrid loading conditions. This system is also required to maintain the charge status of the storage system within the allowable range [13,14]. Table 1 shows the application of technology for different types of energy sources [8]

Table 1. DER Technology Application [8].

	Energy Generation			**Energy Storage**		
Application	**Fuel Cell**	**PV**	**Wind Turbine**	**UPS**	**Battery**	**Flywheel**
Stand-Alone System	✓	✓	✓	Not applicable		
Power quality	Not applicable			✓	✓	✓
Combined Heat and Power	✓	Not applicable		Not applicable		
Connection with network	DC/AC Converter	AC/DC Converter	Asynchronous Generator	Power Converter		
Size Range (kW)	100–250	0.01–8	0.2–5000	40	1–1000	2–1600

2.6. Microgrid Operation Modes

In general, microgrids can operate in both grid-connected mode and island mode [15]. However, in some situations, such as the application of distributed generation systems in power supply to remote areas, island operation mode is the only option available. In general, the operation in island mode can be due to the low power quality of the main grid, the price and conditions of the electricity market, and the unavailability of the main grid due to a fault. In grid-connected mode, voltage and frequency support is provided by the main grid, and therefore distributed generation sources are controlled solely for the purpose of power supply. However, when a microgrid operates in island mode, at least one of the interface converters of the distributed generation sources must operate in grid-forming mode (voltage control), while in grid-connected conditions it operates in grid-following mode (current control).

3. Model Predictive Control Strategies for DER-Based Microgrid

Model predictive control (MPC) is gaining increasing attention by control system researchers for applications, including energy conversion and process control. In power electronics applications, MPC can be divided into two groups: continuous control set MPC (CCS-MPC) and finite control set MPC (FCS-MPC) [16]. The main difference between these two groups lies in the type of modeling, implementation, and complexity [17]. MPC with a continuous input set is defined in the context of the model in the state space for the electronic power converter. Accordingly, the input in the model will be a continuous parameter that is limited in a range [18]. Furthermore, the switching frequency is constant and the control strategy will be applied to the system through a modulator. This type of predictive control is commonly used for other systems and is not specific to electronic power systems [19]. Using hybrid modeling, the input will be continuous and limited, and the switching frequency controller will be fixed for implementation. Model predictive control with finite input sets uses the discrete nature of electronic power converters to reduce computations and data processing time [20]. FCS-MPC has many advantages and special capabilities for power electronics-based energy optimal control. These types of controllers are a suitable solution for researchers in the field of industry and, recently, a lot of research has been conducted in different fields such as motor drives, power quality, and wind and PV energy conversion applications. Figure 3 shows the characteristics of power electronic converters and MPC-related specifications.

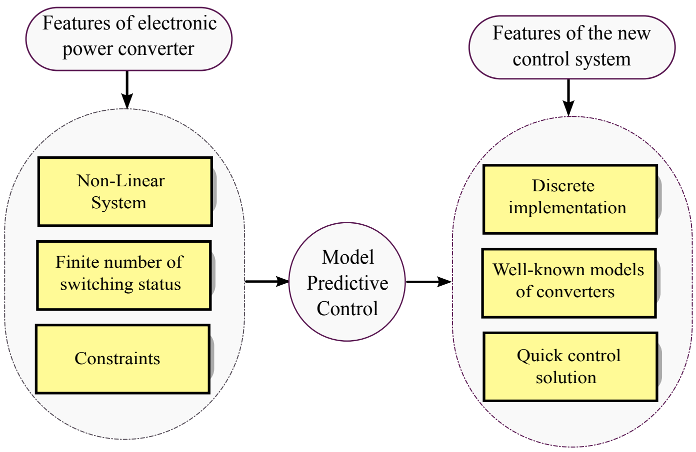

Figure 3. Intrinsic features of electronic power converters for the application of MPC [17].

The outstanding advantage of model predictive control is online multivariable optimization with full consideration of the physical constraints governing the system. Moreover, by including the effort in the cost function, the energy consumption of the system can be reduced, and will reduce the system costs, improving overall efficiency. The receding horizon principle intrinsic to MPC also helps to improve disturbance rejection more effectively than other linear controllers. Unlike complex optimal control theories that require solving complex nonlinear differential equations, MPC can be easily implemented in digital computers. Despite all the advantages of model predictive control, it also has disadvantages. The most important disadvantage of MPC is its need for an accurate model of the process because, in this controller, the future behavior of the system must be predicted in the first step. Therefore, if the mathematical model of the system is compromised by uncertainties, the erroneous state predictions lead to poor control accuracy and performance. Another disadvantage of MPC is the complexity of solving the optimization problem for nonlinear systems. If the dynamics of the system is nonlinear, then the MPC cost function will become a complex function of decision variables, and its optimization becomes more intricate.

An approach based on the model predictive controller for a permanent magnet synchronous motor is proposed that can obtain the reference voltage vector by predicting only one voltage vector during the sampling period using the control specification. For better steady-state performance, a ratio is used to minimize the error between the predicted voltage vector and the synthesis vector by using a symmetric vector switching sequence. The proposed strategy has been compared with the conventional FCS-MPC and its results have been approved [21]. The voltage unbalance at different levels of the system occurs due to asymmetric load and unbalanced power generation in the microgrid. To solve such a three-phase voltage imbalance, an unbalanced voltage control strategy using an MPC approach is proposed [22]. An improved MPC strategy for distributed energy sources in a microgrid is proposed. AC microgrids usually have two or more distributed power sources that have the ability to maintain a constant voltage at the coupling point as well as power distribution between DGs. In this regard, linear controllers have limitations such as transient slow response and disturbances. The proposed control approach uses the mathematical model of a power converter to predict the voltage response for switching modes in each sampling period. In this method, the three-phase symmetric fault current is maintained within the allowable range [23]. A symmetric and asymmetric multilevel inverter topology with a limited number of power switches is presented to overcome the disadvantages of conventional multilevel inverters, which also uses the FCS-MPC approach [24].

3.1. MPC for Wind Conversion

Important control considerations for wind turbines include nonlinear dynamics or indeterminate linear models, stability criteria, and multi-objective performance. In particular, the power received from the wind turbine is non-linearly dependent on the average wind speed, rotor speed, and blade angle. The control system should maximize wind energy input depending on wind speed while minimizing the negative effects of wind turbulence on the turbine. In addition, the system must operate in a wide range of medium wind speed operating points with a number of sensors and actuators. Wind turbines are flexible structures with multiple subsystems that may require multi-objective metrics to control closed-loop wind turbines. Although the reduced model can be a good approximation of a high-order wind turbine system in the desired frequency range, it may result in unmodulated dynamics and its destructive effects on poor wind turbine system performance and instability [25]. A robust predictive controller was reported for the control of a permanent magnet synchronous generator [26]. In this method, the rotor speed and position are estimated using the developed Kalman filter. A disturbance observer was also used to deal with uncertain changes in model parameters. In [27], predictive control with a limited time approach without sensor was used to control wind turbines with a permanent magnet synchronous generator. In this research work, a reference model adaptive observer was used to estimate the rotor speed and position. A new method for load frequency control was proposed by using robust MPC to reduce the effect of uncertainties due to parametric changes of wind turbine and governor and especially load changes. The closed-loop control system with the MPC is robust against the disturbance of the system parameters and has superior performance than classical control [28]. A proper method for high-power wind energy conversion systems (WECS) is the back-to-back power converter architecture for the permanent-magnet synchronous generator (PMSG) with three-level neutral-point-clamped (3L-NPC). For such architecture, a robust finite control set model predictive control (FCS-MPC) was reported in [29]. The proposed strategy not only improves system robustness against parameter variations, but also decreases control variable fluctuations. In [30], multiple-vector direct model predictive control (MV-DMPC) strategy for the grid-side power converter is presented to control the back-to-back converter of PMSG wind turbine systems using FPGA-based solutions. Research findings show that the performance of the control system is much more improved than classical DMPC. Among the problems that wind turbines with doubly fed induction generators face are active and reactive power fluctuations, rotor over-current, and DC link over-voltage under network faults. As hardware protection devices are not the best protection solution to improve fault tolerance, they impose problems for rotor-side converter control. Therefore, researchers in [31] utilized MPC to maintain the DC link voltage, rotor current, and electromagnetic torque within their allowable limits under network fault conditions. In [32], an optimal power control scheme based on MPC for DFIG-based wind farms equipped with energy storage systems is proposed. This proposed scheme, by using the optimization problem based on predictive controller, distributes more optimal power to wind turbines according to wind conditions. In addition to reducing fatigue loads, the wind farm operator manages the charging and discharging capacity of energy storage systems to keep the SOC within the allowable range. Research results show that the proposed scheme has better performance to reduce fatigue loads, in addition to managing wind turbines within the wind farm with more flexibility.

In [33], a predictive control scheme was proposed for the low-voltage ride-through of wind turbines, which are driven by permanent magnet synchronous generator (PMSG). The problem in this study employs the generator-turbine rotor inertia for the storage of excess energy during grid voltage drop. In particular, the converter system includes a three-phase diode-bridge rectifier, three-level boost converter and neutral-point-clamped (NPC) inverter. In [34], through mathematical considerations of uncertainties and nonlinearity, MPC-based wind energy conversion for a PMSG was achieved. The resulting algorithm is robust to load and parametric uncertainties. In [35], a robust continuous time predictive control method for direct control of DFIG power is presented. In this method, Taylor expansion was used to predict stator currents in the synchronous reference frame for three operational conditions: synchronous, sub-synchronous, and super-synchronous. The simplest topology for the wind turbine side is using two-stage power converters consisting of one diode rectifier and a boost converter, as shown in Figure 4. The first stage (rectifier) converts energy from ac to dc without requiring any control signals. The second stage includes controllable power switches to realize maximum power-point tracking (MPPT) and help improve the DC link voltage stability [36]. The MPC scheme integrates sub-costs in an overall cost function with weighted control objectives, as shown in (2)–(4). In (4), the first term tracks inductor current, the second regulates dc-link voltage balance, and the weighted third term minimizes the switching effort. The control system implements the MPPT goal by the control of the wind turbine angle speed.

$$\hat{i}^{*}_{dc}(k+1) = 2i^{*}_{dc}(k) - i^{*}_{dc}(k-1) \tag{1}$$

$$g_{idc}(k) = \left[\hat{i}^{*}_{dc}(k+1) - i^{p}_{dc}(k+1)\right]^2 \tag{2}$$

$$g_{sw,dc}(k) = \left[s^{p}_{dc1}(k) - s^{op}_{dc1}(k)\right]^2 \tag{3}$$

where $i^{*}_{dc}(k)$, $S_{dc}(k)$ are the reference inductor current and the switching signal, respectively. The developed wind turbines can generate high power with increased voltage at the wind generator output. Thus, the conventional two-stage converters that are designed for low-voltage level applications are adapted to these types of wind systems. High voltage standing capability leads to the use of three-level boost converters and rectifiers with series diodes, as illustrated in Figure 5. In this topology, the wind turbine side converter has to regulate the inductor current for MPPT realizing and guarantee the voltage balance of capacitors. Therefore, three sub-cost functions are integrated, as given by (4). The variables are controlled and the optimum switching is realized. The balance of the capacitors voltage depends on the injected power to the grid. This Virtual Load Currents block is built to model the rectifier virtual load behavior. Two reference variables are generated by the MPC module [37]. To improve the efficiency, one-stage power electronics systems are recommended by the researcher for grid-connected wind generation, as shown in Figure 6.

The dc-link current is not available for this topology. Thus, the delivered ac current by the generator is measured and the measured ac current is transformed from ABC to DQ frame. The generator must inject the real power. Thus, both the q and d component must be controlled and the fitness function is defined to conduct this goal [38].

$$g_{dc}(k) = \lambda_{idc}\left[\hat{i}^{*}_{dc}(k+1) - i^{p}_{dc}(k+1)\right]^2 + \lambda_{dc,dc}\left[v^{p}_{C1}(k+1) - v^{p}_{C2}(k+1)\right]^2 + \lambda_{sw,dc}\left(\left[s^{p}_{dc1}(k) - s^{op}_{dc1}(k)\right]^2 + \left[s^{p}_{dc2}(k) - s^{op}_{dc2}(k)\right]^2\right), \tag{4}$$

$$g_r(k) = \lambda_{id}g_{id}(k) + \lambda_{iq}g_{iq}(k) + \lambda_{sw,r}g_{sw,r}(k). \tag{5}$$

where $V_C(k)$, λ_{idc}, $\lambda_{dc,dc}$, and $\lambda_{sw,dc}$ are the DC-link capacitor voltage, weighting factors for the inductor current control, balancing of DC-link capacitors voltage, and switching frequency minimization, respectively.

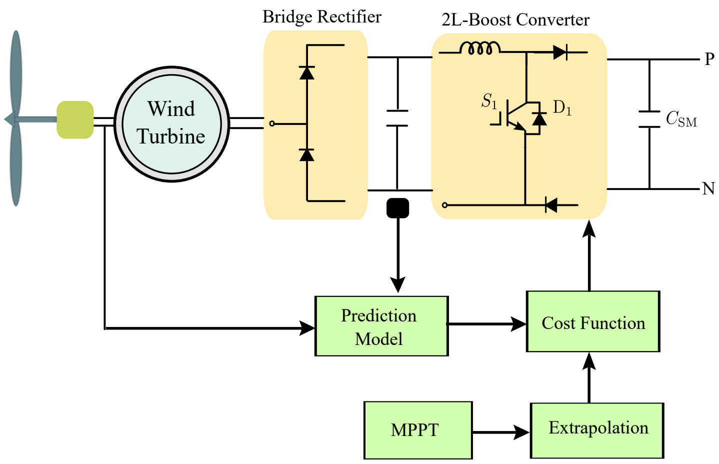

Figure 4. Block diagram of the PCC scheme for a 2L boost converter-based PMSG WECS [33].

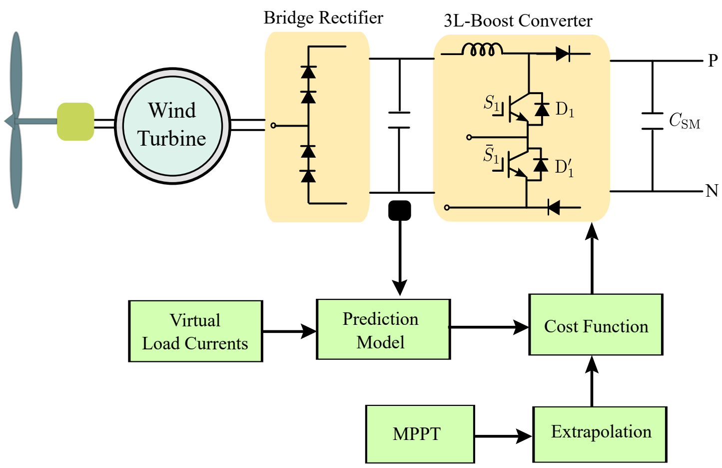

Figure 5. Block diagram of the PCC scheme for a 3L boost converter-based PMSG WECS [33].

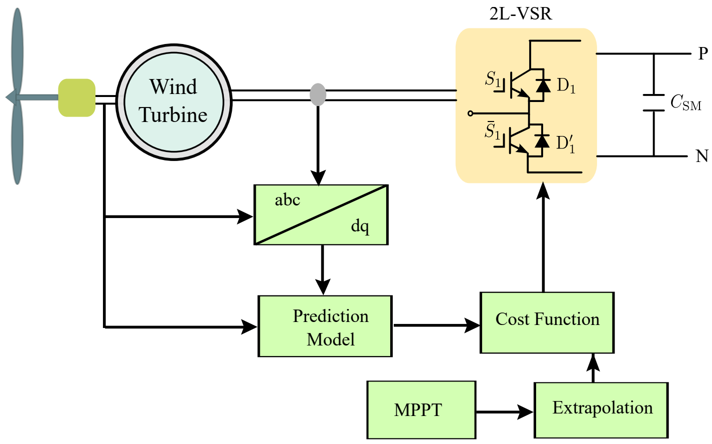

Figure 6. Block diagram of the PCC scheme for control of the PMSG with 2L-VSR [33].

For higher voltage applications, the neutral-point clamped (NPC) rectifier replaces the conventional two-level voltage source rectifier, as shown in Figure 7. The wind turbine converter has to both regulate the generator current for MPPT performance, and guarantee the voltage balance of capacitors. Therefore, four sub-cost functions are integrated, as given by (5). Optimization of the cost function generates the optimal switching states for the converter. The estimator block is employed for voltage-balancing of the capacitors [39]. Equation (6) shows the overall cost function formulation:

$$g_r(k) = \lambda_{id} g_{id}(k) + \lambda_{iq} g_{iq}(k) + \lambda_{dc,r} g_{dc,r}(k) + \lambda_{sw,r} g_{sw,r}(k), \tag{6}$$

where λ_{id}, λ_{iq}, $\lambda_{dc,r}$, and $\lambda_{sw,r}$ are the weighting factors, whereas $g_{id}(k)$, $g_{iq}(k)$, $g_{dc,r}$, and $g_{sw,r}(k)$ are sub-cost functions for the dq-axis currents, balancing the DC-link capacitors voltage and switching frequency, respectively.

A coordinated DC link voltage control strategy is proposed to increase the high-voltage ride-through performance of a wind turbine. The design includes a reactive current controller to regulate the wind turbine reference current. As soon as the DC link voltage exceeds its allowable value, the synchronized control schematic is considering an energy storage system. The performance of the wind turbine is evaluated by using an MPC with the aim of regulating the active power by tracking the reference current. The results of this study show that DC link overvoltage is effectively reduced and high-voltage ride-through is increased under symmetric and asymmetric voltage drops [40]. A fault ride-through (FRT) approach is proposed for DFIGs. The resistors are placed in series with the rotor to reduce overcurrent during voltage drop. The control strategy improves the transmission modes of the system under symmetric fault conditions and reduces overcurrent and torque fluctuations [41]. Extensive studies on MPC based wind systems have been presented. some of these studies are summarized in Table 2.

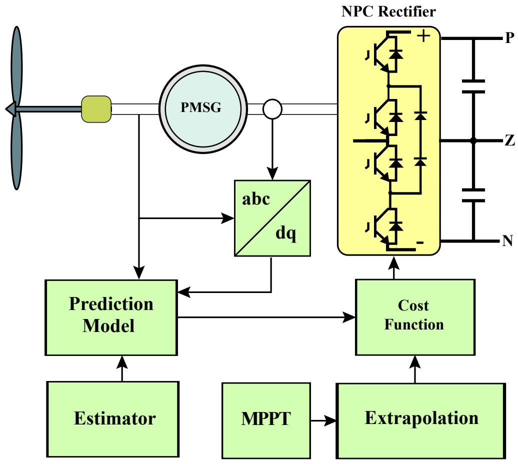

Figure 7. PCC scheme for the control of PMSG with NPC rectifier [33].

Table 2. Recent studies on MPC-based wind systems.

Application	Control Objective	Optimized Parameter	Operating Mode	Ref.
Boost Converter Inverter MPPT	MPPT	Voltage, Current	Island	[42]
Rectifier Boost Converter	Generator Control at Low Speeds	Voltage, Current	Grid-Connected	[43]
Back-to-Back Converter	Wind Turbine Control	Voltage, Current	Grid-Connected	[44]
Four Level Diode Clamped Inverter	Grid-tied Inverter Control	Voltage, Current	Grid-Connected	[45]
NPC Inverter Three level Boost FCS-MPC	Control of NPC Inverter at High Power	Voltage, Current	Island	[46]
Voltage Source Inverter	Reduction of Frequency Fluctuations	Active/Reactive Power	Island	[47]
Rectifier DC-DC Converter Inverter	To develop model MPC for hybrid system	Power/Torque/ Speed	Island	[48]

3.2. MPC for Solar PV Conversion

Authors in [49] applied MPC to the fly-back converter and an H-bridge inverter. The experimental results show a significant improvement in the dynamic performance over linear control. Renewable energy sources can supply power to the main grid through power electronic converter interfaces. These applications are increasing for distributed generation in buildings, nano-, and micro-grids. Nonetheless, considering the challenges associated with intermittent solar insolation, it is essential to extract maximum power from the PV cells at all operating conditions (especially during low insolation). In [49], separate dc-dc converters were employed for each modular PV unit. This approach decoupled the source voltage and regulated unequal power supplied from the units. A distributed MPC controller was implemented by authors in [49] based on the fixed-step MPC. This facilitated MPPT, droop control, and improved response of the power sources units to the grid uncertainties. The work presented in [50] investigated a predictive control for a grid-connected solar PV system to control and manage power in a way to minimize the defined cost function.

The atmospheric-induced variability in PV power supply and uncertainties in demand can result in low power quality if there is a mismatch between supply and demand. Through effective control, the active and reactive power injected to the grid can be optimized. Furthermore, it is important for grid current control to meet regulatory grid standards, e.g., the harmonic spectrum requirements of IEEE-519 standard. These results are obtained by employing a modified two-stage controller to predict the next control variable. These objectives were achieved by the use of the point of common point (PCC) voltage as an auxiliary signal in [51]. A three-stage PV converter control was attained: highly efficient electronic power converters configuration, high-efficiency MPPT, and therefore acceptable overall system efficiency.

One of the motivations for advanced PV converter control is that there are physical, financial, and manufacturing limitations to PV-module efficiencies. Thus, MPPT techniques that optimize the conversion efficiencies of existing hardware technologies are highly sought after. Sensorless control also helps to reduce component count, cost, and energy losses. An MPC control strategy designed for the quasi-Z source (qZS) three-phase converter is presented in [52]. The qZC, which has four legs, does not suffer from the disadvantages of conventional voltage/current source inverters. Fault-tolerant, fast current control with MPC was experimentally verified for both balanced and unbalanced conditions.

Direct current microgrids are beneficial due to higher efficiency, reliability, and easier connection of renewable energy sources compared to AC microgrids. In [53], a study on the control of multiple PV systems in a DC microgrid using a predictive controller was presented. The proposed predictive controller for DC microgrids implements MPPT on bidirectional dc-dc converters for battery power storage system. Using MPC, physical system constraint violation was prevented. The proposed method also ensures maximum output power from the PV system while optimizing battery state of charge (SoC).

In order to reduce the circulating currents between inverters, Ref. [54] proposes an MPC algorithm, which improves the overall power quality of grid-injected current from the PV system. The performance was verified by simulations. In [55], a static distribution compensators was applied to compensate reactive and harmonic power mismatches in a microgrid for linear and nonlinear loads.

In [56], a hybrid MPC (comprising high-frequency and low-frequency) is proposed to solve the challenges of the classical and duty-cycle-optimized MPC techniques applicable for the active neutral-point-clamped (ANPC) converters. The main advantages of this technique are fixed switching frequency for the high-frequency stage of the converter and reduction of the computational burden. The power converter is divided into two stages: the high-frequency side and the low-frequency side. The capacitor voltage balance and improved performance of the converter over linear control were achieved. The proposed structure is shown in Figure 8.

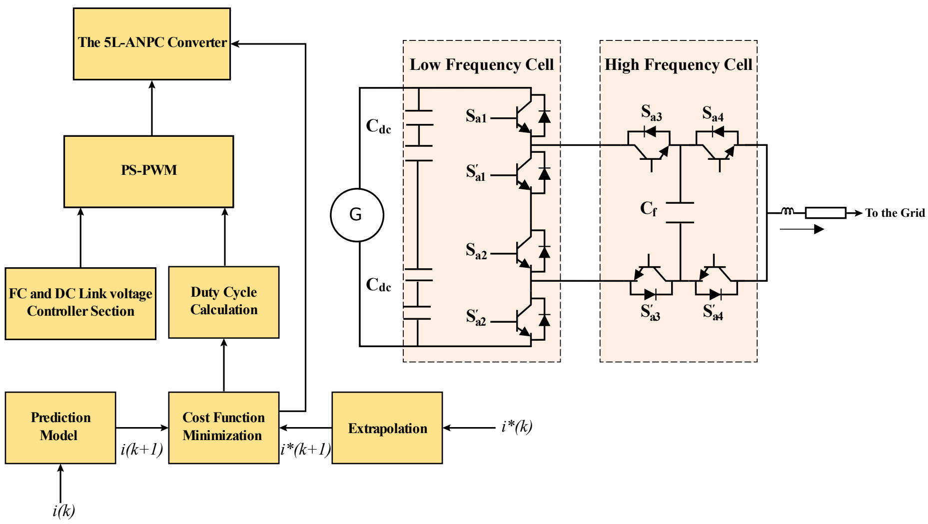

Figure 8. Control Diagram of the proposed MPC [56].

The application of MPC techniques for a seven-level multi-level inverter was investigated by [57] for PV power generation systems. The seven-level multi-level inverter is realized by three stages, as shown in Figure 9. The first stage is responsible for controlling the dc-dc converters using MPC-based MPPT. The switching states are sent to the dc-dc converters' switches and a reference current for the grid-side stage is generated. Three bidirectional solid-state switches are employed in the second stage to actuate the desired output voltage levels. To guarantee the generation of all voltage levels, only one arm must be triggered during every control time interval. The MPC technique is also applied to control the second stage's switches. Finally, the H-bridge changes the polarity in each half-cycle of the grid frequency. The efficiency of MPPT and transient response are improved.

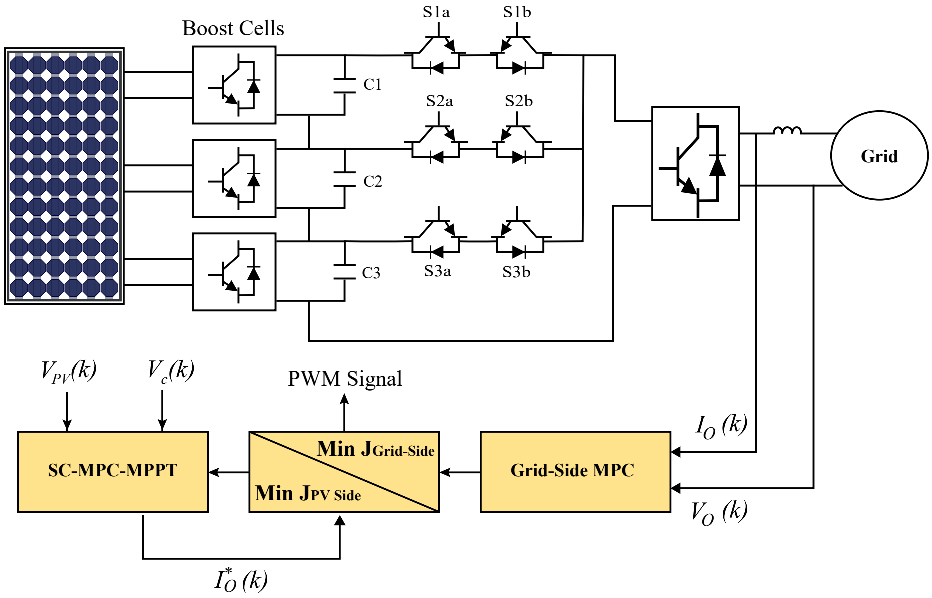

Figure 9. The block diagram of single-phase 7-level multilevel inverter in a PV generation system [57].

The control of power converters by finite control set MPC (FCS-MPC) takes advantage of the solid state switches discrete properties. The computation of target parameters predictions is the first step, and so switching states are selected to minimize the defined cost functions. Ref. [58] reported the implementation of FCS-MPC technique on a cascaded full-bridge inverter in PV applications. Two MPC algorithms based on the current control loop and power control loop are proposed. Figure 10 considered only the current control loop, which simplifies the control. However, the algorithm utilized a linearized sytem model, resulting in high oscillation in output waveforms. The second control strategy causes lower oscillation in the output waveform, while increasing the complexity of the overall control.

Some recent work on the power quality issues of microgrids is concentrated, which is discussed as follows. In [59], a robust predictive controller to increase the power quality of PVs connected to the grid through paralleled VSI is presented. The MPC algorithm is proposed based on the optimization approach with the aim of reducing circulating currents between inverters. The simulation results show the good performance of the proposed controller to improve the power quality and suppress the circulating currents. In [60], an FCS-MPC approach is reported for a voltage source converter with an LC output filter based on tracking the voltage reference trajectory. Accordingly, the proposed approach enhances the quality of network power by decreasing the harmonic distortion of the output voltage. In [61], a new predictive controller is described based on the static distribution compensators with the aim of compensating reactive power and harmonic reduction in microgrids with nonlinear loads. In [62], a modified dual second-order generalized integrator-based model predictive control approach is proposed for power management and control of solar PV integrated to the grid. Due to its simple configuration and effective control implementation, its superior performance is experimentally verified.

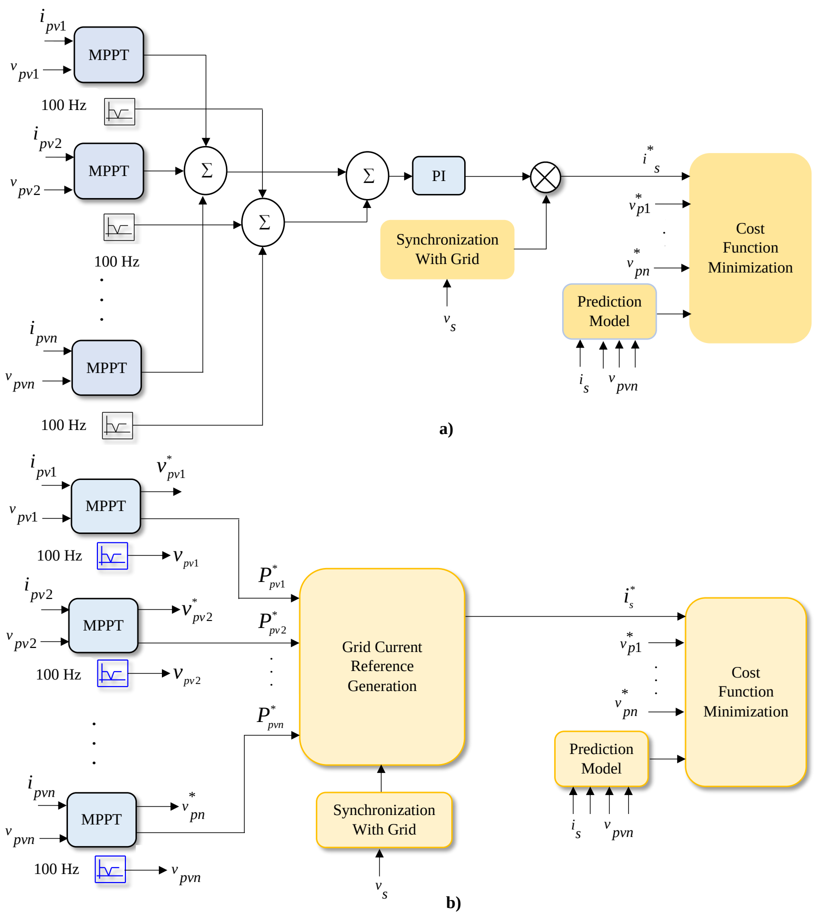

Figure 10. Predictive control block diagrams for the CHB PV system: (**a**) with predictive current loop, (**b**) with predictive current [63].

A multi-level control system based on predictive control with Kalman filter to increase power quality is reported in [64]. Table 3 provides different structures for MPC. The proposed approach, by eliminating and tracking harmonics in the microgrid system, ensures the reliability and optimal performance of the system. Any error in the microgrid causes a deviation of the system voltage and frequency, which affects the power quality. To overcome this, an adaptive predictive control model was conducted based on the robust Kalman filter developed with a harmonic particle swarm removal control system that significantly improves the quality of power delivered to the load [63]. Table 4 provides an overview of recent research on PV. A control structure for a symmetric multi-level inverter based on the model predictive controller is presented. The aim is to select the appropriate vector for the voltage to achieve a DC link with the same output [65]. An advanced control approach for cascaded and asymmetric photovoltaic inverter based on model predictive control is provided to track maximum power point, unit power factor and reduce harmonic distortion [66].

Table 3. Proposed structure for MPC.

Proposed Structure	Control Purpose	Outcome Specifications	Ref.
MPC-PWM	Reduce the circulating current of the inverter, regulation of the currents injected into the grid	Increase system reliability	[59]
FCS-MPC	Switching frequency control and power quality improvement	Reduction of losses by decreasing variable switching frequency	[60]
MPC-DSTATCOM	Reactive power compensation and harmonic reduction	Increase stability	[61]
MDSOGI-MPC	Optimal management of the power transmission	Optimal performance of VSC by estimator SOGI	[62]
MPC-REKF-IPSO	Improvement of power quality	Reduction of harmonic	[63]
MPC-EKF	Increase reliability	Reduction of the computational time	[64]

Table 4. The recent work on MPC-based PV systems.

Configuration	Main Purpose	The Optimized Parameters	Operating Mode	Ref.
Three Phase Inverter	Microgrid Optimization	Inverter Output Current	Grid-Connected	[67]
Three Phase Two Level Four Leg Inverter	DC link Voltage Control for Balanced/Unbalanced Condition	Inverter Output Voltage	Island	[68]
Grid-Connected Solar PV Inverter	The Proper Dynamic Response	Inverter Output Current	Grid-Connected	[22]
Flying Capacitors Inverter, DC-DC Boost	MPPT	Inverter Output Current	Grid-Connected	[69]
Impedance Source Inverter	Regulation of the inverter current	Inverter Output Current	Grid-Connected	[70]
The Grid-tied Inverter	Improved Predictive Method for Inverter Current Control	Inverter Output Current	Grid-Connected	[71]
Load Connected PV/Wind Inverter	The Solar/Wind Power Control	Inverter Output Current	Island	[72]

4. MPC for Frequency Regulation

Frequency control in microgrids has become an important subject because of the inherent weak-grid features of power networks with converter-interfaced DERs [73–77]. This is especially true for DGs such as photovoltaics and wind turbines because the voltage source is connected to the microgrid through the inverter and they have relatively little inertia [78]. Furthermore, due to the high ratio of power changes to small scale energy capacity in island microgrids, frequency and voltage changes are very sensitive. Thus, it is necessary to pay careful attention to the issue of frequency control.

The active power-frequency (P-f) droop method is a common frequency control method for island microgrids [79–81]. In [82], the concept of virtual inertia is proposed to improve the frequency response of a microgrid under perturbations related to large frequency deviations. In [83], based on droop control and the concept of virtual inertia, the issue of using the demand response to control the frequency is addressed. In micro-grids based on renewable energy with converter interface, reduction of inertia caused by the lack of rotary mass in the synchronous generator can cause fluctuations in frequency and voltage, which in turn causes system instability and affects the normal operation of sensitive loads. To reduce these fluctuations and increase the stability of microgrids, a virtual synchronous generator controlled by model predictive control for the energy storage system was proposed. This method can increase the dynamic properties of system voltage and frequency and solve inertia problems [84]. An adaptive model predictive control technique is proposed to control the load frequency of a two-area power system with an island microgrid. A state space model is also used to predict the future behavior of variables to reduce frequency deviations due to parametric changes [85].

In renewable energy-based microgrids, a virtual synchronous generator with energy storage system is used to reduce power fluctuations. In the traditional method, severe load changes cause system frequency deviations, and to compensate these, a recent study proposed a fuzzy controller with model predictive controller. The virtual inertia and attenuation coefficient of the synchronous generator are adjusted by the fuzzy controller and its rated power is optimized using the MPC method [86]. Since changes in wind and load speeds in some way affect the active power and output torque, its compensation can cause severe fluctuations. Thus, a frequency compensation based on this interaction is proposed. Furthermore, MPC is applied for each turbine that allows the fluctuations to be responded to appropriately [87]. MPC's predictive capability to predict future events and take appropriate control actions was further explored in [88] . In [89,90], predictive control, in [91], two-level predictive control, and in [92], multiple predictive control by considering charging and discharging of electric hybrid electric vehicles. The objective is to reduce power fluctuations in corresponding time intervals to the operation and management of the microgrid (application of control signals at intervals of several minutes). Furthermore, [92] a method for providing coordinated control of wind turbine blades and hybrid electric vehicles, based on predictive control, was presented in order to reduce power and frequency fluctuations in the microgrid. The distributed model predictive control method was proposed to control the output frequency of the power plant in order to decrease frequency fluctuations. The advantage of MPC is that it can be directly extended to multiple-input multiple-output (MIMO) systems, which can be quadratic, and take into account process constraints, making it impossible for variables to exceed predefined values [93,94].

5. Reliability

Reliability is an important factor in MGs and its criteria state that each system has the extent that has fulfilled its main task of supplying electrical energy to consumers. Reliability is calculated by a set of general indicators that are accepted almost all over the world. The purpose of reliability assessment is to estimate the effect of power outages on consumers [95]. An improved strategy based on model predictive current control (MPCC) under asymmetric grid faults is proposed. In this proposed structure, the problems of delay and computational volume, as well as the flux measurement of wind turbine during low voltage ride-through (LVRT), are solved [96]. Several studies have been conducted on symmetric and asymmetric faults for inverters and reliability of grids. These studies in the direction of a predictive controller would definitely achieve better results for grid reliability [97,98]. Generally, the evaluation of the life of power inverter elements is done using the MISSION PROFILE consumption profile and assuming symmetric loading on the elements [99]. While the use of MPC approaches may cause asymmetric loading of equipment, this issue must be carefully considered. In [100], the authors have presented an intelligent method based on particle swarm optimization, taking into account availability and equipment costs as constraints. In other research, for optimal energy distribution in a microgrid, an improved optimization algorithm is proposed to reduce the operating costs of microgrids taking into account economic issues [101]. Even though the methods of these studies can improve some reliability indexes, they are for long-term programming. In microgrids, stability and stabilization of voltage and frequency of the network are important, which requires fast and robust control methods that have not been considered in these references. Since the predictive controller provides an optimal response over other control approaches, the use of this control method in this research can play an important role in the development of microgrids. A robust predictive control approach with time-varying linear state feedback design is provided for inverters in the microgrid taking into account uncertainties and distortions [102]. In recent years, the use of renewable energy, distributed generation (DG), energy storage resources, electric vehicles, and load management and response in the distribution network has been increasing [103]. Moreover, various studies have been conducted on distribution networks and improved their reliability. Researchers provides a general framework for assessing the reliability of microgrid distribution systems [95]. The reliability effects of blackout management strategies in distribution networks can be evaluated. The proposed scheme in [104], which is based on the predictive control approach of the model, minimizes the total load reduction in the system and eliminates the uncertainties existing during the blackout period. In [105–107], model predictive control approaches provide for microgrid energy management from the point of view of fault in order to detect online faults that compare actual behavior and model in each sampling period. Another application of MPC control methods in increasing the reliability is improving fault-tolerant and fault management of distributed inverters. Authors in [23,108,109] focus on fault detection of multilevel inverters based on MPC. When an open circuit fault occurs in one of the switches, the control algorithm can detect the fault and remove the faulty switches from the circuit. Post-fault strategies based on the flexible finite control set MPC technique is presented in [110] to keep the acceptable operation for a grid-connected wind generation unit to support the grid in faulty conditions. Using Finite-Set Model Predictive Controls strategies could improve the thermal stresses on the power components [111–113]. The unequal dc-links issue is a stability challenge for Packed U-Cell inverters, which can be solved by the adaptive FSMPC technique [114]. To select the optimum vector in the vector control strategy, the MPC concept is employed to improve the controllability of multilevel inverters [115]. Employing MPC techniques bring other challenges such as predictive error restrictions. Therefore, Ref. [116] tried to solve that problem using a self-correct approach. An MPC-based virtual vector method has been worked out for a single-phase grid-tied converter to improve power quality. To eliminate the harmful effect of current ripple on the fuel cell stack, an MPC-based dc current control schema is presented in [117].

6. Challenges and Future Perspectives

Nowadays, with the increasing interest in integrating distributed energy sources with microgrids presents important challenges in terms of control and reliable performance. This section is a discussion on the trend of recent opportunities for the application of MPC techniques to DER converters.

6.1. Trends in Integration to Power Systems

Many of the challenges created by DERs stem from the fact that they are essentially invisible and cannot be controlled by grid operators, making integration into the overall operation of the grid challenging. Therefore, to solve these challenges, an intelligent solution in real-time is needed to monitor and manage these resources so that the performance of energy resources can be evaluated more accurately. Since renewable and distributed power units are developing rapidly, their performance has to be improved in terms of active/reactive power control, voltage/frequency regulation, and short circuit capabilities. Thus, electric firms assume that distributed conversion technologies will function well as well. The integration of wind turbines, PV inverters, and other distributed generations with electricity systems due to their performance in terms of security, dependability, and power quality, will demand greater attention in the future. As a result, in the future years, grid code requirements for active and reactive power regulation, short circuit power levels, harmonics, and stability will grow [118].

Distributed power sources, such as wind turbine performance are expected to suffer the consequences of the fault ride-through (FRT). One of the challenges for wind power conversion systems is the asymmetrical grid fault [119]. Further investigation is necessary to evaluate the performance of distributed current-source conversion systems with various configurations since current-source converters demand more attention in the design and operation to meet the FRT requirements. Different MPC-based strategies for dynamic voltage restorer (DVR) are proposed in the literature to limit the additional DC link voltage in full-scale wound rotor synchronous generator (WRSG)-based WT under fault conditions. Findings from the results indicate that this approach responds well to different types of errors and remains connected to the grid by an MPC-based DVR [120].

In [41], an improved FRT strategy based on MPC is provided for DFIG to meet grid connection criteria. To reduce the overcurrent of the rotor during voltage droop, a series resistor with the rotor is used. This approach improves system transition modes in fault conditions and reduces rotor overcurrent, torque fluctuations, and DC link overvoltage. It also helps grid voltage restoration by injecting reactive power into the network.

6.2. MPC Challenges in Terms of Solutions for DERs

The control strategies play an important role in the development of DERs to achieve optimal performance, increase efficiency, reduce energy costs, and increase longevity and proper dynamic performance and stability. Recently, the FCS-MPC approach has been used as an optimal and intelligent solution for controlling energy conversion systems. Although several papers have reviewed FCS-MPC, there are still challenges. The volume of calculations increases exponentially in the long-term forecast horizon as well as in the applications of multilevel power converters [121]. The FCS-MPC operates at a variable switching frequency, resulting in extensive harmonicas for the waveforms; therefore, filter design in systems that use FCS-MPC faces a fundamental limitation [122,123].

7. Conclusions

Distributed renewable generation of electricity has become essential for sustainability of the electrical power industry. However, it poses new challenges as control requirements for grid-connected distributed energy resources (DER) become more stringent. Thus, control solutions such as predictive control are beneficial to facilitate the robust, high-performance optimal regulation of DERS. In this article, the model predictive control (MPC) of distributed energy resources (DER) was reviewed: in particular, microgrid DER for low voltage AC and low voltage DC networks. For wind conversion, MPC control of active and reactive power, and generator torque and speed for permanent magnet synchronous generators, and dual-fed induction generators were discussed. Solar photovoltaic applications for minimizing converter circulating current, and reactive power compensation were also covered. The role of MPC for DER-based frequency regulation was also discussed. Finally, the role of MPC in improving the reliability of grid-connected systems was highlighted.

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