A review on state of art development of model predictive control for renewable energy applications

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A review on state of art development of model predictive control for renewable energy applications

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ABSTRACT

Renewable energy sector is undergoing rapid expansion as the global focus is shifting towards cleaner, reliable and sustainable resources. As the new installation of these resources are well underway, there is tremendous potential for exploring these to more advanced control algorithms. Model predictive control is gaining immense popularity because of its flexible controllability, its ability to be used in any of application irrespective of its field as well as the availability of fast processors. This paper presents a systematic review on Photo-voltaic (PV) and wind energy systems controlled by Model predictive control approach. The work presented here will help the researchers to further explore the flexibility of this controller for design, analysis and implementation in renewable energy systems.

1. Introduction

The world is undergoing remarkable development recently and is moving towards green energy technologies, far from fossil fuels. Even though a majority of the countries have started using renewable energy extensively, there is still having a long way to go to utilize this energy to satisfy their daily energy demands. Though the government is concentrating on all forms of renewable energy only wind and solar hold a special place mainly because they are hassle-free. Reasons for the optimistic development of the global renewable energy markets are certainly its financial benefits, uncertain worldwide oil and gas supply, and the urgent need to go for pollution-free technologies in order to reduce the change in climatic conditions and air pollution [1].

Solar energy is inexpensive and its acceptance seems irresistible. The price of PV panels has declined 99% over the last four decades and has dropped by three fourths, helping global PV installations grow 50% per year. Fig. 1 shows the new solar and wind energy installations from the year 2000–2015 and forecasted new installations up to the year 2019.

The world wind power capacity had an increase of more than 20% a year over the past 10 year span. This is because of many credible features such as its declining price and by public policies supporting its expansion [2].

China, the world's prime producer of carbon emissions has projected to install a total of 120 GW of wind power, 43 GW of solar and 320 GW of hydropower at the end of this year. It has targeted at least 20 GW of new wind power installations and 15 GW of additional solar PV capacity next year. Fig. 2 shows the global new installation for the years 2000–2015 and the forecasted installations from 2015 to 2019. Fig. 3 shows the total cumulative capacity for the top 10 countries.

According to data by the International Renewable Energy Agency (IRENA), employment in the wind energy sector is raised to a whopping 23%, having crossed a 1 million jobs milestone in this year, up from 834,000 in last year. The nation to lead in this arena was China with more than 500,000 jobs. The other countries to follow it were US and Brazil. The world-wide wind capacity has attained reached 392′927 MW by the end of June 2015, out of which 21′678 MW were added in the first six months of 2015. Fig. 4 shows total solar cumulative installed capacity of top 10country in 2014 and 2019. All wind turbines installed worldwide by mid-2015 can generate 4% of the world's electricity demand. The global wind capacity grew by 5.8% within six months [3].

Since the growth in the renewable energy sector is inevitable with the global focus shifting towards it, with all the preplanned new installations, it is the responsibility of all us to utilize this energy to a maximum possible extent with an ultimate efficacy. In recent times, developments in power electronics and semiconductor technology have led to several advancements in power electronic conversion systems [4]. The evolution of the fast processors have also played a major role in it

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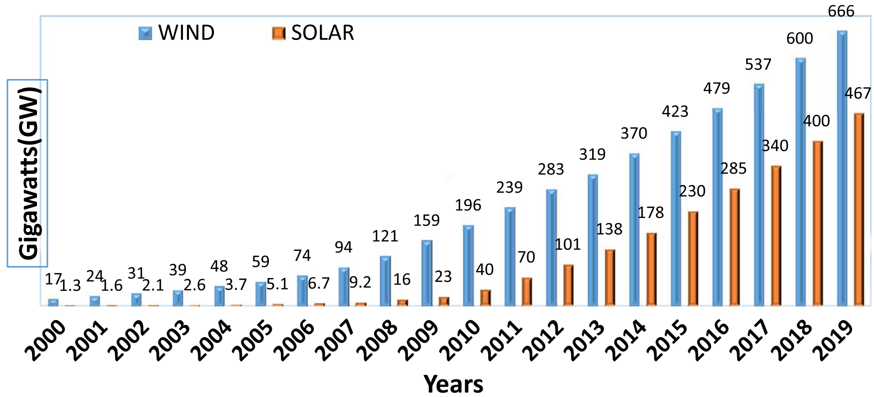

Fig. 1. : Global Cumulative Installation 2000–2019.

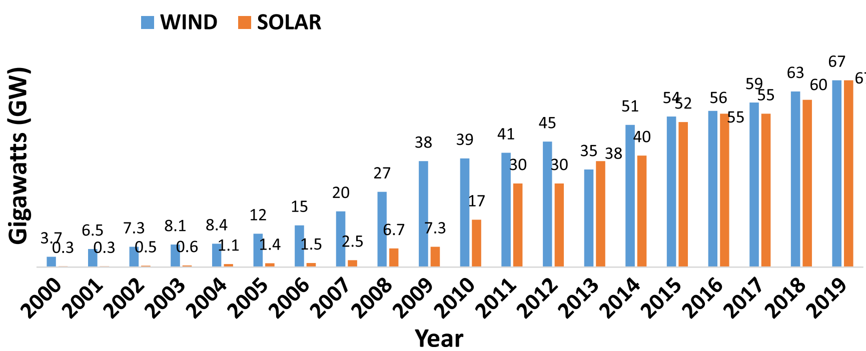

Fig. 2. : Annual New Installations 2000–2019.

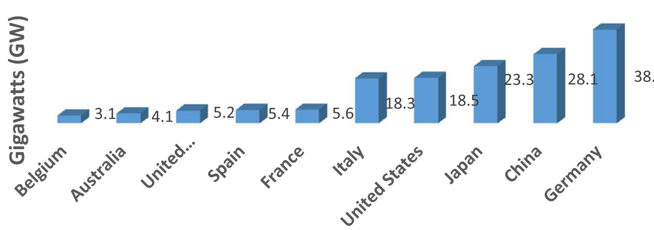

Fig. 3. : Total cumulative capacity by country (top 10) in 2014.

by paving a way for executing many advance, complex and sophisticated control techniques to the converters within a fraction of second. One of these techniques which is gaining huge popularity in recent years in the field of power conversion is the Model Predictive Control algorithm (MPC). The main objective of this review is to present a systematic review on MPC controlled PV and wind energy systems. The focus of this work is to provide an in-depth review on MPC controlled converters with renewable energy source and its applications. The objective or the control law of the any MPC based control is defined in the cost function. Therefore the control variable and the cost function of each predictive controller is described for each renewable energy application. These descriptions are tabulated for the ease in understanding. The main applications of the MPC controlled renewable energy system is to either be used as a standalone application or to be connected to the grid. Thus, the work presented here will help the researchers to further explore the flexibility of MPC controller for design, analysis and implementation in renewable energy power conversion systems.

2. Motivation and research background

Even though the idea of MPC was developed in 1970 in process control industry, the interest in it has reached its pinnacle only in recent days. Its gaining popularity is because of the availability of fast processor which has the ability to implement many complex problems in a fraction of seconds. The main advantages of the MPC controlled

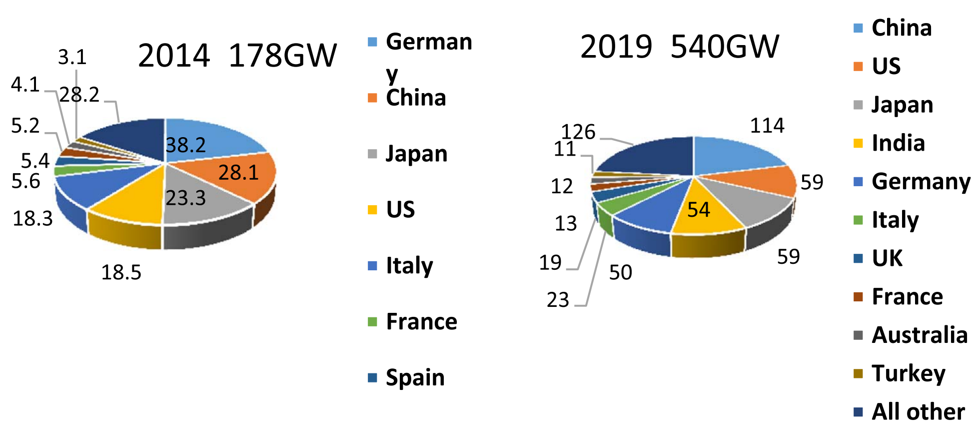

Fig. 4. : Total PV Cumulative Installed Capacity by Country (top 10) in 2014 and 2019.

inverters are absence of modulator, utilization of variable switching frequency, possibility of online optimization, lower complexity for low level inverters and inclusion of constraints.[5–8]. This technique has been used in many areas since several decades [9–18]. Research of MPC in the power electronics has travelled a long road within a short duration of time with its first publication in 2007 applied to a Voltage Source Inverter(VSI) [19]. Generalized control techniques such as PI controller utilizing SPWM, Space vector PWM, Direct Power Control(DPC) and optimization techniques are being used in even now due to its versatility [16–29]. But they are being replaced by MPC because of its same kind of reliability [25–41]. MPC is used for various power electronic applications including control of various converters, induction motor [42–50]. Here a discrete time model of the VSI is used to predict the future values of the load current for all the possible voltage vectors of the inverter. The cost function used here evaluated the current error at the next sampling time. This work was the pioneer of the research for utilizing the MPC for the inverters. Simplified predictive control for a VSI with its comparison with conventional techniques is depicted in [51].

A detailed usage of Finite control set MPC(FCS-MPC) applied to a VSI in given in this paper [52–54]. Along with this, MPC's suitability and its greater potential to be used in inverters particularly, that with the reduced switching states and complex operating principles is discussed. MPC's has the ability to multitask, by addressing the different control objectives in a single cost function of the algorithm. The control objectives include reducing the switching frequency, real and reactive power control, reducing the sub-spectral harmonics. The priorities given to each control objectives in the cost function is decided by the usage of weighing factors.

3. MPC-operating principle

The basic ideas of MPC are: building a model for prediction, representing the required behavior of the system using cost function and minimizing this cost function to produce the actual command [55]. The main advantage lies in control of the various variables at the same time including the restrictions. This is especially important because here we are dealing with units of different kind and magnitude of variables that are getting controlled.

The discrete time model of the MPC using the state space model is given by,

$$x(k+1) = Ax(k)+Bu(k) \tag{1}$$

$$y(k) = Cx(k)+Du(K) \tag{2}$$

Where x, u, y denote, the state, input, output variables. The Eq. (3) defines the cost function of the system in such a way the behavior of the entire system is described taking the references, future states and their actuations into account as well as the error between the predicted and the reference variable like power error, torque error and in this case load current error.

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

$$u(k) = [1 \quad 0\ldots\ldots0]argmin_u J \tag{4}$$

where J denotes the cost function of MPC problem.

Since the MPC is an optimization problem and each sampling instant the problem is solved using the updated data and a sequence of new actuations each time. Using the system model and the data until the time k the prediction can be up to $k + N$ in the horizon of time. The process is repeated with measured data each time. The comparison between a linear controller and MPC controller is shown in Table 1.

Fig. 5 shows the block diagram of a MPC current controller applied to an inverter. The controller mainly consists of the prediction block and the cost function block. The predictive block estimates the prediction *i(k+1)* which is estimated from the model of the load. The second block is represented by the cost-function given by g. The

Table 1
Comparison between a linear controller and MPC controller.

Parameters	Linear controller	MPC controller
Design of controller	Kp, Ki adjustments by root locus or pole placement technique	Defining the Cost function
Modulation Strategy	Using either PWM or SVM	Modulation stage not required
Implementation	Either analog or digital controller	Direct digital implementation
Switching frequency	Fixed	Variable
Flexibility	Inclusion of Constraint	Constraints directly and easily included

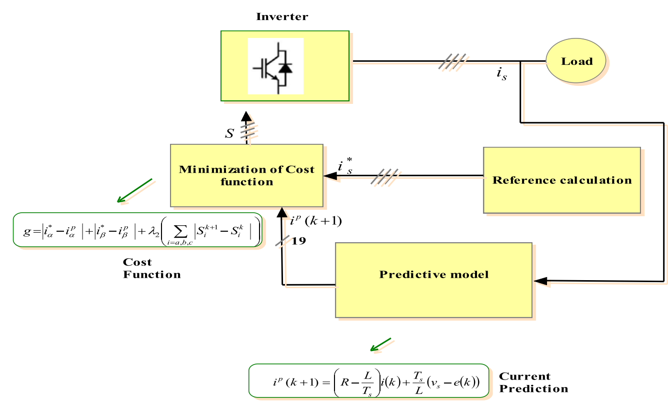

Fig. 5. : An FCS-MPC block diagram for current control.

switching states which correspond to the voltage vector with the minimum cost function is selected [51,54].

3.1. Model predictive current control

MPC's has the ability to multitask, by addressing the different control objectives in a single cost function of the algorithm [57]. The control objectives include reducing the switching frequency, real and reactive power control, reducing the magnitude of sub-spectral harmonics. The priorities given to each control objectives in the cost function is decided by the usage of weighing factors. But the weighing factor design is not discussed here.

Design and implementation of current control of three phase PWM rectifier based on predictive control strategy are discussed [58]. However here the predictive current control technique operates with constant switching frequency using space vector modulation (SVM) and therefore uses a modulator.

The FCS-MPC is used to control a DCMLI [59] acting as a back to back motor drive. Santiago A. Verne et al., show that FCS-MPC controlled DCMLI can be used work as an active front-end rectifier.

Trabelsi et al., proposed a FCS-MPC current controlled FCMLI [60]. Here active and reactive power is control indirectly by controlling the current in rotating reference frame. It is proved that controller does an excellent job of controlling a grid connected inverter.

Cortes et al. proposed the FCS-MPC for three phase five level CMLI for a fixed RL load [61]. Since a five level inverter has 125 voltage vectors, calculating the current prediction for all of these vectors in space one sampling time becomes complicated. The controller has to spend the entire computational bandwidth only for calculating the 125 predictions. Therefore here in the proposed work, only 61 voltage vectors out of all of 125 possible voltage vectors are considered. This is done in order to reduce the number of calculations and make it suitable for implementation in a standard control platform. These 61 voltage vectors can be further reduced to 19 voltage vectors with the same functionality but with reduction in computational time [56,62].

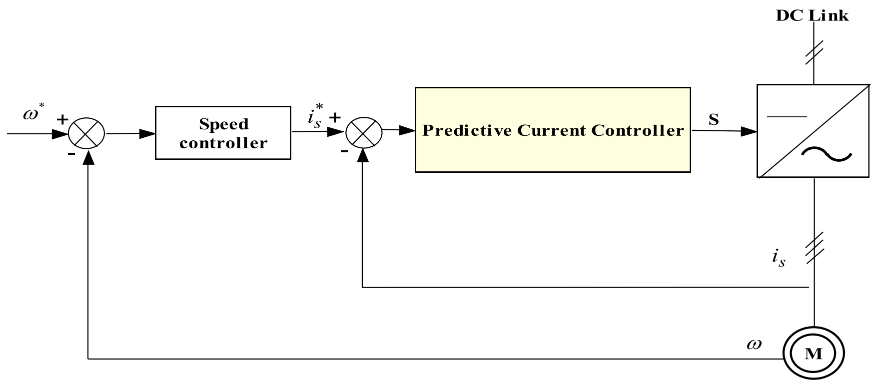

Fig. 6. : Predictive current control with reference tracking for the three-phase inverter with induction motor.

Yaramasu et al. proposed FCS-MPC current control strategy for a four leg VSI to deliver power to the balanced, unbalanced and non-linear load [63,132]. This topology has 16 possible switching states. The current prediction of the load currents is done for each of the 16 possible switching states. This work confirms that this control strategy works well for balanced, unbalanced and non-linear loads as well as balanced and unbalanced references for a three phase four wired system..

Young et al., analyzed and validated the performance of the FCS-MPC for a VSI comparing it with the linear PI-SVM technique which is considered as the classical digital control technique [64]. The validation is done for both steady state and transient performance indices. In addition to this, in-depth harmonic analysis of the current has also been carried out to prove that the FCS-MPC current control works in par with the classical linear controllers.

Fig. 6 shows the classical cascade control scheme of an induction motor having the outer speed control loop and inner current control loop using predictive control [65]. For the external speed control to work efficiently the inner current control has to be 100–500 times faster [66]. Thus on the basis of its versatile application and its fast control performance, predictive current control proves to be an excellent choice to serve this purpose. The main aim of this current control loop is to control the inverter such that the stator current of the induction motor is controlled.

3.2. Predictive selective harmonic elimination

Selective harmonic elimination (SHE) is one of the predominantly used modulation techniques owing to its simplicity. Fundamental switching frequency carry additional weight since for high power converters it produces more switching losses if used in high switching frequency. From a predetermined output voltage waveform its fundamental and harmonic components are separated using the Fourier series which results in the non-linear transcendental equations. These equations can be solved by using classical techniques such as Newton-Raphson. Here the non-linear the equations are linearized and solved producing appropriate angles are switching states which are to be given to the inverter.

Optimizations techniques can also be used to solve these non-linear equations and to find these switching angles. Ant colony optimization [67], Genetic algorithm [68] Particle swarm optimization [69,70], Artificial bee algorithm [71], Shuffled-frog-leaping algorithm [72] are used to find the optimal switching angles. SHE can also be used for all the topologies of multilevel inverters provided the predetermined output waveform of the inverter is at the appropriate level. A complete review of the multilevel SHE technique which includes the discussion on the various solving algorithm, implementation and its applications are discussed in [73]. The SHE problem implemented for the CMLI is discussed in [74].

Even though the implementation of all these techniques is relatively easier it has two major drawbacks. All these SHE techniques are offline techniques. The switching angles are obtained from a predetermined output waveform through various optimization techniques and the stored in the look-up table. Therefore if there are any variation in the output voltage or if there are any changes in the input dc link voltage, these switching angles would be null. Therefore in the applications where there are input or load voltage changes these off-line techniques would not work.

Kouro et al., explore the possibility of the online SHE technique by introducing Finite Control Set Model Predictive controlled SHE (FCS-MPC SHE) [75]. Fig. 7 shows block diagram of FCS-MPC SHE. It is shown that SHE can be used very well for a VSI and a NPC inverter. FCS-MPC SHE technique is the implementation of MPC on the SHE problem having the elimination or reducing the voltage harmonics as its main objective. PC-SHE involves the sliding discrete Fourier transform (SDFT) in its cost function. SDFT is the recursive application of the discrete Fourier transform. Sozański used SDFT the harmonic compensation of the current for the active power filter applications [76].

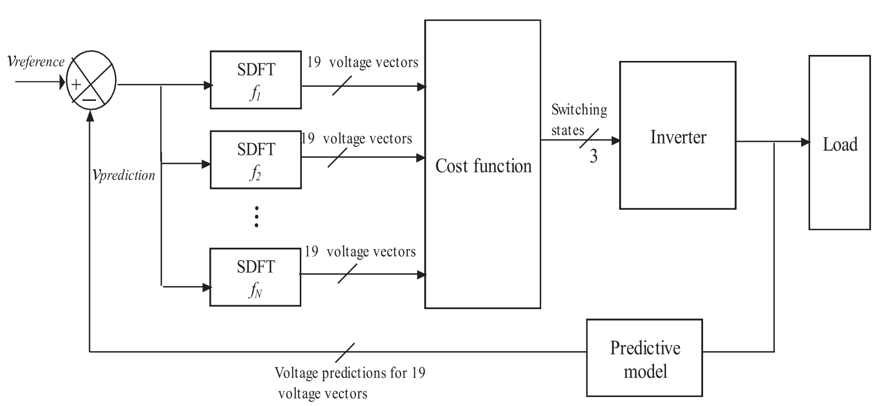

Fig. 7. : Block diagram of FCS-MPC SHE controlling a inverter.

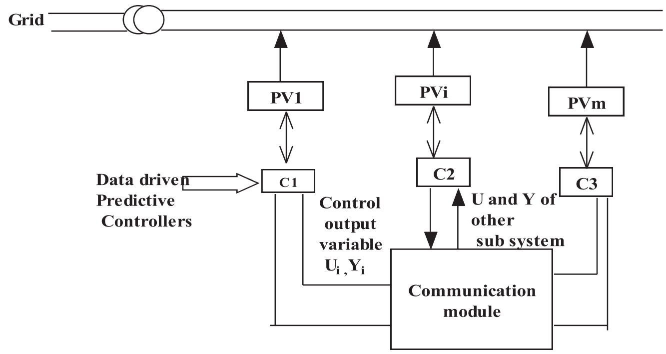

Fig. 8. : Model predictive control strategy for PV systems.

Aggrawal et al., proposed a FCS-MPC SHE technique for a three phase CMLI, where the magnitudes of the harmonic eliminated are all meeting the IEC 61000-4-30 class A grid code standards [75].

4. MPC for solar

Nowadays, most of PV systems are integrated with grid because for stand-alone systems, batteries are required to store the energy which will increase the cost of the entire system. The government has announced the subsidies those who are generating the power on their own and also injected the generated power into the grid, therefore people shift their focus towards the PV system. Therefore most of the research on PV based systems are based on grid based systems [77–80]. Soft computing based schemes for control of PV based systems are in great focus in recent years [81–84].

Data-driven distribution predictive control in solar PV generation system is discussed in [107] and shown in Fig. 8. The large-scale solar PV generation system is divided into several interacting subsystems and the control purpose is to achieve the global performance of the entire system by controlling the output currents of each subsystem to track the reference output currents. However, the influence of the grid-impedance variation on the current control has not been discussed.

Qi et al., proposed a supervisory control system shown in Fig. 7 via MPC is designed for a wind/solar energy generation system to compute the power reference for wind and solar subsystem to minimize the cost function at each sampling time [86]. The objective of the solar subsystem is to track the desired power reference which is calculated by the controller. The Maximum power point tracking (MPPT) of the PV system is calculated as,

$$\frac{\partial P_{PV}}{\partial v_{pv}} = \frac{\partial i_{pv}}{\partial v_{pv}} v_{pv} + i_{pv} = 0 \tag{5}$$

Maximum PV power P_{pvmax} is calculated by the following equation

$$P_{pvmax} = P_{pv,max}(x) = -\frac{\partial i_{pv}}{\partial v_{pv}} v_{pv}^2 \cong -\frac{\Delta i_{pv}}{\Delta v_{pv}} v_{pv}^2. \tag{6}$$

Even though the MPPT is done and maximum power is obtained, the system startups and shut downs are not addressed here (Fig. 9).

The signals are sent to two local controllers, which drive the two subsystems to the requested power references. Yang et al., proposed two distributed supervisory MPC controllers replacing a centralized supervisory control as shown in Fig. 9 [85]. Each distributed controller takes care of applying optimized power reference to the local controller. However several issue are not addressed, e.g., system startup or shut. Table 2 shows the summary on recent developments in MPC controlled PV systems.

Perez et al., proposed a control technique to manage in real time power production of a grid-tied PV system with energy storage capability [100]. This control technique also forecasts the future saturation of the energy storage system, which will take place at reduced ratings. The validation is done by using the actual data for various days, at different atmospheric condition and at different degrees of accuracy. The cost function is given as,

$$J_N = \sum_{K=0}^{N} \lambda(k) c(t+k) T (P_{grid}(t+k) - Pref(t+k)) + C_{SOC}(t+N+1) E_{ES}(t+N+1) \tag{7}$$

Where $P_{ref}(t+k)$ is the future constant-by-hours power production committed by the PV plant, $P_{grid}(t+k)$ is the power fed to the grid at instant $(t+k)$, that is $P_{grid}(t+k) = P_{pv}(t+k) + P_{ES}(t+k)$ $P_{PV}(T+K) + P_{ES}(T+K)$, being $P_{pv}(t+k)$ the panel production and $P_{ES}(T+K)$the power exchange with the ESS. $E_{ES}(T+N+1)$ is the energy stored in the ESS at instant (t+N+1), $C(t+k)$is the imbalance cost at instant $(t+k)$, $C_{SOC}(t+N+1)$ is the value of the energy stored in the ESS at instant $(t+N+1)$. $\lambda(k)$ is weighting sequence and $T$is the sampling period of the MPC. The energy stored in the ESS at any future instant $E_{ES}(T+K)$ can be calculated as,

$$E_{ES}(t+k) = E_{ES}(t+k-1) - TP_{ES}(t+k-1) \tag{8}$$

Micro-grid constitutes of storage units, DGs, non-controllable devices like renewable energy resources and controllable loads. One of the main motivations behind using micro-grids is that they are capable of managing and coordinating DGs, storages, and loads in a more decentralized. Hence, the optimization of the micro-grid operations is important in order to cost efficiently manage its energy resources. In [102], an energy management system based on a rolling horizon strategy is proposed for an islanded micro-grid comprising photovoltaic (PV) panels, two wind turbines, a diesel generator, and an energy storage system. Energy management system for a renewable-based micro-grid. The energy management system provides the online references for generation units while minimizing the operational cost and taking into account the forecast of renewable resources, load and water consumption. The cost function which includes various constraint is given as,

$$J = \delta_t \sum_{t=1}^{T} C(t) + \sum_{t=1}^{T} O_A(t) + C_{US}\delta_t \sum_{t=1}^{T} P_{US}\delta_t(t) + C_{Tf} \sum_{t=1}^{T} V_{Tf} + C_{\pi}(T) \tag{9}$$

Where δ_t is the duration of time period t, $C(t)$ is the cost function of the

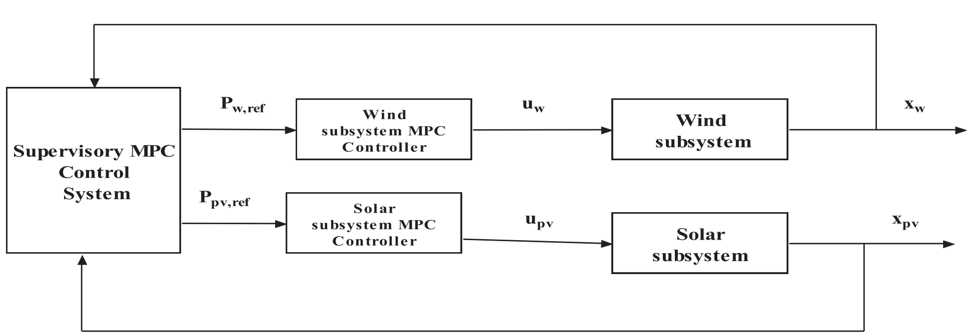

Fig. 9. : Supervisory MPC control of a hybrid system.

diesel generator, $C_s(t)$ is the start-up cost function of diesel generator, P_{US} is the unserved power in the system,C_{US} is the price for unserved energy,V_{Tf} is the unserved water,C_{Tf} is the cost of unserved water,$C_\pi(T)$ is the cost of using the LAB.

Parisio et al., proposed the optimal operation planning of a microgrid as shown in Fig. 10 [95]. Here, the overall micro-grid operating costs is reduced to meet predicted load demand of a certain period while taking into consideration the operational constraints, such as the energy balance, and controllable generators minimum operation time and minimum stop time.

MPC is proposed to solve the unit commitment problem with wind power generation [96]. Further, an MPC-based dynamic voltage and VAR control scheme has just been developed for reactive power control, in order to avoid unstable voltage conditions in micro-grids, especially during islanded mode operation with no support from the utility grid.

$$J(x_k^b) = minu_k^{T-1} \sum_{j=0}^{T-1} [c_u'(k+j)u(k+j) \quad + \quad c_z'z(k+j) - OM^bF'(k+j)$$
$$u(k+j) - OM^bf'w(k+j)] \tag{10}$$

$$S_i \quad . \quad P_i(k+j) + \quad s_i \quad \le \sigma_i(k+j); i=1. \quad . \quad . \quad . \quad N_g x^b\left(\frac{k}{k}\right) = \quad x^b(k) \tag{11}$$

Where C_Z and C_U are column vectors, S_i and s_i are the vector of disturbances profile,$w(k+j)$ is assumed to be known over the prediction horizon for j=0,….,T-1; The term $OM^bF'(k+j)$ in the objective function does not affect the optimal solution

Kakosimos et al., proposed a MPC approach is used for a PV system based on single phase nine level cascaded MLI connected to grid connected system [94]. The MPC controls several important characteristics such as regulation of each separate DC-link voltage enabling the control scheme to satisfy RE systems' need of interfacing various and different power sources into the grid as well as unity power factor. Moreover, care is taken for the neutral point potential to maintain each cell's capacitor voltages balanced. The control strategy is exposed to transient phenomena in both DC and AC side and the response is also investigated under dynamic reference.

Fig. 11 shows the detailed block diagram for MPC controlled PV systems. Two separate PV strings on the input side are controlled by applying transient phenomena like variation in PV irradiation, reference voltage variation and grid voltage drop.

$$J = \quad \sum_i \lambda_i . \ ((Predictedvalue_i) - (Reference_i))^2 \tag{12}$$

More specifically, the quadratic error of the grid current and input DC voltages at time $t_{k+1}(i_s^*(t_k), v_{dn}^*(t_k))$ from the actual values $(i_s[t_{K+1}]), v_{Cnj}[t_{k+1}])$ at time t_{k+1} have been set as the desirable references and included in the adopted cost function as shown in below

$$J = \lambda_A . \ (i_s[t_{k+1}] - i_s^*(t_k))^2 + \sum_{n,j}^{\substack{j=2\\n=2}} \left[\lambda_v . \left(\frac{V_{dn}^*(t_k)}{2} - V_{Cnj}[t_{k+1}] \right)^2 \right. \tag{13}$$

Where $i_s^*(t_k)$ and $V_{dn}^*(t_k)$ are the desirable grid current and DC-link voltages. The λ constants are employed as weighting factors adjusting the cost function value,

$$\lambda_A = \frac{1}{i_{nom}}, \quad \lambda_v = \quad \frac{1}{v_{d.nom}}$$

5. MPC for Wind Energy systems (WES)

Currently the effective energy generation is not only the key factor of economic power usage but also the storage and supply to the load.

Table 2
Summary on recent developments in MPC controlled PV systems.

Ref.	Converter/ topology used	Parameters to be optimized	Main objective	Stand-alone/Grid connected	Description
[132]	Three phase Two level four leg inverter.	Inverter output voltage	High quality load and Dc link voltage for balanced, unbalanced and nonlinear loading conditions	SA	Compensates the effect of uncertainties in the load and dc-link voltage No penalty in the transient and steady state operation.
[85]	Single- phase grid Connected Solar PV inverter	Inverter output current	High quality power, Good dynamic response	GC	Data- driven predictive controllers-divides the entire system to the different subsystem and controls the output current of each subsystem.
[86]	Three phase load connected wind/solar PV inverter.	Output power control	Tracks the maximum power point and therefore control the power of solar and wind systems.	SA	Supervisory model predictive - Determines online the operation mode of both generation subsystems, switching from power regulation to maximum power conversion
[87]	Open delta three phase inverter	Inverter output current	Apply MPC to efficiently optimize the Microgrids	GC	Minimizing the overall microgrid operating costs to meet predicted load demand Various operational constraints are taken into account
[88]	Flying capacitors inverter fed by DC-DC boost converter	Inverter output current with UPF stabilizes the capacitors	To extract the output current with unity power factor (UPF)and maximum power from solar PV panel	GSC	Boost converter steps up the PV voltage to the stable required dc level for direct grid feeding without using a line transformer, The real time digital MPC is proposed to control the flying capacitor voltage of the inverter5and output current with unity power factor
[89]	Impedance source inverter	Output current of T-source inverter	Control the inverter load current. Extract maximum solar power from the panel through MPPT algorithm and FSMPC model	GSC	Inverter gain is raised by lowering their Turns Ratio towards unity. The output current, passive component voltage and current are well regulated.
[90]	Asymmetrical Impedance -source inverter	Inverter output current	Incremental conductance MPPT algorithm and FSMPC model is developed to control the output current of the grid-tied Inverter	SC	The inverters gain is raised by lowering their Turns ratio towards unity. Input current drawn by the proposed inverters is smoother and

(continued on next page)

Table 2 *(continued)*

Ref.	Converter/ topology used	Parameters to be optimized	Main objective	Stand-alone/Grid connected	Description
					hence more adaptable by source.
[91]	Voltage source inverter	Load voltage, current, power	To the control horizon length, load demand forecast accuracy are also investigated	GSC	The forecast model predicts load demand signals for a model energy management strategy achieves 96–98% of the optimal NG performance derived via dynamic programming (DP)
[40]	Three phase four leg Inverter	Current and voltage control	Internal current of a PV system is controlled by MPC, external voltage controlled by PI controller	GC	Fast dynamic response and high flexibility. MPC is used as an internal controller in a PV system with external voltage controller to run MPPT Algorithm.
[92]	Single phase multilevel inverter	Inverter current	To produce high gain and control the amplitude and frequency of the current injected into the grid.	GC	Reduced harmonics and efficient power conditioning system for grid-tie photovoltaic applications
[93]	Current source inverter	Inverter voltage	To increase efficiency of the system	GC	Continuous control set model predictive control to control the output Inverter currents.
[94]	NPC-H-Bridge Inverter	Inverter current	Two separate PV strings controlled while being subject to transient phenomena related to asymmetric string conditions in terms of solar radiation and reference voltage variation.	SA	The inverter topology of NPC bridges in cascade allows low current THD factor to be achieved using a simple inductor instead of complicated LCL filters benefiting also from low capacitor banks in the DC-link Bus.
[95]	Distributed generation inverter	Harmonics elimination, inverter current	Improving the reliability and stability of the network and preserving the output voltage of primary generation unit	GC	Fast sampling system to track the periodic signals and to optimize steady state and transient state problems, to reduce computational time, harmonic elimination, power quality improvement
[41]	Single phase grid connected Inverter	Inverter voltage	The highest accuracy waveform of output is derived and the smallest order. The model composes of piecewise-linear estimators and linear parameter with pole, zero and delay	GC	Accuracy of nonlinear voltage model is around 97.34% and transformed to state space model, to generate control horizon with predicted output voltage from MPC
[96]	Voltage source inverter	Inverter power	To achieve high power quality, fast and smooth grid connection of renewable and distributed power sources, high quality electricity and grid-friendly' support	GC	High-performance of distributed generations and innovative control techniques MPC is developed at tertiary level
[97]	Single phase grid connected inverter	Inverter current	To construct the mixed sensitivity performance and to satisfy the performance of future control mixed sensitivity	GC	Good tracking performance. THD is less than 1%, $H\infty$ controller has a good tracking performance for different power rates and power change.
[98]	Three phase voltage source inverter	Inverter current	To achieve more reliability and accuracy, high stability	SC	Operating in d-q reference frame synthesizing the sinusoidal current, this model is validated using the 35.7 kW PV system
[99]	Three phase current source grid connected inverter	Inverter voltage, current	Injecting energy, controlling directly amplitude of the output currents	GC	Good dynamic and ensures fixed switching frequency, current control is performed by measuring the grid current and grid voltage
[100]	Three phase current source inverter	Inverter power	To manage the power deviations of daily and intraday electricity markets	GC	Improving the performance and good optimization in economically, more accurate prediction of PV power
[101]	Current source inverter	Inverter power	To reduce the peak values of inrush or surge currents and control the power for Wind/Solar at each sampling	SC	Supervisory predictive control architecture

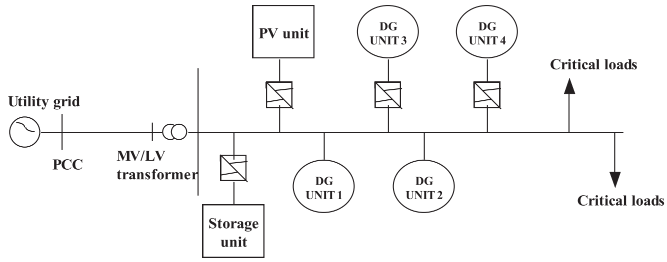

Fig. 10. : Schematic diagram of Micro-grid system.

Large scale wind penetration is increasing the variability in the power flow of grid, provides the need for reserve requirements [103–105]. Filho et al., proposes a model-based predictive controller for a power control of DFIG [106]. The control law is derived by optimization of an objective function that considers the control effort and the difference the actual between the predicted active and reactive power outputs and its references.

Kusiak et al., proposed that the non-controllable variables such as wind speed can be included in the cost function to predict the control variable [107]. Here the control variables are rotor speed and turbine power output as shown in Fig. 12.

Chirapongsananurak et al., proposed that the optimal control signal

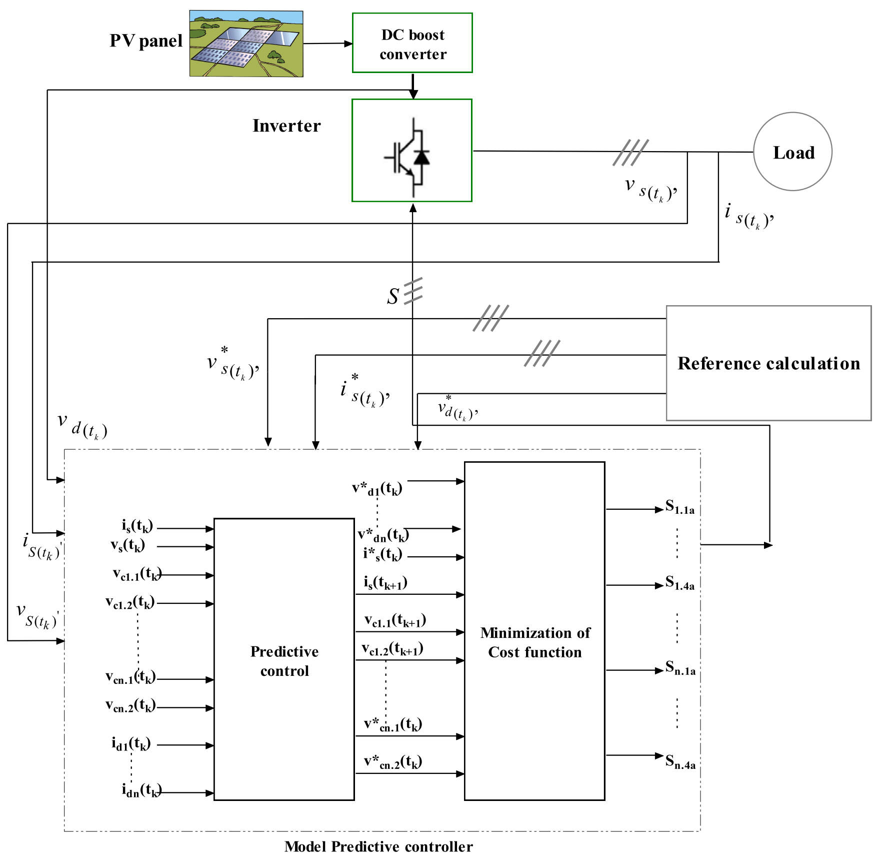

Fig. 11. : Detailed block diagram for MPC controlled PV systems.

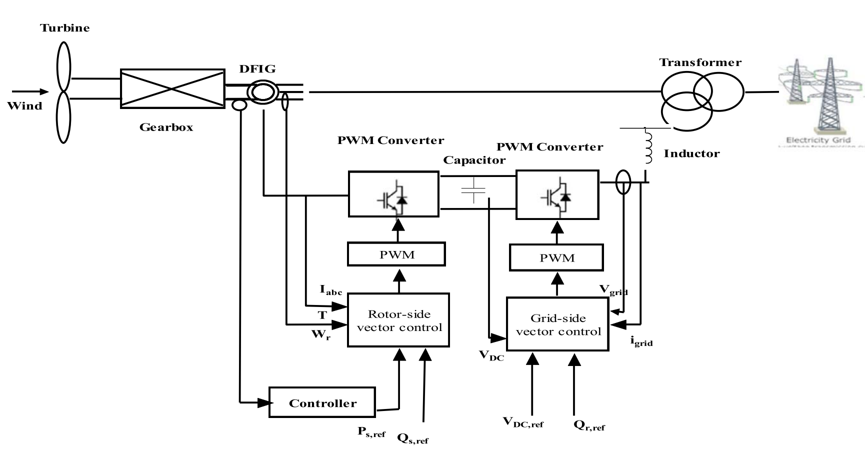

Fig. 12. : Conventional controller for the wind energy systems.

Table 3
A summary on recent development in MPC controlled wind energy systems.

Ref.	Topology/Control	Parameters to be controlled	Main objective	Grid connected/ Stand alone	Description
[109]	Matrix converter	Voltage, frequency, current	To synchronize voltage and frequency to the grid	GC	Seven to three phase DMC (Direct Matrix converter) for connecting multiphase generator to three phase grid. Controls input current at unity power factor, output current magnitude and frequency.
[110]	Multiple MPC	Pitch angle, generator torque	Control of variable speed, variable wind turbine above rated speed	SA	Provides the trade-off between numbers of partitioning to increase the linear approximation accuracy. Improves the power quality. Reduces load due to switching.
[111]	Boost converter, Rectifier	Dc voltage, current	To control the generator and to provide voltage elevation at lower speeds.	GC	FCS-MPC (Finite Control Set) controls the dc-link voltage, current distribution while maintaining a stable commutation frequency. A new strategy is used in MPC algorithm to fix switching frequency.
[108]	VSI	Real power rotor angle reactive power	To maximize energy output and limit system frequency negative impact	SA	Output power is less fluctuating. Linearization technique is used to obtain the model
[112]	–	Torque, frequency	Control algorithm for variable speed wind turbine	SA	Soft starting and smooth starting to the optimal trajectory are obtained. Maximum power capture is done.
[113]	Neural network based MPC	Torque, frequency	To control wind tunnel match number control system	SA	Control of nonlinear multiple variables, large lagging and time-varying system.
[114]	PHEV (Plug-in Hybrid Electric Vehicle)	energy	Balancing capacity of wind farm	SA	PHEV provides additional balancing power. MPC uses short term forecast COSMO−2 for storage utilization.
[115]	Adaptive control	Power, voltage	To accurately and smoothly track the grid references	GC	Wind speed characteristics are tuned by adaptive control. Power trajectories are controlled by MPC.
[116]	Novel algorithm, MPPT, Boost converter, inverter	Voltage, current	MPPT algorithm for variable speed wind turbine	SA	Modified Incremental Conductance (INC) with variable steps is applied. Maximum output power even though there is fluctuations weather including wind velocity.
[117]	Inverter, rectifier	Voltage, current	Power control of DFIG under unbalanced conditions of grid	GC	Power compensator enhance the wind turbine in terms of ensuring sinusoidal stator currents. the cancellation electromagnetic torque oscillations
[118]	Rectifier, inverter, dc-dc converter	Current, power, speed, torque	To develop model MPC for hybrid system	SA	Optimum set points are obtained by quadratic programming. Improve the subsystem control without global optimum control.
[119]	Battery Energy Storage System (BESS)	Voltage, charging rate and discharging rate of battery	To design a controller with battery energy storage to smooth output power.	GC	Battery capacity constraint affects the smoothening measurement. Stability of the system is ensured.
[120]	Battery Energy Storage System (BESS)	Battery power, Generated power	To compensate the intermittency of wind power and also to make more dispatchable	SA	Novel control scheme along with BEES applied to manage dispatchability. Avoids BESS to be overcharged or depleted.
[121]	Back-to-back converter	Current, Voltage, speed	Control strategy for wind turbine based PMSG(permanent Magnet Synchronous Generator)	GC	Robustness to parameter variation. Fast dynamic response.
[122]	Chance-constrained MPC	Power, frequency	To smooth the power output of hybrid wind-solar thermal plant	GC	Novel wind power smoothening is applied. Level of fluctuation, risk of fluctuation leak is minimized.
[123]	VSI	Pitch control, Speed, power	Field-oriented control of DFIG	GC	Steady state error is negligible both at above and below rated speeds,
[124]	Multi variable control strategy	Pitch angle, torque	Optimizing the aerodynamics efficiency.	SA	Improve in efficiency with an acceptable drive train transient loads. Improve in the transition between power optimization and power

(continued on next page)

Table 3 *(continued)*

Ref.	Topology/Control	Parameters to be controlled	Main objective	Grid connected/ Stand alone	Description
					limitation
[125]	Load frequency control	Speed, Power, voltage	Load frequency control design in the presence of wind turbine	SA	Reduction in uncertainty due to governor and load parameter variation. Robust against the parameter perturbations.
[126]	Four level diode clamped inverter	Voltage, current	Control grid-tied inverter for high power wind farm	GC	Reactive power control is by D-axis and q-axis grid currents. Reduction in switching frequency while maintaining power quality.
[127]	NPC inverter, three level boost converter, FCS-MPC	Voltage, current, speed	Control of three level boost converter and NPC inverter for high power PMSG based wind farm	SA	Simple, low cost, reliable and efficient solution for multi variable operation. dc-link voltage is constant
[101]	Inverter,Rectifier, Supervisory control	Voltage, current	Optimal management and operation of hybrid wind-solar energy stations.	SA	Predicted outputs are calculated using linear space model. Machine parameter variation can be neglected.
[128]	PI –MPC controller	Mechanical power, frequency, governor output	To reduce uncertainty due to governor,load disturbance, variation in turbine parameters	SA	Faster oscillation damping. Reduction in variations and enhancement in frequency.
[129]	DFIG	Pitch angle, Pitch torque	To control wind turbine fed with DFIG (Doubly Fed Induction Generator)	GC	Energy capture maximization, mitigate drive train transient loads. Smooth power generation while reducing the pitch actuator activity.
[130]	Fast gradient method, D-MPC (distributed)	Speed, power	Active power control of wind farm with D-MPC	SA	Balance between power tracking and reference and the wind turbine load minimization. Robustness to errors and system parameter variation.
[131]	Non-linear MPC, back-to-back converter	real and reactive power, current	to make power generation cost effective and reliable	GC	Good reference tracking and stability for the rotor speed. Electromagnetic torque ripple is minimum for the steady state and transient response of DFIG.

Table 4
Simulation parameters.

S No	Component	Value or Number
1	Dc link voltage V_{DC}	300 V
2	Nominal reference current	10 A
3	Nominal reference frequency	50 Hz
4	MOSFET	IRF540
5	Diode	RTF20
6	Resistor	60 Ω
7	Inductor	48 mH
8	Sampling Time	25µs
9	dSPACE	DS1103

can be determined from input signal, objective function, and constraints [108]. With this concept, maximum power generation and fluctuation of injected power will be compromised. This paper introduces the method to design a controller for a wind power generation using MPC technique. It will maximize output energy, while adverse impacts on system frequency have been kept within specified limits. The maximized output energy is given as,

$$E = Max\sum_{i=1}^{N} P(k+i) \tag{14}$$

Subjects to constraints such as,

$$I_l \le I(k+i) \le I_u$$

$$\Delta I_l \le \Delta I(k+i) \le \Delta I_u$$

$$P_l \le P(k+i) \le P_u$$

$$\Delta P_l \le \Delta P(k+i) \le \Delta P_u$$

$$\omega_l \le \omega(k+i) \le \omega_u$$

$$i = 1, 2, 3, \quad . \ . \ . \ . \ . \ . \ , \quad N$$

Where P is the power, I is current reference signal (control signal), ω is Rotor speed,N is a prediction horizon. The cost function of the power is given by,

$$J_{power} = w_{y1}[y_1^* - 1600] + (1 - w_{y1})|y_1^*(t+1) - 1600| \tag{15}$$

Where w_{y1} is a weight coefficient between 0 and 1. A sample weight scheme is given by

$$J_{rotor} = w_{y2}|y_2^*(t) - y_2| + (1 - w_{y2})\frac{|y_2^*(t+1) - y_2^*(t)|}{h} \tag{16}$$

Where w_{y2} is a weight coefficient between 0 and 1. The overall cost function is given by,

$J = wJ_{power} + (1-w)J_{rotor}$ (17) Where w is a weight coefficient between 0 and 1. Note that $J_{power} and J_{rotor}$ need to be scaled by their appropriate values to ensure the weighted average is not biased. Here $J_{power}$is scaled by 1600, J_{rotor} is scaled by 23. Table 3 shows the summary on recent development in MPC controlled wind energy systems. The details include the main objective and the application where it is used i.e.grid or stand-alone applications.

In [131] a non-linear MPC is proposed for the rotor side control for controlling the real power reactive power and grid current control for a wind energy systems connected grid connected inverter as shown in Fig. 11. The generator speed from the doubly fed induction generator, grid current and grid voltage is measured from the grid and fed to the MPC controller. The controller shows good reference tracking and shows excellent stability for all rotor speed.

Masaki proposed proposes multi-variable control strategy for controlling pitch angle and generator torque to maximize energy capture, lessen drive train transient loads and to smoothen the power generated [122]. Therefore overall efficiency and power generated is improved. The main aim is to develop an overall control strategy that can work in both partial and full load regions. The overall cost function is given as,

$$J = \sum_{j=1}^{j=N_p} \|e^i(k+j)\|^2_{Q^i} + \quad q_3^i z^i(k+j)^2 \tag{18}$$

$$\underset{j=0,1,\ \ldots\ .N_C-1}{Min \quad \forall\Delta u(k+j)} \sum_{j=0}^{j=N_C-1} \|\Delta u(k+j)\|^2_{R^i} + \quad \|u(k+j)\|^2_{R_u^i} \tag{19}$$

Subject to:

$x^i(k) = \hat{x}^i\left(\frac{k}{k}\right)$ (20) $x_d^i(k) = \hat{x}_d^i\left(\frac{k}{k}\right)$ (21) $\Delta\beta_{min} \le \Delta\beta^*(k+j) \le \Delta\beta_{max}, \quad j=1, 2, 3, \ . \ . \ . \ . \ . \ . \ , \ N_c$

$$\Delta\beta_{min} \le \Delta\beta^*(k+j) \le \Delta\beta_{max}, \quad j=1, 2, 3, \ . \ . \ . \ . \ . \ . \ , \ N_c$$

$$\beta_{min} \le \beta^*(k+j) \le \beta_{max}, \quad j=1, 2, 3, \ . \ . \ . \ . \ . \ . \ , \ N_c$$

$$0 \le T_g^* \le T_{g,max}, j = 1,2,3, \ldots.., N_c$$

$$\omega_g^i(k+j) \le \omega_{g,max}, \quad j=1, 2, 3, \ . \ . \ . \ . \ . \ . \ , \ N_p$$

$$P_{DFIG}^i(k+j) \le P_{DFIG,\ max,} \ j=1, 2, 3, \ . \ . \ . \ . \ . \ . \ , \ N_p$$

Here N_p is the prediction horizon, N_c is the control horizon $[\omega_g^*(k) - \omega_g^i(k)P_{DFIG}^*(k) - P_{DFIG}^i(k)]^T$is tracking error and $\Delta u(k)$Is defined as $u(k) - u(k-1)$.

Soliman et al., proposed MPC technique applied to control a Double Fed Induction Generator (DFIG) which is widely used in wind energy

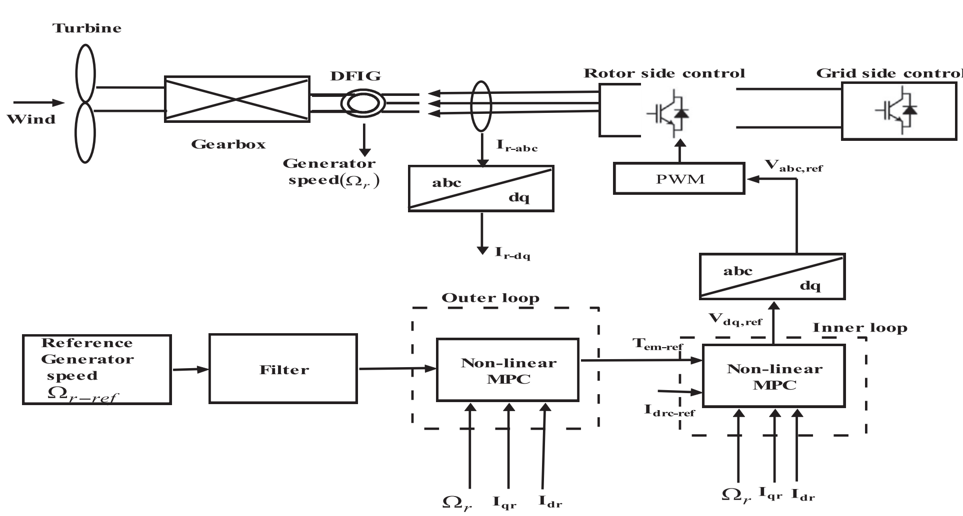

Fig. 13. : Schematic diagram of Controlling Double fed Induction Motor with Non-linear MPC in WIND Energy Conversion.

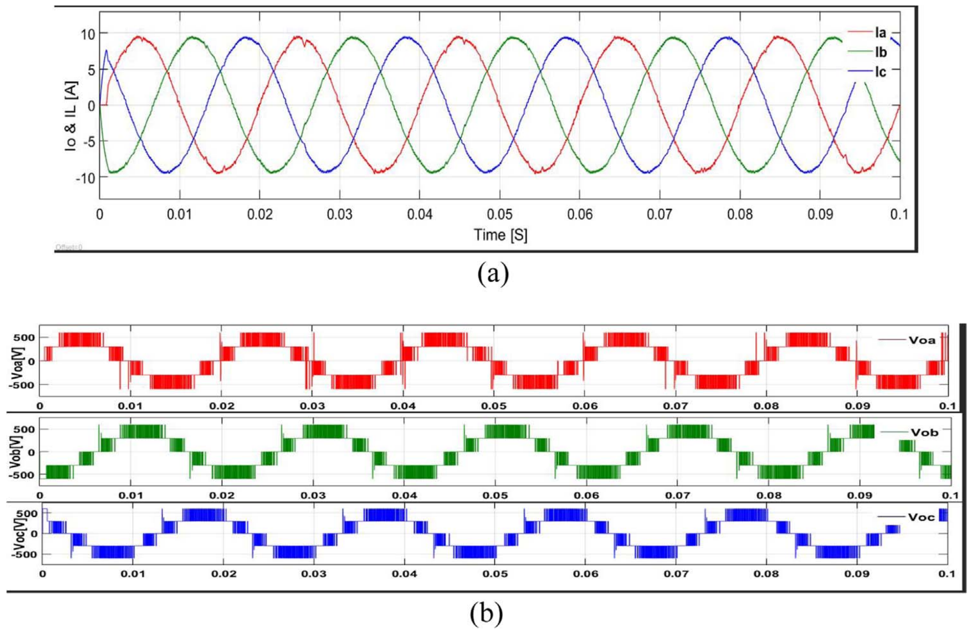

Fig. 14. : (a) Three phase load current (b) Load voltage for sampling time 25μs.

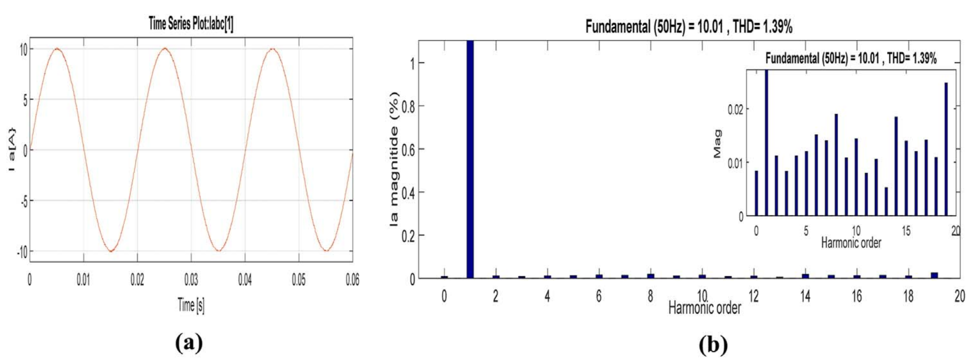

Fig. 15. : a) Load current of the inverter (b) its harmonic analysis.

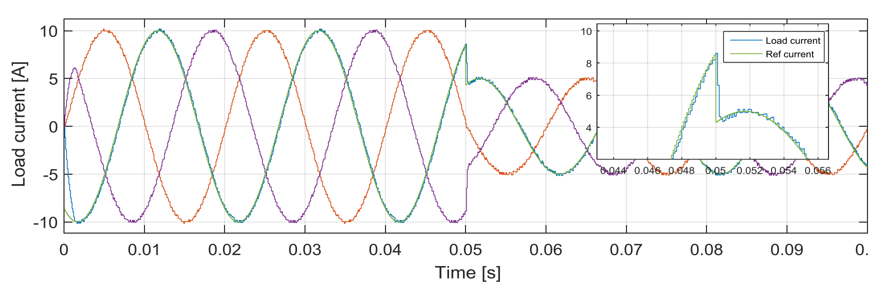

Fig. 16. : Load current with its reference current depicting dynamic condition.

systems [129]. The control law works on the principle of optimization of objective function which can be calculated by difference between the reference and the predicted output (active and reactive power). These are calculated by linearized state-space model. The control law can also be used in the calculation of supply voltage to the rotor and also applies the constant frequency which prevents the drawback of conventional Direct Power Control (DPC). At different operating conditions and machine parameter variations the power control can be done effectively.

In order to further achieve the efficiency of DFIG, Bernard et al., opted for new robust control technique which is combination of traditional and predictive control [128]. The load changes and abnormal conditions results in mismatch frequency and power interchanges between the areas. This can be eliminated by the combination conventional Proportional Integral (PI) and MPC controller. This design reduces the effect of uncertainty due to governor and variation in turbine parameter and load disturbances. For enhancement of network frequency quality the technique can also be implemented on single-area power system in which an aggregated generator unit is introduced. PI-MPC controller is much more advantageous and effective than that of MPC and conventional PI controller responses. It also controls the uncertainties in parameters and changes in load effectively. Even though MPC and PI-MPC are robust, PI-MPC technique provides the advantage over MPC in damping oscillations, enhancement in frequency and in reducing variations.

Rahim et al., adapted the MPC to a seven to three phase matrix controller for connecting multiphase generator to three phase grid [109]. The main objective here is to synchronize voltage and frequency to the grid. Model Predictive controller controls the input current at unity power factor, in addition to it also controls magnitude and frequency. The cost function is given as,

$$J = |i_{o\alpha}^{*} - i_{o\alpha}^{p}| + |i_{o\beta}^{*} - i_{o\beta}^{p}| + |i_{s\alpha}^{*} - i_{s\alpha}^{p}| + |i_{s\beta}^{*} - i_{s\beta}^{p}| \tag{22}$$

Where $i_{o\alpha}^{*}$ currents and $i_{o\beta}^{*}$ are the real and imaginary parts of the reference output current vector, Currents $i_{o\alpha}^{p}$ and $i_{o\beta}^{p}$ are the real and imaginary parts of the predicted output current vector, $i_{s\alpha}^{*}$ and $i_{s\beta}^{*}$ are the real and imaginary parts of the reference source current vector, $i_{s\alpha}^{p}$ and $i_{s\beta}^{p}$ are the real and imaginary parts of the predicted source current vectors.

Yamarasu et al., proposed the MPC for a multilevel grid-tied inverter for a high power wind farm for controlling active and reactive power [126]. A four-level diode clamped inverter is used for indirect power control wherein grid voltage and current is measured and fed to the controller. Here reactive power is controlled by manipulating D-axis and q-axis grid currents along with the DC link voltage. The average switching frequency of the inverter is also maintained minimum by considering it as an objective in the cost function.

$$J = (i_{dg}^{*}(k+1) - i_{dg}(k+1))^2 + (i_{qg}^{*}(k+1) - i_{qg}(k+1))^2 + \lambda_{dc} * \left\{ \sum_{j=1}^{2} ([v_{cj}(k+1) - v_{cj+1}(k+1)]^2) + [v_{c1}(k+1) - v_3(k+1)]^2 \right\} + \lambda_{SWC} * \sum_{x=a,b,c} SWC_X \tag{23}$$

Where λ_{dC} and λ_{SWC} are weighting factors for DC-link capacitor voltages balancing and switching frequency reduction. SWC_x is the number of semiconductor communications involved in phase-x and given as,

$$SWC_x = |S_{jx}(k) - S_{jx,\ op}(k)|, \quad j=1,\ 2,\ 3, \quad x = a,\ b,\ c \tag{24}$$

Where $S_{jx}(k)$ is the predicted gating signal of phase-x. To improve the dispatchability, large energy systems must be connected with wind farms which can be achieved by storing the energy over the schedule of energy generation and at period of under the schedule sourcing the energy providing on-site reserves which can be achieved by MPC. It also enables the control action to anticipate the fast changes such as wind ramps. It also improves the system performance compared to other approaches reduces the rate of change of wind plant output. Especially the rate of changes in reduction in scheduling error,-improvement reserve requirement, reduction in number of ramp events are at noticeable rates. The balancing area authority is used to decide the scheduling horizon as though it is not a degree of freedom for the system designer of energy storage but it is important constraint as it shows large impact on performance of system. The selection of shorter scheduling horizon results in the shift of burden of variability away from generation scheduled, which reduces the need for on-site energy storage for wind farms.

Aguirre et al., proposed almost same type of PV control with the exception of using a three level boost converter instead of using conventional converter [111]. FCS-MPC is used to control the both active and reactive power indirectly along with the DC link control. A three level boost converter and NPC inverter used for this high power PMSG wind farm. The entire system is validated experimentally and provides simple, low cost, reliable and efficient solution for multi variable operation

$$J_t(k) = [i_{dc}^{*}(k+1) - i_{dc}(k+1)]^2 + \lambda_{dc,\ b} * [v_{c1}(k+1) - [v_{c2}(k+1)]^2 + + \lambda_{SWC,\ b} * \sum_{j=1,\ 2} |S_{jt}(k) - S_{jt,\ op}(k)| \tag{25}$$

Estimate the future value of the reference dc current $i_{dc}^{*}(k+1)$ using the present and past sample

$$i_{dc}^{*}(k+1) = 4i_{dc}^{*}(k) - 6i_{dc}^{*}(k-1) + 4i_{dc}^{*}(k-2) - i_{dc}^{*}(k-3) \tag{26}$$

Where $\lambda_{dc,b}$ and $\lambda_{SWC,b}$ are weighting factors for the DC-link capacitor voltages balancing and switching frequency reduction.$S_{1t,op}(k)$ and $S_{2t}(k)$ are the predicted gating signals in the previous sample. Estimating the future value of reference grid currents, the vector angle extrapolation is a be suited approach for the stationary frame variable. The predicted value of the grid currents given in stationary frame is given as,

$$\begin{bmatrix} i_{\propto g}^{*}(k+1) \\ i_{\beta g}^{*}(k+1) \end{bmatrix} = e^{j\omega_g T_s} \begin{bmatrix} i_{\propto g}^{*}(k) \\ i_{\beta g}^{*}(k) \end{bmatrix} \tag{27}$$

Where ω_g is the grid angular frequency. The grid side cost function is defined as follows,

$$J = [i_{\alpha g}^{*}(k+1) - i_{\alpha g}(k+1)]^2 + [i_{\beta g}^{*}(k+1) - i_{\beta g}(k+1)]^2 + \lambda_{SWC,\ i} * \sum_{j=1,\ 2} \sum_{x=a,b,c} |S_{jx}(k) - S_{jx,\ op}(k)| \tag{28}$$

Where $\lambda_{SWC,i}$ is the weighting factor for switching frequency reduction of NPC Inverter. A new medium voltage power converter topology using a diode rectifier, three-level boost converter, and neutral-point-clamped (NPC) inverter is proposed for a high-power permanent magnet synchronous generator-based wind energy conversion systems [132].

6. Results

Simulation of a five level MLI for a RL load is carried out using MATLAB/Simulink, using the parameters listed in Table 4. Fig. 13 shows the load current and voltage waveform respectively for 19 vector scheme for sampling time 25 µs.

Fig. 14 shows the output currents and its corresponding harmonic analysis. It is seen that the output current shows a THD of 1.39%.

The ability to respond fast to the dynamic step change in reference current has always been a merit of MPC which is shown in Fig. 15. Fig. 16 shows the inverter load current for a step change from 10 A to 5 A depicting the transient behavior of the controller. The inserted image is the enlarged view of the load current following its reference current showing absolutely no overshoot during the transients.

7. Conclusion

Since the growth in the renewable energy sector is inevitable with the global focus shifting towards it with all the pre-planned new installations, it is the responsibility of all us to utilize this energy to a maximum possible extent. As the new installation of renewable energy systems are well underway, there is tremendous potential for exploring these systems to more advanced control algorithms. Due to the advancement in processor speed, the usage of MPC in power conversion field has now become a reality. Along with its ability to adapt to any kind of applications, it has now become an appealing preference from many control technique. In order to explain the versatility of the Model predictive control in power electronics field, its usage as a current controller and selective harmonic elimination is explained in detail. In addition to this predictive control application in control of induction motor is also dealt with. This paper gives a systematic review of various the work carried out in MPC controlled PV and WES systems. MPC used for various objective like voltage, current and power on various converters are reviewed. Finally, the results of the predictive current controlled three phase five level cascaded multilevel inverter are discussed to validate the controller both in steady state and transient conditions. All the worked carried out so far were discussed in details and their pros and cons are examined. The focus of this work is to provide an in-depth review on MPC controlled converters and its applications. The control variable and the cost function of each predictive controller is described for each renewable energy application. Thus, the work presented here will help the researchers to further explore the flexibility of MPC controller for design, analysis and implementation in renewable energy power conversion systems. Therefore, the main objective of this review which is to present a systematic review on MPC controlled PV and wind energy systems is satisfied.

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