Modeling and Simulation of a MPC Based Grid-Tied PVDG system

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Abstract- One of the key factor which has limited the expansion of photovoltaic distributed generation (PVDG) system has been its low efficiency compared to the conventional non-renewable energy sources. Maximum power point tracking (MPPT) techniques such as Perturb and observe (P&O) and incremental conductance (INC) are widely used methods for extraction of maximum available power from PV array to increase its efficiency. However, accuracy of tracking, slow dynamic response, increased oscillation and power losses are some of the challenges of these MPPT techniques. Current harmonics, voltage and frequency fluctuations and power flow control are some of the major control areas for efficiency improvement in a grid-tied PVDG system. Shunt active power filter (SAPF) can be used for harmonic compensation but it leads to increase in the overall system cost and complexity. Controllers such as PI based current controllers can be employed for eliminating the need for SAPF. However, they have a slower response. This paper presents the modelling of a grid-tied PVDG system with model predictive control (MPC) implemented for MPPT and inverter control for achieving multiple control objectives such as DC-link voltage control, active and reactive power flow and power quality control. MPC provides a faster MPPT response under rapidly changing atmospheric conditions and an effective inverter control strategy with power quality enhancement and improved efficiency. Here, a two stage PVDG system topology has been adopted for quicker MPPT response and wider operating range. The performance evaluation of the PVDG system model has been done using MATLAB simulations.

Keywords Modelling and simulation, MPC, Grid-tied, PVDG, MPPT.

1. Introduction

The rise in global energy demand and the increasing concerns of climate change has led to the rapid growth of PV energy systems, steadily replacing the conventional sources of energy generation [1]. The share of solar power in the global electricity supply has increased from 0.01% in 2008 to greater than 2% in 2018 [1]. Solar energy is a form of clean renewable energy. Its abundance in nature, ease of handling and low maintenance cost has been a pivotal driving force for its acceptance as an alternative to the non-renewable energy resources [2]. However, some of the major challenges for the PV system which has subdued its growth is its high installation cost and low efficiency which is only about 10 to 20% for commercially available PV devices [3-4].

The PV array output voltage and current has a non-linear relation and the array delivers maximum power only at a unique operating point due its dependence on the environmental conditions such as solar irradiance and cell temperature. Hence, numerous MPPT methods have been adopted for extraction of maximum power from the PV array to increase its efficiency [5-8]. Perturb and observe (P&O) and incremental conductance (INC) are some of the widely accepted and used methods because of their simple control structure. However, they have a slower response to the changing environmental conditions and provides increased losses due to large oscillations around the region of the maximum power point [7-10]. At present, due to the increased processing capabilities of the new microprocessors, control technique such as model predictive control which has a higher computational requirement can be easily implemented to provide a quicker dynamic response with small deviations at the maximum power point (MPP) resulting in reduced losses and better efficiency [11-14].

A grid tied PVDG system in comparison to a standalone system requires several additional controls to optimize the system for increased efficiency [15-17]. Voltage transients, frequency variations, faults, harmonics and other abnormal grid conditions all directly or indirectly effect the power quality output of the PVDG system reducing its efficiency [15-20]. A shunt active power filter (SAPF) can be placed at the connecting point between the PV system and the grid for harmonics and reactive power compensation. However, having a fixed SAPF component in a PVDG system increases the cost and adds to the complexity of the overall system [21-23]. This can be overcome by using controllers such as PI based current controller as presented in [20] for generating switching pulses with harmonic compensation and reactive power control integrated together. However, a PI controller relies on feedback control mechanism to obtain the appropriate control signal and requires a cascaded control structure to control multiple variables leading to a comparatively slower response [24]. MPC can be used to provide a comprehensive control method with power quality control integrated within the control structure [24, 31]. Since, the raw power generated by the PV system is DC in nature whereas our domestic utilities and the grid work with AC power. The, PV inverters are also used for conversion of DC to AC power. In a grid-tied PV system when the environmental conditions are favourable for energy generation i.e. on a bright sunny day or when the power requirement at the load side is less, then the PV system feeds the energy to the load and also supplies the extra energy generated to the grid. However, when the PV energy generation is on low side due to low availability of sunlight or when the power demand is high, the grid supplies the additional power required by the load. Hence, active power flow control is required between the PV system and the grid depending on the energy generation and load demand [20, 27].

This paper evaluates the implementation of model predictive control (MPC) for MPPT and power quality enhancement of a PVDG system for increased efficiency. MPC is a mathematical model based control technique which uses the system model to predict the future state of the system variables for different control inputs and selects the control input which produces output that closely approximates the desired output. It is a soft computing technique and does not require any additional hardware, the control logic itself aids in power quality improvement reducing the use of bulky, high cost filters and also results in cost saving. Also, MPC allows modelling of system non-linearities and multiple variable control within the control structure [24-31]. Application of MPC for MPPT and power quality control has been found to be effective and efficient producing a faster response to changing environmental conditions with significant improvement in power quality [11-14, 20, 27-31].

2. PVDG System Components

A schematic diagram of a grid-tied PVDG system has been given in Fig. 1. It consists of a PV array, DC-DC converter, DC-link capacitor, inverter, controller and the grid. A PVDG system can be implemented with two different topologies: single-stage topology and two stage-topology. In a single stage topology there is only an inverter in which both MPPT and grid-integration specific functionalities are implemented, whereas a two stage topology consists of an intermediate converter in which MPPT control is implemented and grid specific controls are applied at the inverter side [14, 27]. This paper uses a two stage topology for modeling of the PVDG system. A higher conversion efficiency can be achieved with a single stage topology but it requires a large DC-link capacitance which leads to slow response of the MPPT, increase in system size and low life span. However, a faster response of MPPT along with wide

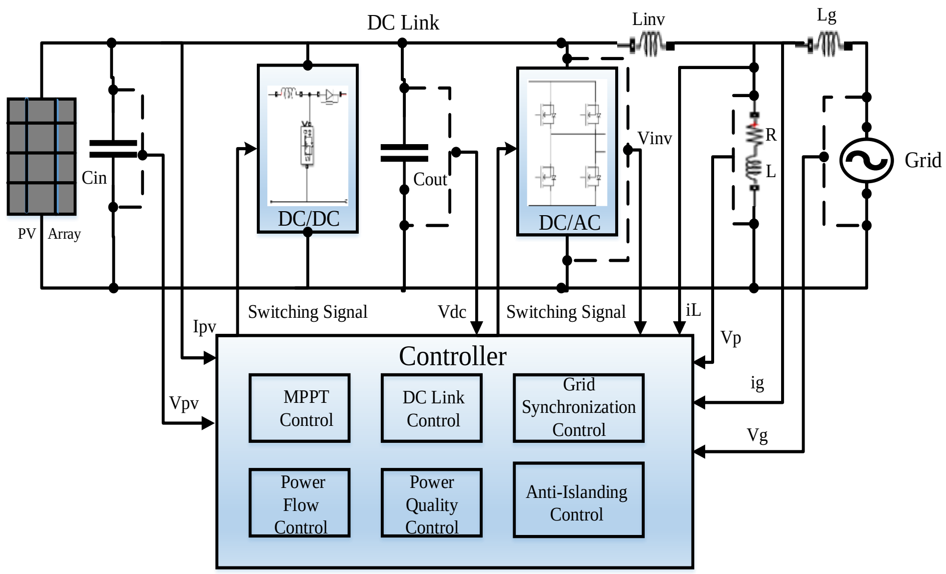


Fig. 1. Schematic diagram of a grid-tied PVDG system

operating range of PV voltage in a two stage topology provides an edge over a single stage topology [18, 19].

The PV panels are the source of energy generation for the PVDG system and are composed of PV cells which are photoelectric devices and produces electricity as the sunlight strikes the surface of the cell. The PV panel output voltage and current are fed to the MPC controller which generates a switching signal to adjust the operating point of the DC-DC converter for extraction of maximum power from the PV arrays under rapidly varying input conditions. The input capacitor 'C_{in}' is employed to provide a stable PV output voltage. The DC-DC converter and the inverter are connected through a capacitive filter 'C_{out}' known as the DC link capacitor as it acts as a link between the DC and AC side of the PVDG system. It provides a smooth input DC voltage to the inverter and decouples a direct connection between the PV panel and the AC output. It also provides an energy buffer and helps to endure power disturbances. The inverter converts the input DC voltage into AC and feeds it to the local load or the grid. In addition, the control functions for the process of grid integration of the PV system are also implemented at the inverter.

3. Fundamentals of Model Predictive Control

Model predictive control is an advanced computation based control technique which computes the n^{th} future state of a system variable using prediction based on the present value of the variable from the system's mathematical model. It is a highly efficient method and provides a faster rate of convergence towards the optimum system operation [24]. In MPC a set of probable outputs are mathematically computed for a range of expected input conditions. A comparison of the outputs with the desired output condition results in selection of the control input which provides least deviation from the desired output. One of the primary elements of MPC which results in faster convergence and efficient control is its ability to evaluate the optimum control input without the system having to actually pass through all the unwanted states. In addition, a MPC method can be used to control several system variables simultaneously and can also be used effectively for modeling non-linearities of the system [24].

There are three basic elements of a MPC controller: prediction model, cost function and prediction horizon. First of all, a system model is required based on which the computation for the future state of the system variable is performed, it is called the prediction model. The cost function evaluates the deviation of the predicted values from the desired output, which decides the optimum control input to be chosen for implementation based on smallest value of cost function. Lastly, the n^{th} state till which the prediction is to be made should be decided, which is called the prediction horizon. All these elements have to be predetermined for implementing MPC. While multiple variables can be controlled simultaneously by including the variables in the cost function, each variable may have different units and magnitudes and their contribution or significance in the cost function may be different. Hence, each variable can be assigned a suitable weight known as the weighing factor of the variable in the cost function. A basic structure for implementing MPC has been provided in Fig. 2. Here, x(k) represents the system variable to be controlled, while $x^*(k)$ represents the desired reference value of the variable. The prediction model predicts the next state value of the variable (x(k+1)) for the given input conditions based on the system model. The cost function is then evaluated by comparing the predicted value with the reference and the switching signal which results in minimization of the cost function is selected for operating the converter.

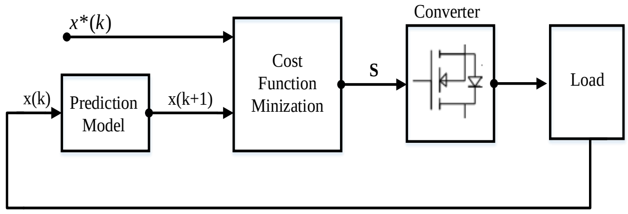


Fig. 2. Functional block diagram for MPC.

In order to implement MPC the system variables to be controlled has to be identified and a system model has to be developed. The system model used for prediction in MPC is a discrete model. A discrete model for a first order system based on Euler's forward method is given in Eq. (1). x(t) is the controlled system variable, whereas, x(k) and x(k+1) represents the present and predicted values of the variable. Eq. (2) and (3) provides a general state space representation of a discrete-time system model for prediction, where x(k), y(k) and u(k) are the system variables [25].

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

$$x(k+1) = Ax(k) + Bu(k) \tag{2}$$

$$y(k) = Cx(k) + Du(k) \tag{3}$$

A general expression for modelling of cost function with two variables has been presented in Eq. (4). 'C_F' represents the cost function, 'x' and 'y' are the controlled variables and 'a' and 'b' are their weighing factors respectively.

$$C_F = a.[x - x^*] + b.[y - y^*] \tag{4}$$

4. MPPT with Model Predictive Control

MPPT is an important component of a PVDG system as it is directly related to the solar energy conversion efficiency. An MPPT controller determines the operating voltage and current for a PV array at which it generates maximum power under the present input conditions and generates control signals to operate the PV system at determined maximum power point (MPP) of voltage and current. A review of different MPPT techniques have been presented in [5-8]. Perturb and observe (P&O) is one of the widely used and the earliest MPPT techniques developed in which a gradual change is introduced in the operating voltage or current to determine the MPP. In this paper, MPPT is achieved by using MPC combined with P&O method for a faster MPPT response.

4.1. Modeling of MPC-MPPT Controller

In a two-stage PVDG system topology, MPPT control is implemented at the boost converter in order to extract maximum available power from the PV array. Hence, the prediction model for MPC-MPPT control is developed by modelling the boost converter. The MPC controller generates control signal to adjust the boost converter switching. Fig. 3(a) is the boost converter circuit used for modeling. The operation of the boost converter during on and off conditions of the converter switch has been shown in Fig. 3(b) and 3(c) respectively. The discrete-time models applying Euler's forward method of Eq. (1) can be represented by Eq. (5), (6), (7) and (8). Eq. (5) to (8) can be combined to obtain a discrete-time state space representation of the boost converter model as given by Eq. (9). Here, 'i_{pv}' and 'v_c' are considered as the system variables to be controlled for MPC in a sampling time 'T_s'. The state of the switch 's = 0' is considered when the switch is closed and 's =1' when it is open [11].

$$i_{PV}(k+1) = i_{PV}(k) + \frac{1}{L}V_{PV}(k)T_s \tag{5}$$

$$v_c(k+1) = \left[1 - \frac{T_s}{RC}\right]v_c(k) \tag{6}$$

$$i_{PV}(k+1) = i_{PV}(k) - \frac{T_s}{L}v_c(k) + \frac{T_s}{L}v_{PV}(k) \tag{7}$$

$$v_c(k+1) = \frac{T_s}{C}i_{PV}(k) + \left[1 - \frac{T_s}{RC}\right]v_c(k) \tag{8}$$

$$\begin{bmatrix} i_{PV}(k+1) \\ v_c(k+1) \end{bmatrix} = \begin{bmatrix} 1 & -s\frac{T_s}{L} \\ s\frac{T_s}{C} & 1-\frac{T_s}{RC} \end{bmatrix}\begin{bmatrix} i_{PV}(k) \\ v_c(k) \end{bmatrix} + \begin{bmatrix} \frac{T_s}{L} \\ 0 \end{bmatrix} v_{PV}(k) \tag{9}$$

4.2. MPC-MPPT Control algorithm

The algorithm for implementing MPPT with MPC consists of two parts. The first part implements P&O MPPT method for determining the reference current signal (i_{ref}) to track the maximum power point of the PV array. The second part implements MPC for selecting appropriate switching signal (s) for the DC-DC converter to operate the PV array at its maximum power point.

(i) P&O MPPT Control algorithm: P&O is a well described MPPT method in the literature and popular because of its simple control structure. The P&O MPPT algorithm has been shown in Fig. 4(a). Here, small perturbances are gradually introduced in the PV current and the corresponding change in the output power is measured. The process is repeated till the maximum power point of the PV array is determined. Once the MPP is reached, the PV system oscillates around the MPP. The reference current (i_{ref}) corresponds to the PV current at MPP and is supplied to the MPC block for determining the appropriate switching signal (s) for the DC-DC converter.

(ii) MPC control algorithm for MPPT: The MPC algorithm utilizes prediction to evaluate the best possible control action. MPC-MPPT algorithm has been shown in Fig. 4(b) The PV array voltage (v_{pv}) and current (i_{pv}) along with the boost converter output voltage (v_c) and the reference

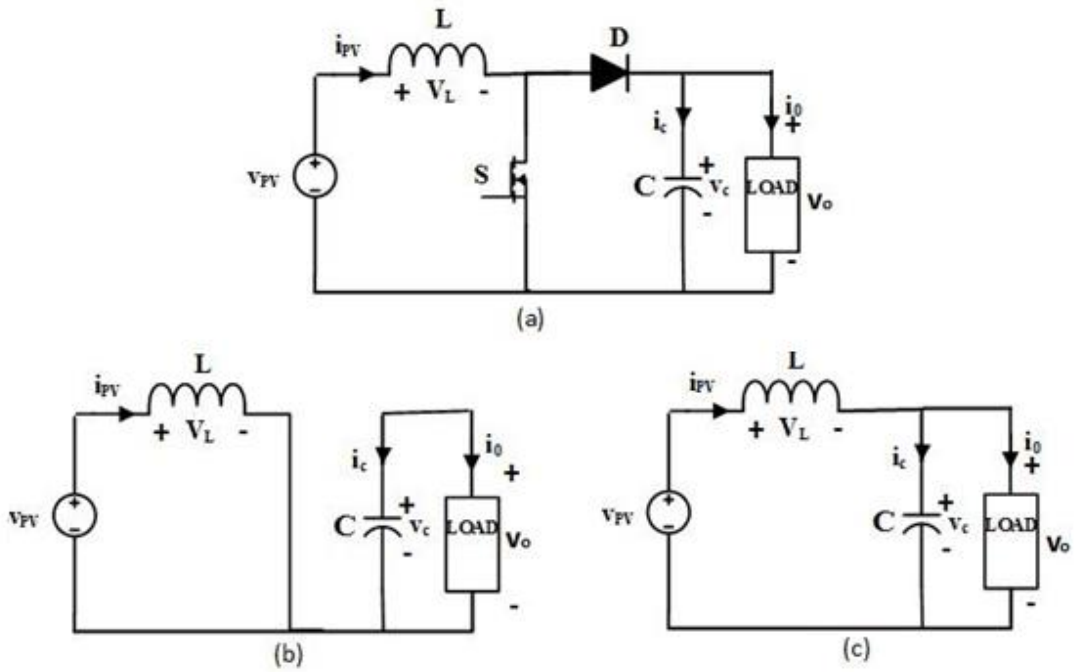


Fig. 3. Boost converter circuit for MPC modeling [11].

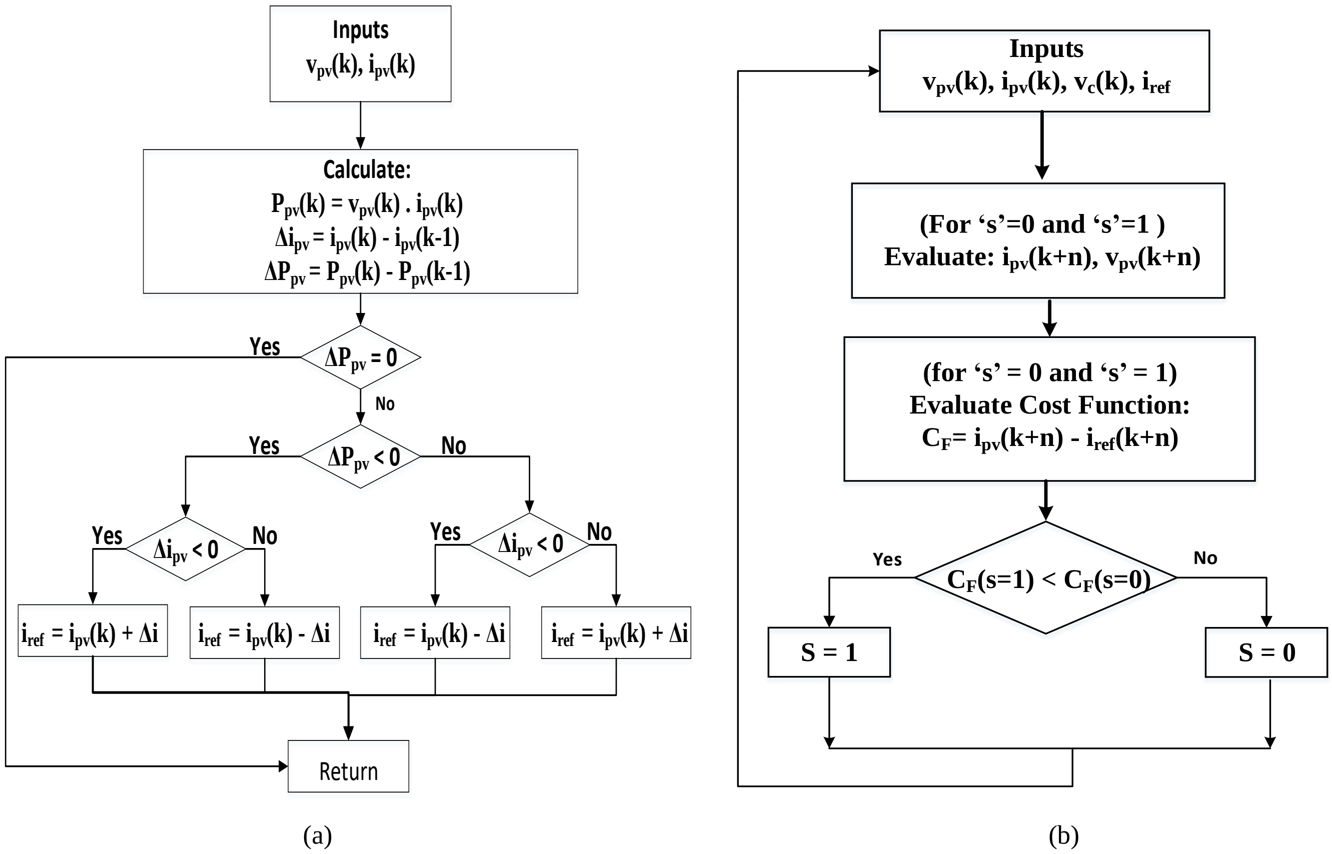


Fig. 4. (a) P&O MPPT algorithm (b) MPC-MPPT control algorithm [11]

current (i_{ref}) are applied in the form of inputs to the MPC block, which computes the n^{th} future state of the system variables using the prediction model obtained in Eq. (9). The cost function evaluates the difference between the predicted and the reference current values for the switch states 's = 0' and 's = 1'. The MPC controller finally selects the switching state which results in minimum cost function.

5. PV Inverter Control with MPC

The use of MPC as a control technique for control of power electronic devices has been studied for many decades now and appears to be very attractive for researchers in the field, due to its advantages of faster dynamic response, a combined multivariable control and accommodation of non-linearities and additional constraints [24-26]. In a grid-tied PVDG system in addition to providing DC to AC power conversion, PV inverters are employed to provide several additional functionalities such a power quality control, grid synchronization, active and reactive power flow control and DC-link voltage control [20, 27-31]. In this paper modelling and simulation of a comprehensive MPC based PV inverter control strategy has been provided to achieve these objectives.

5.1. *Modelling of MPC based PV Inverter Controller*

The prediction model for MPC based inverter control can be obtained from Eq. (10) to (12), where inverter current 'i_{inv}' is considered as the controlled system variable [27].

$$v_{inv} = L_{inv}\frac{di_{inv}}{dt} + v_p \tag{10}$$

$$v_g = L_g\frac{di_g}{dt} + v_p \tag{11}$$

$$v_p = Ri_L + L\frac{di_L}{dt} - 2v_d \tag{12}$$

Here, 'v_{inv}' represent the inverter output voltage, whereas 'v_p' and 'v_d' represent the voltages at the point of common coupling (PCC) and across an individual diode present in the rectifier load respectively. 'i_{inv}', 'i_g' and 'i_L' represents the inverter, grid and load currents respectively. 'L_{inv}', 'L_g', 'L' represents the inductances at the inverter, grid and the load sides, while 'R' represents the load resistance. Applying Euler's forward method, the discrete time model for the inverter current can be given by Eq. (13). Where, $i_{inv}(k+1)$ is the predicted value of the inverter current for the (k+1) instant of time, whereas $i_{inv}(k)$, $i_L(k)$, $v_g(k)$, $v_p(k)$ and $v_{inv}(k)$ represents the present values of currents and voltages and 'T_s' is the sampling time. The cost function for the selection of the appropriate switching state can be obtained from Eq. (14).

$$\left\{\begin{array}{l} i_{inv}(k+1) = i_{inv}(k) + \dfrac{T_s}{L_{inv}+L}[v_{inv}(k) - \dfrac{L}{L_g} \\ \{v_g(k) - v_p(k)\} - Ri_L(k) - 2v_d] \end{array}\right\} \quad (13)$$

$$C_F = | i_{inv}(k+1) - i_{ref} | \quad (14)$$

The inverter output voltage (V_{inv}) can either be V_{dc}, 0 or -V_{dc} depending on the switching states. For S_0 = 1001 ($S_1S_2S_3S_4$), $V_{inv} = V_0 = V_{dc}$; For S_1= 0000 ($S_1S_2S_3S_4$), $V_{inv} = V_1 = 0$; For S_2 = 0110 ($S_1S_2S_3S_4$), $V_{inv} = V_2 = -V_{dc}$.

5.2. MPC based PV Inverter Control structure

In the proposed MPC based inverter control of PVDG system, a single phase bridge inverter has been implemented. The DC-DC boost converter and the inverter are linked through a DC-link capacitor. The complete control structure for generation of inverter switching signals has been shown in Fig. 5.

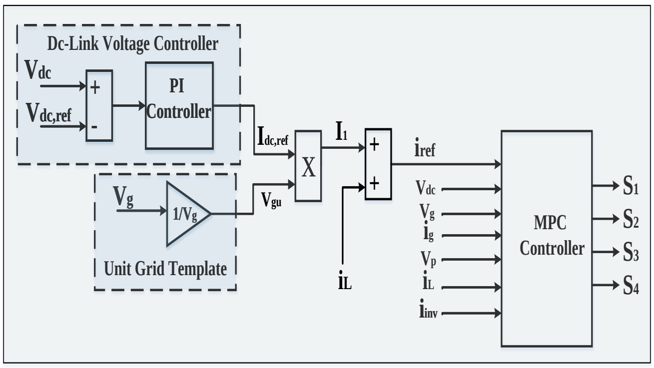


Fig. 5. Inverter control structure.

Generally, MPC-MPPT control of boost converter results in a variable DC-link voltage. The DC-link voltage is maintained at a constant level by using a PI based voltage-control loop which generates a reference control signal by comparison of the DC-link voltage (V_{dc}) with a desired reference DC voltage ($V_{dc,ref}$). For synchronization of the PV inverter output with the grid, a unit template of grid voltage (V_{gu}) is obtained and multiplied with DC-link voltage reference signal ($I_{dc,ref}$). The load current (i_L) is then added to the resulting control signal (I_1) to generate a reference signal (i_{ref}) for the MPC controller. The MPC controller block then generates appropriate switching signals (S_1, S_2, S_3, S_4) for control of the PV inverter. The MPC control algorithm for inverter control is given in Fig. 6.

6. Simulation Results

The MATLAB simulation model for the grid-tied PVDG system with MPC implemented for MPPT and inverter control has been shown in Fig. 7. The PV array has been developed using a single diode model as discussed in [32]. The parameters of a 40 watt solar array (Model No. SFTI 40 Wp, Sunfuel Technologies) as shown in Table 1 has been used for simulation.

In the simulation model, irradiation and temperature values are provided as inputs through separate blocks to the PV array for evaluating the system performance for varying input conditions. 'v_{pv}' and 'i_{pv}' are the voltage and current values measured at the PV array output. The capacitor 'C_{in}' connects the PV output to the DC-DC boost converter block providing a stable PV input voltage. 'L_{boost}' represents the boost converter inductance, 'D' is the diode and 'S' is the converter switch. The DC-link capacitor 'C_{out}' connects boost converter output to the PV inverter. A single phase H-Bridge inverter has been used for conversion of DC to AC

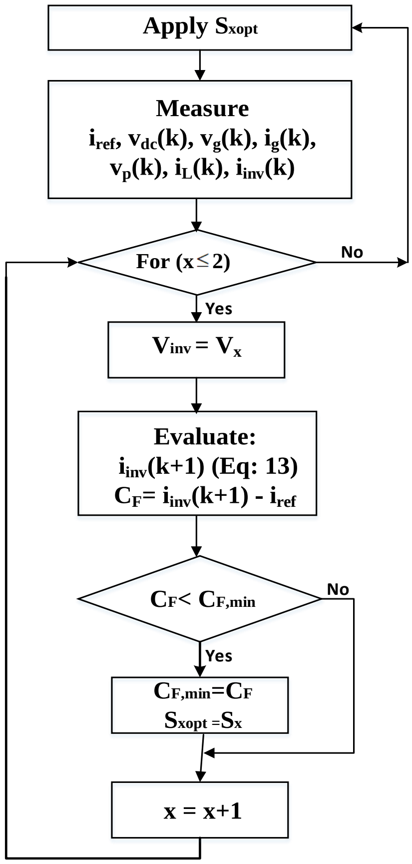


Fig. 6. MPC algorithm for PV inverter control

Table 1. PV array parameters at STC.

$P_{max,e}$	40 W
I_{mp}	2.2 A
V_{mp}	18.22 V
I_{sc}	2.33 A
V_{oc}	21.5 V
K_v	-0.32 V/^{0}C
K_I	0.03 A/^{0}C
N_s	36
a	1.2
R_p	2.1387 x $10^6\Omega$
R_s	0.0542 Ω
N_{ss}	10
N_{pp}	3

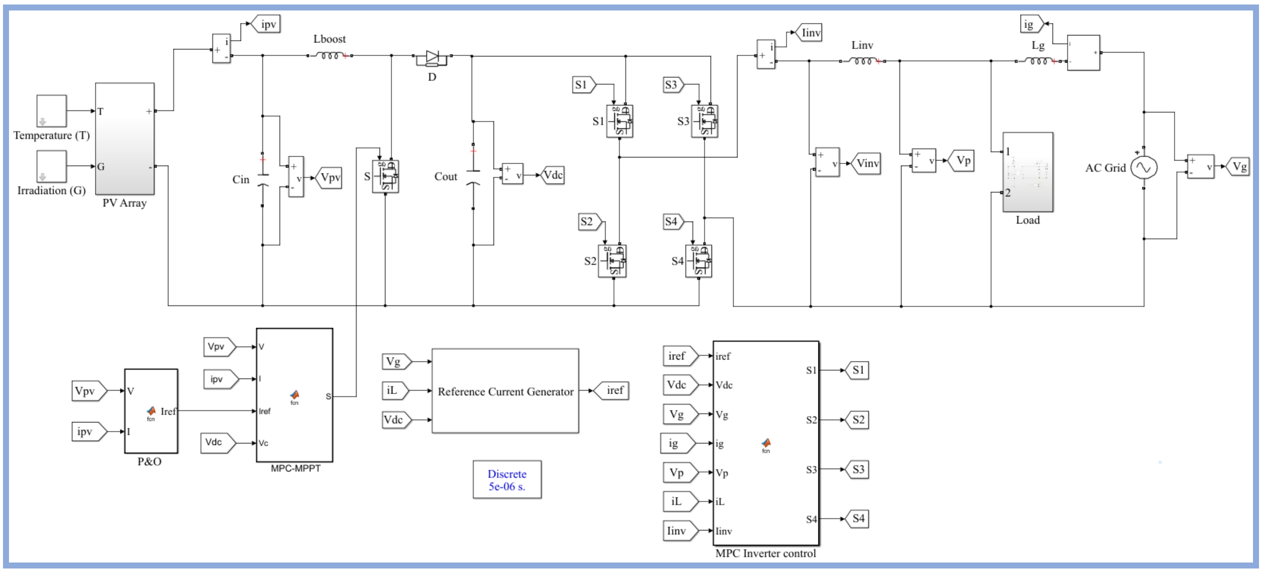


Fig. 7. MATLAB/Simulink model of the MPC based grid-tied PVDG system

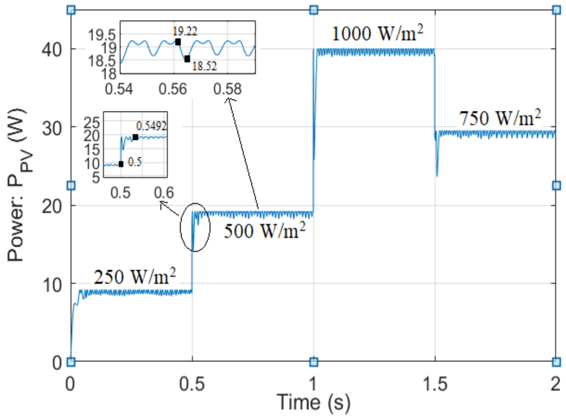
power for connection with the grid, where S_1, S_2, S_3 and S_4 are the inverter switches. 'I_{inv}' and 'V_{inv}' are the measured inverter output current and voltage respectively. An inductance 'L_{inv}' is used for filtering the harmonics introduced by the inverter. While 'L_g' represents the grid side inductance. The voltage at the point of common coupling (PCC) is measured as 'V_p' while, 'V_g' represents the grid voltage. A non-linear load comprising of a single phase uncontrolled rectifier with RL load has been connected at the PCC for adding harmonics in order to evaluate the harmonic compensation capabilities of the MPC inverter control. A 220 V, 50 Hz AC source has been used as the grid.

The system parameters used for MATLAB simulation has been given in Table 2. The designing of boost converter has been discussed in [33]. The P&O and MPC-MPPT blocks are the MATLAB function blocks in which the MPC based MPPT control algorithm as discussed in section 4 has been implemented. P&O block generates the reference signal for the MPC-MPPT block which ultimately generates switching signal for the boost converter to operate the PV array at its MPP. The simulation results for the PV system with simple P&O method and MPC-MPPT control for changing irradiation values at 25°C temperature has been shown in Fig. 8(a) and (b) respectively.

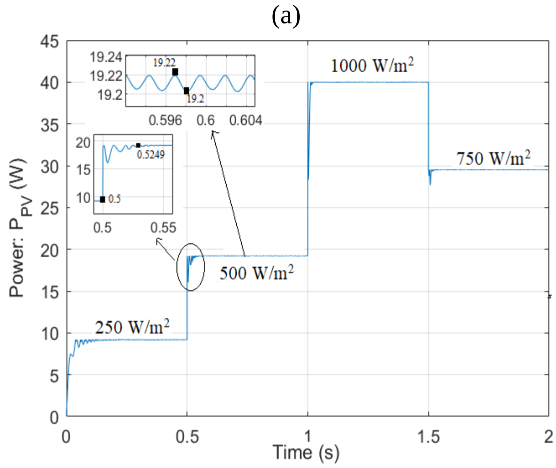
Table 2. System Parameters

L_{boost}	26.3 mH
C_{in}, C_{out}	2200 μF
$V_{dc,ref}$	500 V
L_{inv}	10 mH
L_g	8 mH
V_g	$220*\sqrt{2}$ V, 50 Hz
Rectifier with RL load	Load 1: R=20 Ω, L=30 mH Load 2: R=80 Ω, L=120 mH
T_s	5 μs
PI controller gains	K_P = -0.3; K_I = -0.1

MPC-MPPT method provides a tracking response time of 24.9 ms while a simple P&O method has a response time of 49.2 ms for change in irradiation from 250 to 500 W/m². While, MPC-MPPT method has maximum power oscillation of 0.02 watts around the steady state, P&O method provides power fluctuations of 0.7 watts at irradiation of 500 W/m².



(a)



(b)

Fig. 8. PV output power (a) Simple P&O (b) MPC-MPPT

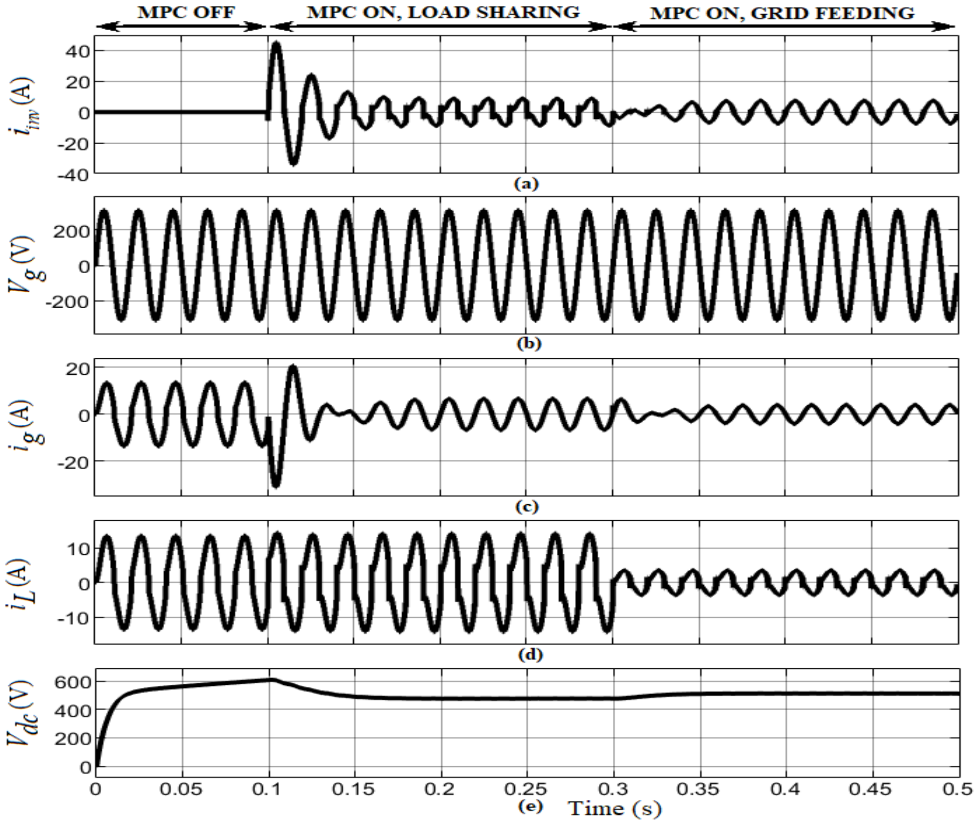


Fig. 9. Simulation results for the MPC based inverter control (a) inverter current (b) grid voltage (c) grid current (d) load current (e) DC-link voltage.

For MPC based inverter control, the reference current generator block evaluates a reference current for DC-link voltage regulation, load current harmonics and power flow control as discussed in section 5.2. The reference current is then fed to the MPC inverter control block which implements MPC control algorithm as presented in Fig. 6 for generating the switching signals S1 to S4 for the inverter. The simulation results for the MPC based inverter control has been shown in Fig. 9. The simulation is divided into three different time zones. From 0 to 0.1s the MPC controller for the inverter is switched off. Here, the inverter does not supply any current as seen from Fig. 9(a) and the harmonic demand of the load is fulfilled by the grid. As a result both the load and the grid current has a THD of 10.91% as shown in Fig. 10(a) and 10(b). During this mode the MPPT control is on, therefore the DC-link voltage slowly increases from zero to a steady state value as shown in Fig. 9(e). Form 0.1s to 0.3s, the MPC controller is turned on with load 1 connected. During this period, both the PV inverter and the grid supply current to the load while the load harmonic demand is fulfilled by the inverter. The THD for the load, inverter and grid currents have been shown in Fig. 11. The THD for the inverter current is at 32.05 %, while the THD for the grid current is 2.07% which is below 5% as per IEEE 519 standard. From 0.3s to 0.5s the MPC controller is kept on while load 2 is connected and the PVDG system operates in grid feeding mode. THD for load, inverter and grid currents for this mode has been shown in Fig. 12. During this mode the THD for the grid current is 3.08%, while the grid voltage and current are 180^0 out of phase as seen in Fig. 9(b) and (c) respectively.

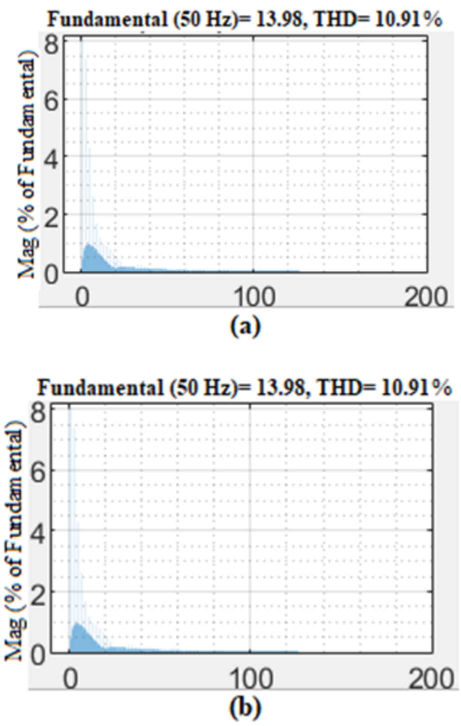


Fig. 10. THD at MPC OFF : 0 to 0.1s (a) load current (b) grid current

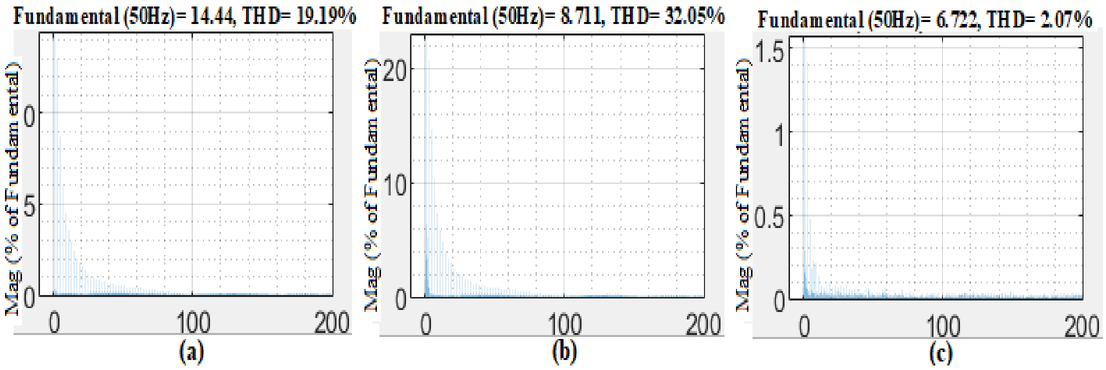


Fig. 11. THD at MPC ON, LOAD SHARING: 0.1 to 0.3s (a) load current (b) inverter current (c) grid current

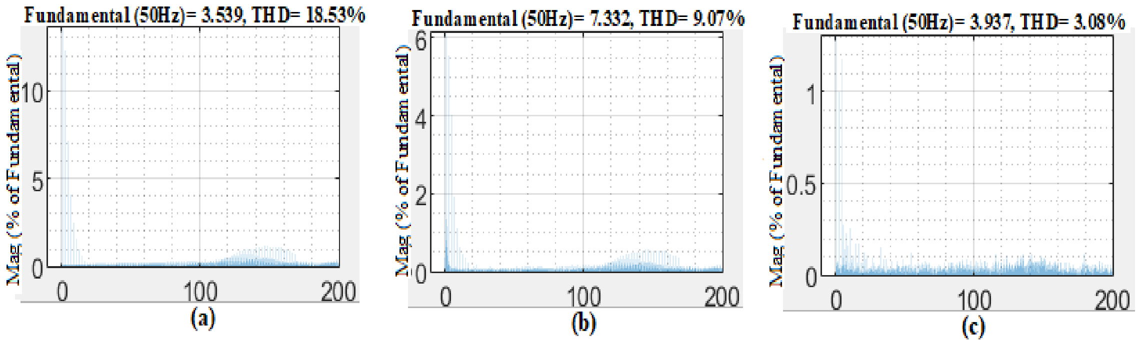


Fig. 12. THD at MPC ON, GRID FEEDING: 0.3 to 0.5s (a) load current (b) inverter current (c) grid current

7. Conclusion

In this paper modelling of a MPC based grid-tied PVDG system for MPPT and inverter control has been presented and its effectiveness has been evaluated through MATLAB simulations. The efficiency of MPC for MPPT has been studied in comparison with a conventional P&O method. MPC-MPPT control provides a faster tracking response by about 24.3 ms for change in irradiation from 250 to 500 W/m^2 at 25^oC temperature. Also, with MPC the power oscillation around the MPP is reduced to 0.02 watts from 0.7 watts for P&O method. This results in reduction in power loss and increased efficiency. The MPC based inverter control has also been successfully implemented in the proposed system for power flow control, harmonic reduction and control of DC-link voltage. In load sharing mode, both the PV inverter and the grid feed power to the load. While, in grid feeding mode in addition to supplying power to the load the surplus power is fed to the grid. With MPC the THD for grid current in both load sharing and grid feeding modes are below 5% as prescribed in the IEE 519 grid code. While, without MPC the THD for grid current is observed to be at 10.91%. MPC is an effective control method and its performance could be further enhanced by increasing the prediction horizon for better prediction of system variables and by optimization of the cost function.

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