Flexible Power Regulation of Grid-Connected Inverters for PV Systems Using Model Predictive Direct Power Control

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Abstract

This paper presents a Model Predictive Direct Power Control (MPDPC) strategy for a grid-connected inverter used in a photovoltaic system, as found in many distributed generating installations. The controller uses a system model to predict the system behavior at each sampling instant. Using a cost function, the voltage vector with least power ripple is generated. The resultant voltage vector is applied during the next sampling period which gives flexible power regulation. The effectiveness of the proposed MPDPC strategy is verified using MATLAB/SIMULINK.

Keywords*: inverters, model predictive control (MPC), power regulation.*

1. Introduction

Due to the cost of fossil fuel and carbon dioxide emissions in generation of power, distributed generation (DG) units are progressively developed and connected to the local low-voltage power system through a power converter. In DG units, sources may be Photovoltaic (PV) panels, fuel cell systems and/or smaller wind turbines [1], [3]. But mostly PV panels are very popular due to low cost and easy maintenance rather than other sources. Ability and ease of control of the DGs leads to enhanced system reliability and power quality. This can be achieved when DGs are integrated into a common AC or DC bus with an energy storage system to form a micro grid [4-5]. The main advantage of a DG system is its grid support capacity.

In power system, stabilization is a difficult assignment due to fluctuations in load demands. To overcome this, DGs should be operated to provide active power and reactive power compensation to stabilize the main power system in terms of voltage and frequency [6]. Thus, to maintain high power quality and dynamic stability the DG power converter is required to operate more efficiently and effectively. In order to control these grid-connected inverters, various control strategies are in use [4-5]. Amongst these, Direct Power Control (DPC) is one of the most popular, which highlights to control the power directly. In recent technology, this method is used as conventional switching-table-based DPC (SDPC) because of its advantages such as simplicity, robustness, and excellent transient response [7-8].

More recently, a Model Predictive Directive Power Control (MPDPC) for a grid-connected inverter with an *LCL* filter was developed. The power injected into the grid was not controlled directly by the filter capacitance. In addition, the additional poles introduced by the LC induce resonance into the system, leading to stability issues [9]. In this work, PV inverter with inductor filter connected to the Grid is considered. A Model Predictive Control (MPC) is proposed to control the power regulation of the power converter injected in to the grid, with easy inclusion of system constraints and nonlinearities. This control technique is implemented to predict system behavior with the help of control action and measured inputs. With the help of cost function principal optimal switching state is applied to the inverter [10]. The control objectives of MPC can vary considerably according to the application. For example, the control objectives are active and reactive powers for rectifiers [11-13], electromagnetic torque for electric drives [14-15], and voltage or current for inverter systems [16-19].

This paper is organized as follows; The Section II describes the modeling of the PV system and P&O algorithm for tracking the maximum power from PV panel. Whereas Section III describes the Model Predictive Power Control and the Modeling of Three phase Grid connected

Inverter and load. The Section IV explains the flexible power regulation. Finally, the simulation results and discussion are presented in Section V.

2. Modeling of PV Cell
2.1. Modeling of PV Cell

Generally, a PV cell is a simple P-N junction diode which converts solar irradiation into electricity. PV cell is represented as a combination the current source (I_{pv}), shunt resistance(R_p), diode and a series resistance(R_s). In order to overcome the imperfections of PV single diode modeling at high voltages and low voltages, a two diode model of PV solar cell is considered in this work as shown in Figure 1 [20].
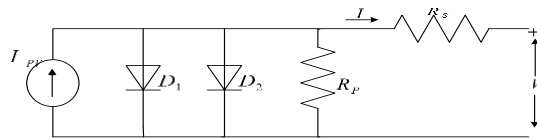

Figure 1. Two-diode Model of PV Cell

The PV cells are connected in series (Ns×Np cells, where Np= 1) to produce the PV module. Basic equation that describes the current output of PV module using the two- diode model is given by equation. The PV cell voltage-current relationship in equation (1) is modified for PV module as [21-22].

$$I = N_p \times I_{pv} - N_p \times I_{o1}\left[\exp\left\{\frac{q \times (V + IR_s)}{N_s A_1 kT}\right\} - 1\right] - N_p \times I_{o2}\left[\exp\left\{\frac{q \times (V + IR_s)}{N_s A_2 kT}\right\} - 1\right] - \left(\frac{V + IR_s}{R_p}\right)$$

(1)

In grid connected PV system, modules are configured in series- parallel structure with any number of PV modules (Nss×Npp modules) to produce the PV array. Then the PV module voltage-current relationship in equation (1) is modified for PV array and it is given by (2). [23]

$$I = N_{pp} \times I_{pv} - N_{pp} \times I_{o1}\left[\exp\left\{\frac{q \times \left(V + IR_s\left(\frac{N_{ss}}{N_{pp}}\right)\right)}{N_{ss} A_1 kT}\right\} - 1\right] - N_{pp} \times I_{o2}\left[\exp\left\{\frac{q \times \left(V + IR_s\left(\frac{N_{ss}}{N_{pp}}\right)\right)}{N_{ss} A_2 kT}\right\} - 1\right] - \left(\frac{V + IR_s\left(\frac{N_{ss}}{N_{pp}}\right)}{R_p\left(\frac{N_{ss}}{N_{pp}}\right)}\right)$$

(2)

Where I_{pv}, I_{o1}, I_{o2}, R_s, R_p, A_1, and A_2 are the parameters of the individual modules, N_s and N_p are the number of cells connected in series and parallel of module respectively, N_{ss} and N_{pp} are the number of modules connected in series and parallel respectively for array. In this work for doing the MATLAB simulation KC200GT solar module is considered. Solar Array is designed for 12KW, 150V.

2.2. Maximum Power Point Technique (MPPT)

Irradiation and temperature varies during the day which effects short circuit current, open circuit voltage of the PV module, causes to change in the PV characteristics of the module for optimal use of the PV Module or Array. It necessary to extract the maximum power from the PV array with changing the parameters. In this work P&O algorithm is used [24] with Boost converter to extract the maximum power from PV Array and also step up the voltage up to 300 V which is suitable to the 3 phase inverter.

3. Model Predictive Control (MPC)
3.1. Model Predictive Control (MPC)

Model predictive controllers depending on dynamic models of the system, the main advantage of MPC is the fact that it allows the current timeslot to be optimized, while keeping

future timeslots in account. This is achieved by optimizing a finite time-horizon, but only implementing the current timeslot. MPC has the ability to forecast the future events and can take control actions accordingly. It uses the system measurements, the state variable, model of the system and the process variable targets and limits to calculate future changes in the dependent variables. These changes are calculated so that dependent variables close to target while imposing the constraints on both independent and dependent variables. The MPC typically sends out only the first change in each independent variable to be implemented and repeats the calculation when the next change is required [25].

MPC is based on iterations, finite horizon optimization of a plant model (Figure 2). At time 't' the current system state is sampled and a cost minimizing control strategy is computed for a relatively short time horizon in the future: [t, t+T] Specifically, an online or on-the-fly calculation is used to explore state trajectories that emanate from the current state and find (via the solution of Euler–Lagrange equations) a cost-minimizing control strategy until time t+T [26].
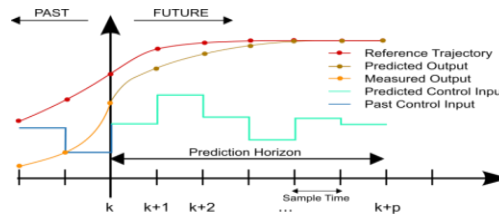

Figure 2. Discrete MPC Scheme

3.2. Three-Phase Grid-Connected Inverters and Load Modeling

The three-phase DC/AC voltage source inverters are extensively being used in motor drives, active filters and unified power flow controllers in power systems and uninterrupted power supplies. The frequency and magnitude of the output voltage of the is controlled using various pulse width modulation techniques (PWM) [2]. Power circuit diagram of a 3-Phase bridge inverter using six IGBTs are shown in the Figure 3.
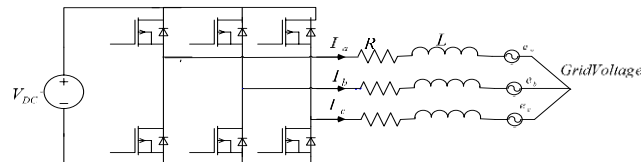

Figure 3. Three-phase Grid Connected Inverters

The DC input is obtained from a solar array. The switching states of the converter are determined by the gating signals S_a, S_b, and S_c as follows,

$$S_a = \begin{cases} 1, & \text{if } S_1 \text{ on } \& \ S_4 \text{ off} \\ 0, & \text{if } S_1 \text{ off } \& S_4 \text{ on} \end{cases} \tag{3}$$

$$S_b = \begin{cases} 1, & \text{if } S_2 \text{ on} \& S_5 \text{ off} \\ 0, & \text{if } S_2 \text{ off} \& S_5 \text{ on} \end{cases} \tag{4}$$

$$S_c = \begin{cases} 1, & \text{if } S_3 \text{ on } \& S_6 \text{ off} \\ 0, & \text{if } S_3 \text{ off} \& S_6 \text{ on} \end{cases} \tag{5}$$

In vector form, $S = \frac{2}{3}(S_a + aS_b + a^2 S_c)$ (6)

where, $a = e^{j(2\pi/3)}$,

The output-voltage space vectors generated by the inverter are given by

$$V_i = \frac{2}{3}\left(V_{aN} + aV_{bN} + a^2 V_{cN}\right)$$ (7)

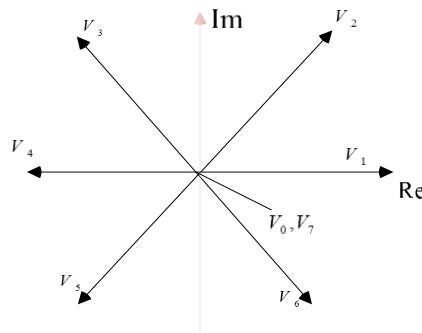Where V_{aN}, V_{bN}, V_{cN} are the phase voltages (Figure 4).

Figure 4. Possible Voltage Vectors Generated by the Inverter

Then, the load voltage vector 'V$_i$ 'can be related to the switching state vector 'S 'by

$$V_i = V_{dc}S$$ (8)

where V_{dc} is the dc-link voltage. Thus, eight switching states and consequently, eight voltage vectors are obtained by considering all possible combinations of the gating signals.

3.3. Load Modeling
In a balanced three-phase load, the current can be defined as a space vector by

$$i = \frac{2}{3}\left(i_a + ai_b + a^2 i_c\right)$$ (9)

And space vector representation of the grid voltage

$$E = \frac{2}{3}\left(e_a + ae_b + a^2 e_c\right)$$ (10)

In this way, the load current dynamics can be described by the vector equation

$$V = Ri + L\frac{di}{dt} + E$$ (11)

where R is the load resistance, L the load inductance 'V$_i$' is the inverter voltage vector and'E' the grid voltage vector. By using these inverter model and load model equations, predictive controller for the grid connected inverter is designed.

3.4. Flexible Power Regulation

To achieve flexible power regulation, the system model uses active and reactive powers as the state variables. However, the system model uses the line current and grid voltage as the state variables, and it is not related directly to the output power [7]. Consequently, an accurate model for active and reactive powers is required. The instantaneous active and reactive powers injected intothe grid by the grid-connected inverter system can be described as a state equation [27], where:

$$y = \begin{bmatrix} P \\ Q \end{bmatrix} = \frac{3}{2} \begin{bmatrix} E_\alpha & E_\beta \\ E_\beta & -E_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{12}$$

The active and reactive power derivatives with respect to time$t$ can be derived from (20) as

$$\begin{bmatrix} \dfrac{dP}{dt} \\ \dfrac{dQ}{dt} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} \dfrac{dE_\alpha}{dt} & \dfrac{dE_\beta}{dt} \\ \dfrac{dE_\beta}{dt} & -\dfrac{dE_\alpha}{dt} \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} + \frac{3}{2} \begin{bmatrix} E_\alpha & E_\beta \\ E_\beta & -E_\alpha \end{bmatrix} \begin{bmatrix} \dfrac{dI_\alpha}{dt} \\ \dfrac{dI_\beta}{dt} \end{bmatrix} \tag{13}$$

Combining (19), (20) and (21) yields

$$\frac{dy}{dt} = Cy + \frac{3}{2L} DV - \frac{3}{2L} FE \tag{14}$$

$$C = \begin{bmatrix} -\dfrac{R}{L} & -\omega \\ \omega & -\dfrac{R}{L} \end{bmatrix} \tag{15}$$

Where:

$$D = \begin{bmatrix} E_\alpha & E_\beta \\ E_\beta & -E_\alpha \end{bmatrix} \tag{16}$$

$$F = \begin{bmatrix} E_\alpha & E_\beta \\ 0 & 0 \end{bmatrix} \tag{17}$$

It can be seen that the grid-connected inverter system is now represented by a state-space system with$P$and$Q$as the state variables and 'V_i'as the input; 'E'can be measured. A discrete-time model of (22) for a sampling time'T_s'is

$$y(k+1) = y(k) + \left[Cy(k) + \frac{3}{2L} DV(k) - \frac{3}{2L} FE(k) \right] T_s \tag{18}$$

Since the sampling time, T_s is very small, it can be assumed that

$$e^{CT_s} = 1 + CT_s + \frac{(CT_s)^2}{2!} + \dots + \frac{(CT_s)^2}{n!} \approx 1 + CT_s \tag{19}$$

Therefore, the discrete-time model of (26) can be further simplified to

$$y(k+1) = C_d y(k) + \frac{3}{2L} D_d V_i(k) - \frac{3}{2L} F_d E(k) \tag{20}$$

$$C_d = e^{CT_s} \tag{21}$$

$$D_d = \int_0^{T_s} e^{C\tau} D d\tau \tag{22}$$

$$F_d = \int_0^{T_s} e^{C\tau} F d\tau \tag{23}$$

By using the above equations the model predective drecte power control is proposed (MPDPC). All possible system transitions $Y_{pi}(k+1)$ are predicted using the discrete-time model of the system for all control actions (or the time horizon)of N(N=1,2,3,...,n)

The system behavior at (k+1) instant is predicted with the measured value y(k) and 'n' possible voltage vectors, resulting in 'n'possible values $y_{p1}, y_{p2},...,y_{pn}$. Now, suppose that y_{p7} isclosest to $y*$; the voltage vector producing y_{p7} is selectedand applied between the k and (k+1) instants [12] Figure 5. The MPDPC control strategy for a gridconnected inverter system in order to obtain flexible power regulation (Figure 7). The measurements of the line currents and grid voltages are used to calculate the active power P(k) and reactive power Q(k) in Figure 6. The values at the next sampling instant P(k+1) and Q(k+1), for all possible voltage vectors, can be predicted using the discrete-time model (28).

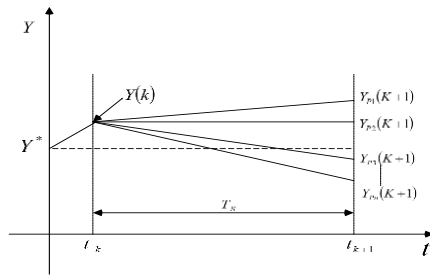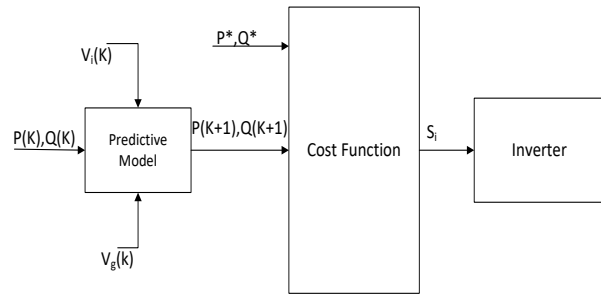| Figure 5. Voltage Vector Evaluation and Selection | Figure 6. Block Diagram Representation of Predictive Control |

To select the optimal voltage vector, all predicted powers are compared using a cost function. The voltage vector that minimizes this cost function is chosen and applied at the next sampling period.The cost function is to minimize the power error [10, 19] and is given by:

$$J = \left(P^* - P(k+1)\right)^2 + \left(Q^* - Q(k+1)\right)^2 \tag{24}$$

where P*is the reference active power and Q*is the reactivepower. This cost function has been chosen in order to minimize the power errors so that the grid-connected inverter systemcan inject any amount of active and reactive powers within its capacity. This is a very useful attribute for DG units.

Table 1. System Parameters

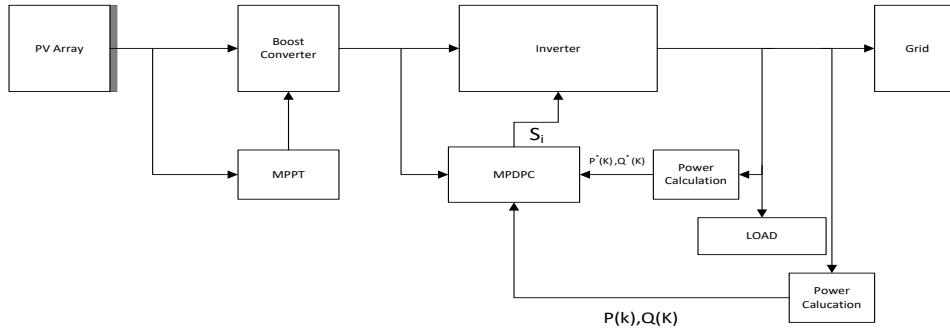|		
Filter resistance	R_f	0.36Ω
Filter inductance	L_f	4.7mH
Grid voltage (r.m.s)	V_g(L-L)	133V
Voltage frequency	f	50Hz
Dc input from PV array	V_{dc}	300V
Sampling period	T_s	50µs
Capacitance	C	15mF
Inductance	L	0.1mH
	Real Power	5 KW
Load	Reactive Power	2 KVAR

Figure 7. Complete Block Diagram of the Pv System Connected to the Grid With MPDPC

4. Results and Discussions

In this paper, PV array is designed for a power of 12 KW with an output of 150 Volts, 80 Amperes. It consists of 5 modules in series and 10 strings in parallel. Open circuit voltage of the PV array depends on the number of modules connected in series. Open circuit voltage and short circuit current of the PV array are shown in the Figure 8 & Figure 9 respectively.
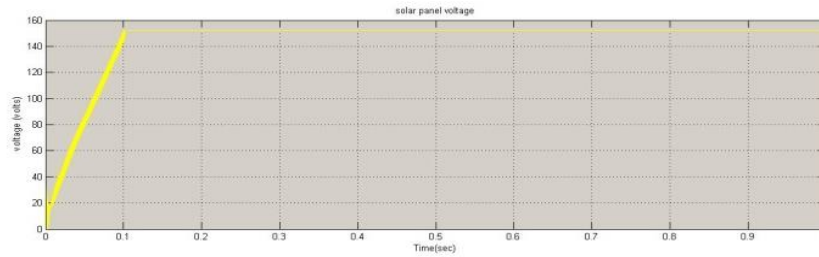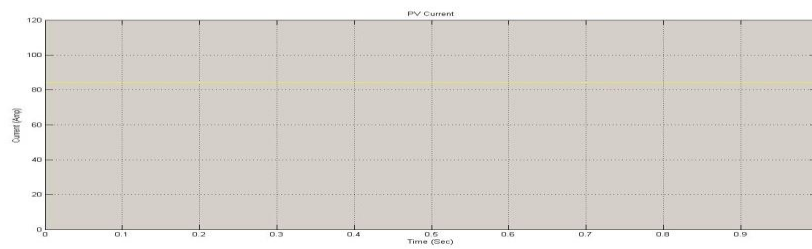

Figure 8. Voltage of the PV Array

Figure 9. Current of the PV Array
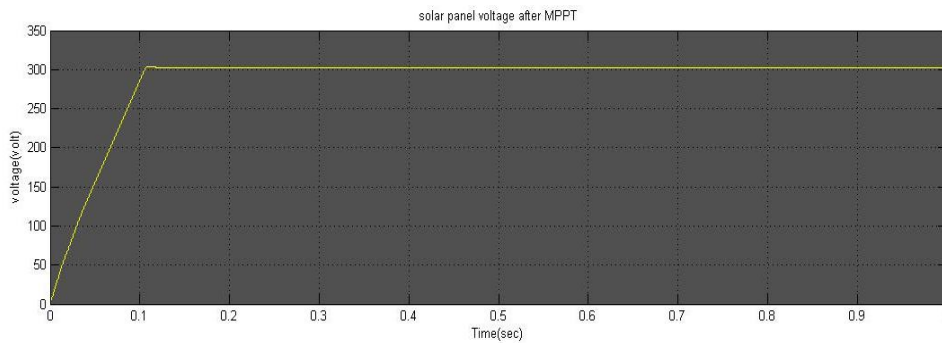
Figure 10. Voltage of the PV Array after MPPT

By means of the buck-boost converter, the output voltage will be increased to 300 Volts, as shown in Figure 10. Which acts as an input to the three phase inverter circuit.
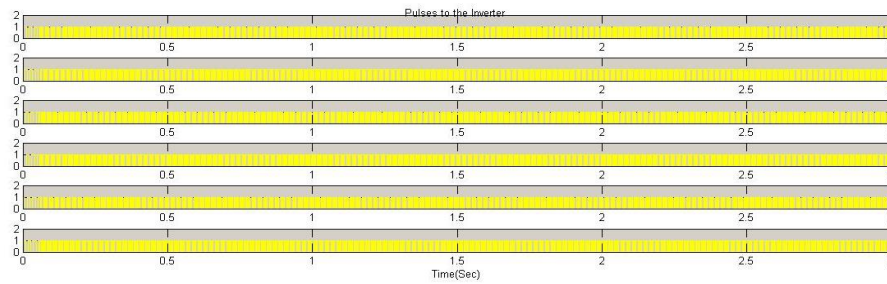

Figure 11. Pulses to the Switches in the 3-Ph Inverter

There are pulses generated by MPDPC controller for the Six Switches in the 3-Ph. Inverter connected to the grid for the load has a real power of 5KW and Reactive Power of 2 Kvar as showm in the above Figure 11.
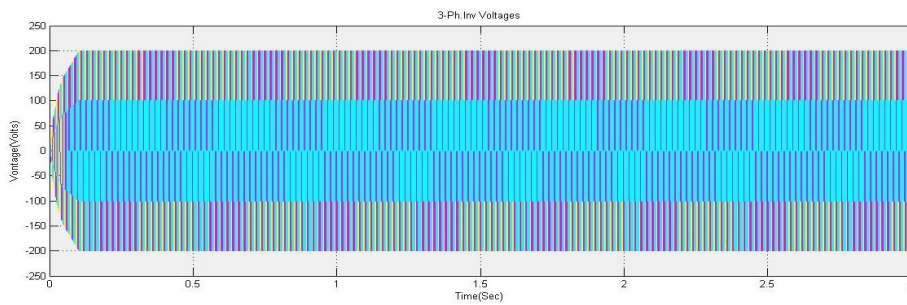

Figure 12. Three phase Inverter Output voltages

MPDPC controller has less trasient response upto 0.05 sec in the output voltage of the Grid connected 3-Ph.inverter. The peak value of the line voltage is 200 V, as shown in the Figure 12.
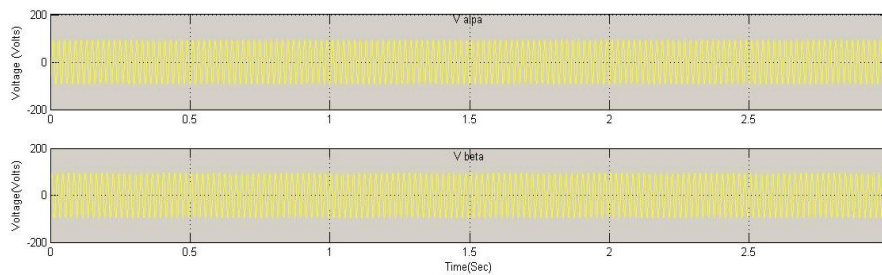

Figure 13. Inverter output voltage V_α and V_β

Vα ,V_β are the output voltages of 3-Ph.inverter whose peak value is 100 volts as shown in Figure 13. These are used as the input the MPDPC controller.
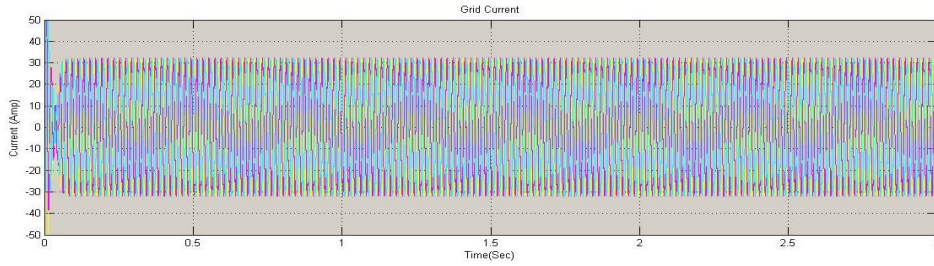
Figure 14. Three Phase Currents of Grid

Figure 14 shows the 3-Phase Grid currents when the load is 5 kw, 2 Kvar. Grid currents have a peak value of 32 Amperes with the transient response up to 0.05 Sec.
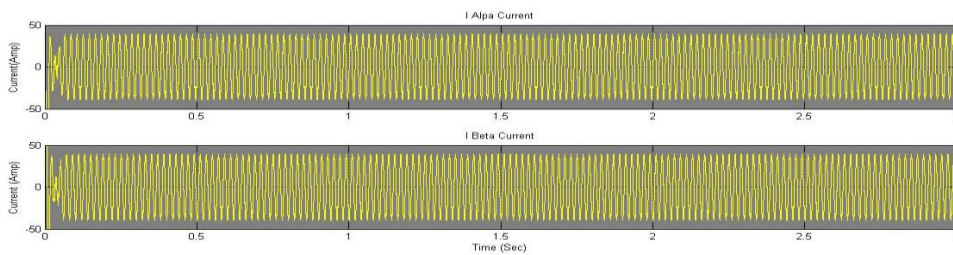

Figure 15. Grid connected inverter currents, I$_\alpha$ and I$_\beta$

Iα ,I$_\beta$ are the grid currents with peak value of 40 A. We can find the same transient response up to 0.05 sec, which are used as the inputs to the MPDPC controller.
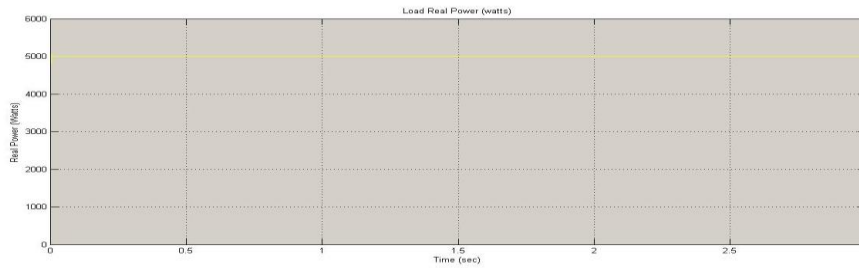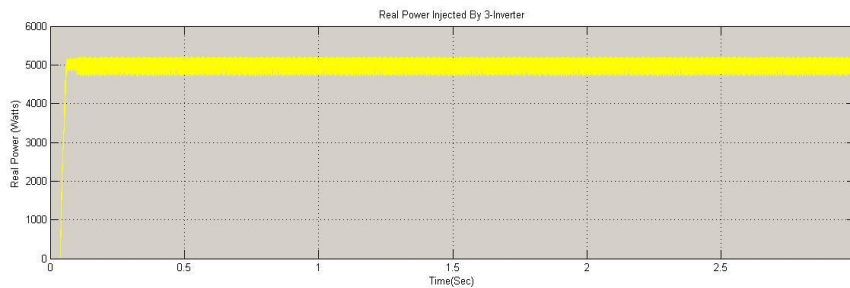

Figure 16. Load Real Power

Figure 17. Real Power Injected by the 3-Phase Inverter

Figure 16 &17 shown that MPDPC controller has very fast response in tracking the real power with less steady state error at load real power of 5 KW.
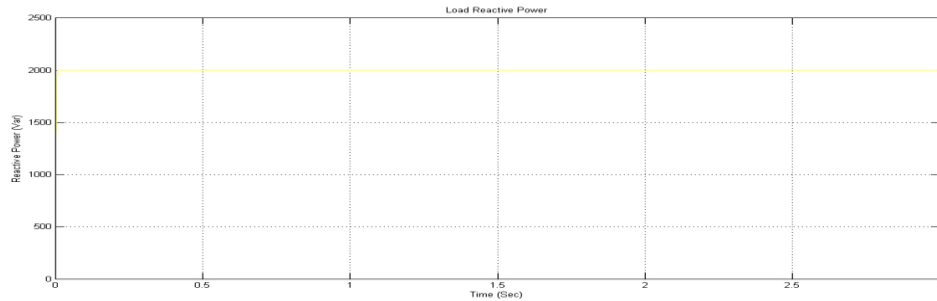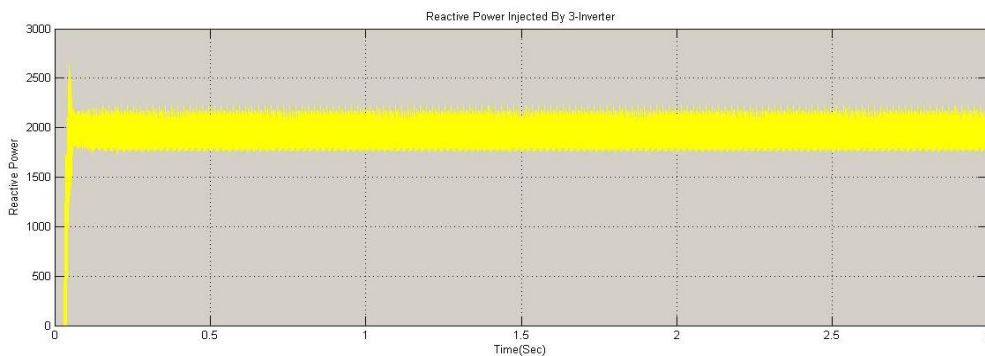

Figure 18. Load Reactive Power

Figure 19. Reactive Power Injected by the 3- Phase Inverter

Figure 18, 19 and 20 highlight that MPDPC controller has very fast response in tracking the reactive power with less steady state error at load reactive power of 2 KVAR. This asserts the flexible power regulation with accepted performance for grid connected systems.

For grid connected systems, THD is very important because harmonics in the grid current affect the harmonics in the Grid voltage. In this work, THD value of the Grid current is 2.55 % which is accepted value as per the IEC standards.

The grid connected inverter injects a real power of 5KW and reactive power of 2 KVAr into the utility grid at regular intervals of [0.5 1 1.5 2 2.5 3] sec as per the load requirement.
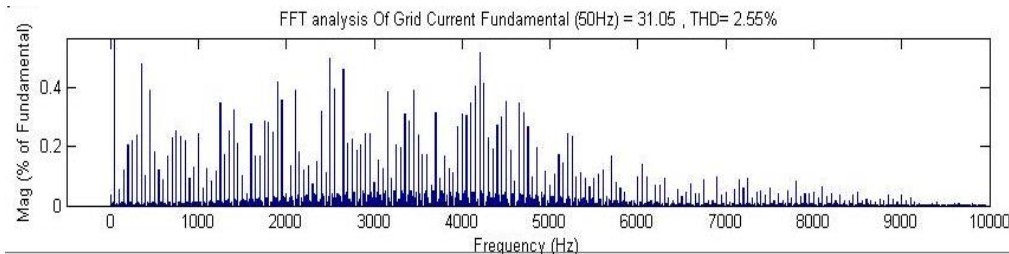

Figure 20. Line Current Spectrum in Steady State

5. Conclusion

This paper work proposed an MPDPC method with good transient and steady-state performance. It shows a grid connected inverter system with flexible power regulation, which is very suitable for distributed renewable power generation. The controller is simple and powerful. It uses a system model to predict the system behavior; a cost function is then utilized to select the most effective voltage vector.

From the simulation results, it can be observed that, proposed control strategy doesn't need any PWM modulators or lookup tables and any complex modulation techniques. This control strategy generates the gate signals for the IGBTs of inverter. The simulation results validate effectiveness of the proposed control strategy. It can be concluded that the proposed MPDC is suitable for distributed renewable power generation to maintain the stability of a power system for fluctuating demands.

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