MPPT Based Model Predictive Control of Grid Connected Inverter for PV Systems

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***Abstract*—This paper presents a Maximum Power Point Tracking(MPPT) based Model Predictive Control (MPC) approach to obtain high accuracy and fast dynamic response. The tracking capability of the base algorithm is improved by the combination of two-methods. The proposed control approach tested on a three-phase grid-connected inverter that fed by PV panel group. Switching signals of the inverter are generated by the MPC algorithm. Reference current of the MPC algorithm determined by Perturb and Observe MPPT method. Thus, power flow is controlled by the MPC algorithm based on MPPT. Power flow, MPPT efficiency and THD analyzes are examined in a simulation that performed by using MATLAB/Simulink environment. Especially, the effectiveness of the proposed approach has been tested under varying irradiation and cloudy conditions. Besides the MPPT analyzes, current tracking capability of the MPC algorithm is examined under dynamic transition conditions. Results show that, MPPT efficiency of the proposed control approach is 98%.**

Keywords—model predictive control; maximum power point tracking; three-phase inverter; current control

I. INTRODUCTION

The decreasing of fossil fuel reserves and the reduction of photovoltaic cell costs have increased the using of PV systems. Even if the PV panels have a low cost, popularities of MPPT methods are continuing as part of control the power electronic converters [1]. In general, secondary control algorithms [1-5] are preferred to increase of sensitivity and dynamic capability of control algorithms. MPC [2] and sliding mode control (SMC) [6] techniques are popular methods in terms of dynamic responses. Although these methods need high computational power, the challenge has eliminated by technological improvements on microcontrollers.

Different solutions are proposed to improve the effectiveness of MPPT algorithm. In [7-10], Adaptive Neuro Fuzzy Inference and P&O MPPT methods are combined to obtain better tracking performance. As a result of the study, the combined algorithm is offered better results than the classical method. Mechanical tracker usage is another method for improving the tracking efficiency [11]. This system type can be implemented for low power PVs, but mechanical observer usage is not a realistic approach for high power systems. Because of the challenges on mechanical observer, advanced control algorithms are used to obtain a better dynamic response and sensitive control.

Fast dynamic response, robustness and insensitive to system parameters are certain advantages of the sliding mode control algorithm. Because of these advantages, the SMC method is preferred in many study to control of power electronic converters. In [12], SMC and MPPT algorithms are used for power transfer from PV to grid. PV panel group is connected a DC/DC converter and the converter is controlled by a variable step incremental conductance MPPT method. Power flow from DC/DC converter to grid is provided by an inverter that controlled with the SMC algorithm. The paper points out that, the fast dynamic response is obtained by using SMC algorithm. MPC method is another control method that has similar advantages to SMC. The MPC algorithm has been applied to most parts of power electronic converters in the past decade. Besides the only voltage or current control, the MPC algorithm is combined with MPPT to obtain better tracking performance [2, 13]. Especially, the algorithm offers a better performance under varying irradiation conditions. In [13], both DC/DC and DC/AC power converters are controlled by the MPC method. Thus, tracking performance is improved under cloudy weather conditions. The predictive based algorithm is used for improving the MPPT efficiency in [14]. A grid-connected Z-Source inverter is controlled by the algorithm. Comparative results with P&O method and proposed algorithm shown the algorithm offers better performance. Only one stage power converter is used in the study.

One stage power converter usage is another highlight of the paper. In general, the first power stage is used to increase the input voltage. As in [12], [13] and [15], two-stage power layer usage increases the total cost of the system. Instead of that, single-stage power converter usage suggested to reduce the cost of system in [16]. But, in that case, series-connected panel group is needed to increase the DC bus voltage. Even if different solutions are proposed to increase of DC bus voltage [14, 17-19], one-stage power layer usage with series-connected PV panels is continuing to be the most preferred model [15, 20].

With the above motivations, a grid-connected PV system is proposed in the paper. The system includes a three-phase inverter that controlled by MPPT-MPC algorithm. MPP is determined by the MPPT algorithm and it generates a reference current for the inverter. MPC algorithm generates the switching signals by depending on the reference current. Thus, power flow has been provided by all the power and control structures.

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II. SYSTEM MODEL & CONTROL METHOD

General circuit schema and control techniques are given in Fig. 1. PV panel group is directly connected to grid through a three-phase inverter. Inductance and capacitance of the LC filter can be calculated by Eq. (1) and Eq. (2), respectively.

$$L_f = \frac{0.1U^2}{2\pi f P_p} \tag{1}$$

$$C_f = \frac{0.05P_p}{2\pi f U^2} \tag{2}$$

PV power is used as a total system power for calculations. PV panel group contains 24 series and 4 parallel arrays and total input power is 20kW. Filter parameters are calculated by using the power value per phase. The inductance and capacitance values are calculated as 6.9mH and 5μF, respectively.

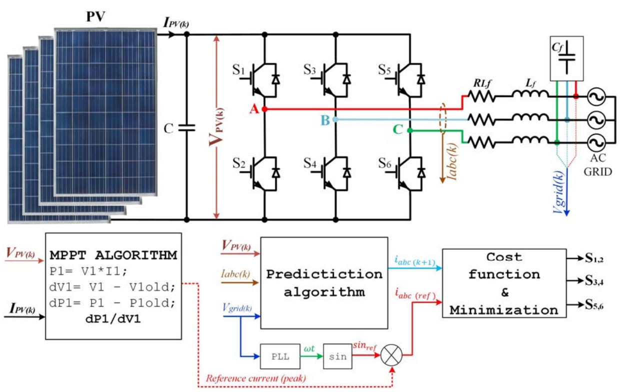


Fig 1. General schema of the system

The classic P&O MPPT algorithm that detailed discussed in [2] is used to determine the reference current for the inverter. Because of that, this study focuses on model predictive current control method which is used to control the inverter current (i_{abc}). General voltage equation of the inverter is given in Eq. (3).

$$V_{inv} = V_{Lf} + V_{Rf} + V_{grid} \tag{3}$$

Output current can be expressed by replacing of inductor voltages in Eq. (4):

$$\frac{di_{(k)}}{dt} = \frac{1}{L_f}\left(V_{inv(n)} - V_{grid(k)} - R_{Lf}\, i_{(k)}\right) \tag{4}$$

Where, $V_{grid(k)}$ is measured grid voltage in the current sampling interval. All the measured parameters are converted to α-β coordinate by using Clarke transformation. V_{inv} is inverter voltage vector that used for predictions. Space vectors of the voltage are shown in Fig. 2. As shown in the figure, three-phase inverters have six active and two “0” states. It shows that the inverter has 8 possible states. Phase states (S_A, S_B, S_C) are defined as an array that contains all voltage states. Inverter voltage states can be expressed with Eq. (5) in α-β frame [19]. Thus, all the control parameters in Eq. (4) are defined in α-β frame. In Eq. (5), n is state number $\{1,2 \ldots\ldots 8\}$

$$V_{inv(n)} = \frac{2}{3}\left[S_{A(n)} + \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right)S_{B(n)} + \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)S_{C(n)}\right] \tag{5}$$

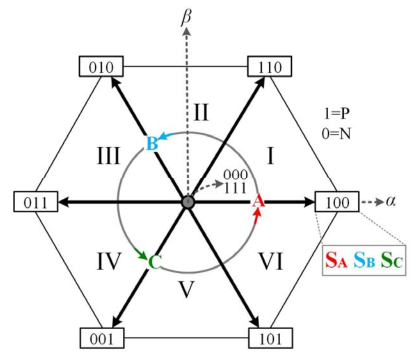


Fig 2. Space vectors of three-phase two-level inverter

A. Model Predictive Current Control Method

The MPC algorithm works by minimizing the control parameter error between the reference and the next sampling interval. MPC can be summarized in two steps as prediction and minimizing. Discretization methods are using to predict the control parameter. Exact discretization and forward Euler are widely used methods. Exact discretization method has high accuracy. But, the method increases the computational burden. Because of that, the forward Euler approximation method (6) is preferred in low order systems.

$$\frac{di}{dt} \approx \frac{i_{(k+1)} - i_{(k)}}{T_s} \tag{6}$$

Eq. (7) can be obtained by substituting the Euler method to the derivative in Eq. (4).

$$\frac{i_{(k+1)} - i_{(k)}}{T_s} = \frac{1}{L_f}\left(V_{inv} - V_{grid(k)} - R_{Lf}\, i_{(k)}\right) \tag{7}$$

The prediction equation (Eq. 8) can be obtained by arranging the Eq. (7).

$$i_{(k+1)} = \left[\frac{T_s}{L_f}\left(V_{inv(n)} - V_{grid(k)} - R_{Lf}\, i_{(k)}\right)\right] + i_{(k)} \tag{8}$$

Current values are predicted for all possible voltage states ($1 \ldots n$) by using Eq. (8). As mentioned before, the minimization of error is the second step of the MPC algorithm. Most part of control algorithms uses difference between reference and measured value. Different from the other methods, the MPC algorithm uses the error between reference and predicted value. Thanks to this feature, the algorithm generates an action for the next step. Therefore, MPC has a better dynamic capability. To calculate the error term, cost functions are using in the MPC algorithms. The cost function of the control algorithm is represented in Eq. (9). $i\alpha$ and $i\beta$ refer to real and imaginary value of currents, respectively.

$$g = \left|i_\alpha^* - i_{\alpha(k+1)}\right| + \left|i_\beta^* - i_{\beta(k+1)}\right| \tag{9}$$

Similar to the prediction equation, the cost function is evaluated for all possible voltage vectors in each sampling interval. Thus, error values are obtained for all possible switching positions. The minimization step selects the optimum cost function that has the minimum error. Switching signals are generated according to the optimum cost function.

III. Simulation Results

System model and proposed control structures in Fig. 1 are verified with simulation studies. Simulation parameters are given in Table I. Firstly, the dynamic performance of the model predictive current control algorithm has been tested with step changes on the reference. As seen from the results in Fig. 3, the reference current is defined as 15A at the beginning of the simulation. Peak value of the inverter current successfully regulated to the reference value by the MPC algorithm. Then, the reference current changed from 15A to 30A. As seen from the detailed results, inverter current is regulated to the new reference in less than 1ms. Step down test is performed by decreasing the reference from 30A to 15A. The results show that, reference tracking is achieved in 0.1ms. As seen from both step-change results, the peak values of inverter currents are successfully fixed to the reference by the MPC algorithm.

TABLE I. System Parameters

Parameter	Value
U (Grid voltage)	380V
f (Grid frequency)	50Hz
P (Nominal power)	20kW
L_f (Filter inductance per phase)	6.9mH
R_{Lf} (Resistance of inductor)	0.7Ω
C_f (Filter capacitance per phase)	5μF
C (DC link capacitance)	330μF
PV Panel (24 series and 4 parallel)	213W_{MPP} and 29V_{MPP}
T_S (Sampling time)	20μs

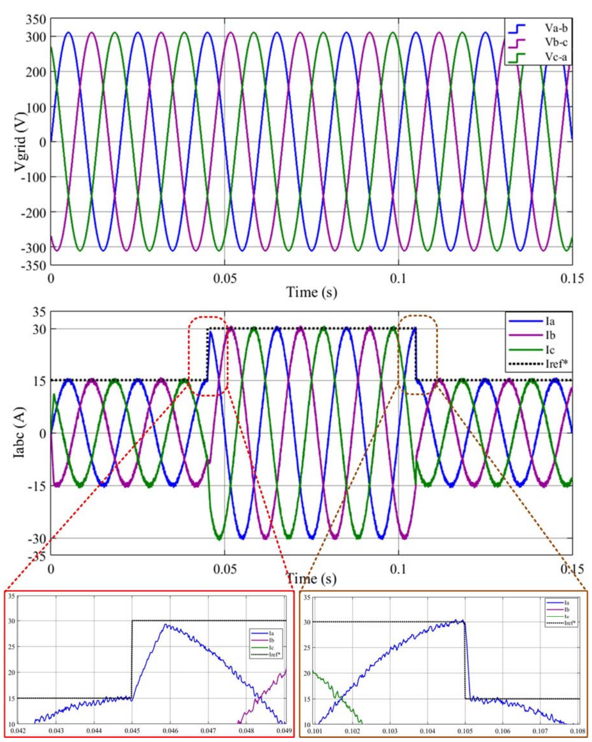


Fig 3. Step change results

After the dynamic performance analysis, power flow control performance of the proposed control algorithm has been tested under varying irradiation conditions. The irradiation curve is given in Fig. 4. As seen from the figure, the curve also includes two cloud effects. PV power results are given in Fig. 5. As seen from Fig. 5(a) and Fig. 5 (b), the MPPT algorithm is tracking the MPP with 98% efficiency. Even if the efficiency decrease in cloud conditions, the efficiency increased to 98% after these times.

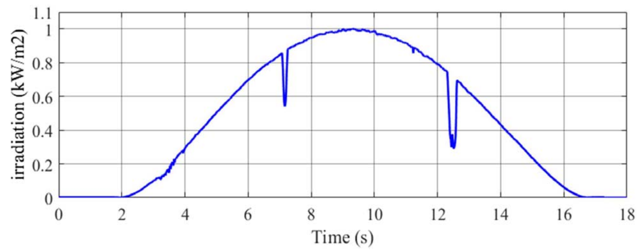


Fig 4. Irradiation curve

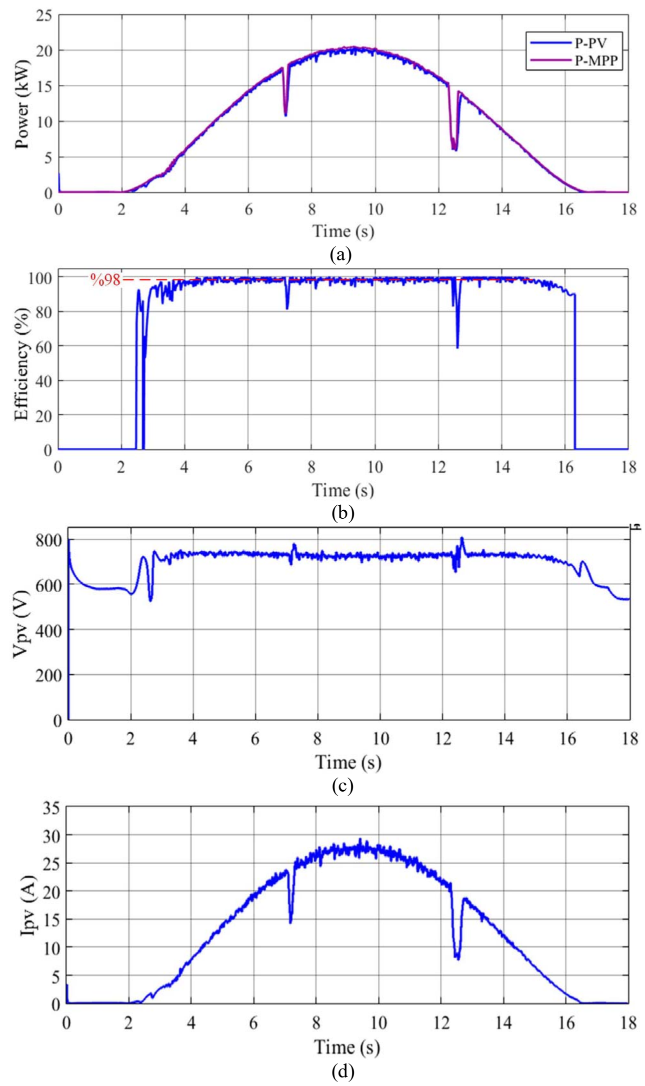
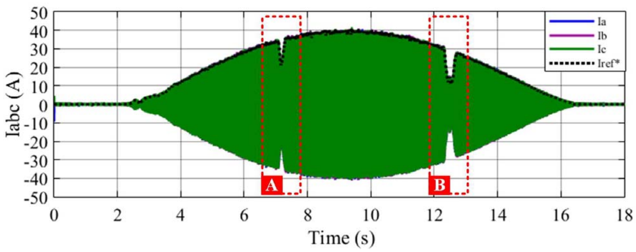


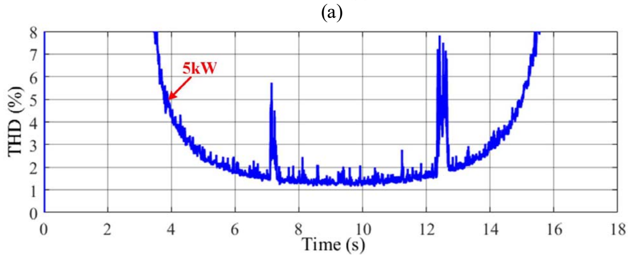
Fig 5. PV results, a: Power, b: MPPT Efficiency, c: PV voltage, d: PV current

Voltage and current results of the PV panel group are given in Fig. 5 (c) and Fig. 5(d), respectively. While the current is increasing up to 28A, PV voltage approximately constant. It's caused by natures of MPPT control in PVs and it gives information about the control performance.

Besides the performance test of the MPPT algorithm, the inverter side is examined in terms of power, efficiency and harmonic distortions. As shown in Fig. (6), the inverter currents are successfully fixed to the reference value (I_{ref}^*) by the MPC algorithm. Because of the MPPT algorithm changes the reference current value, the output currents of the inverter are also changed depending on the irradiation curve in Fig. (4). Fig. 6(b) show that, harmonics are lower than 5% for bigger power values than 5kW. The THD value is lower than the specified limit in standards [21].

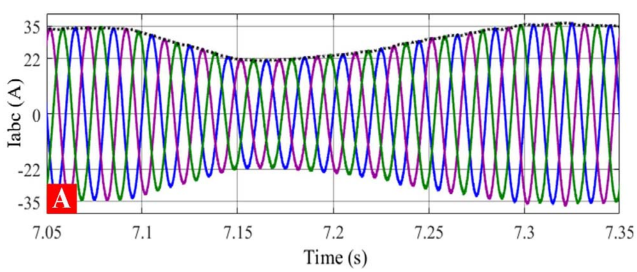


(a)

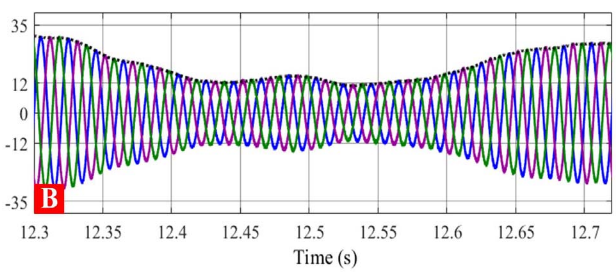


(b)

Fig 6. Inverter results, a: Currents, b: THD



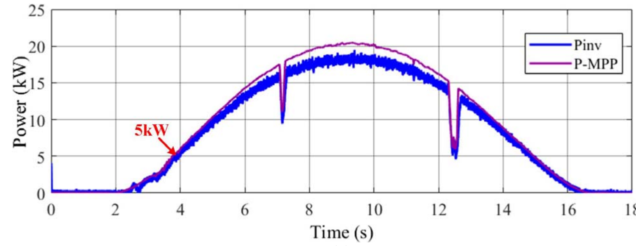
(a)



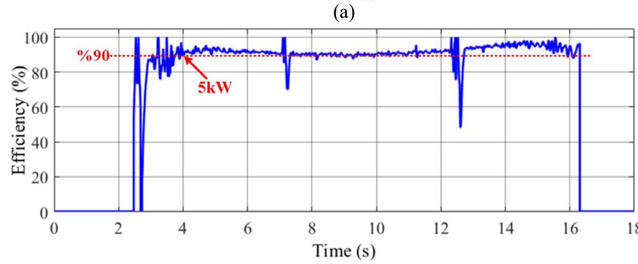
(b)

Fig 7. Detailed current tracking results in cloudy conditions, a: “A”, b: “B”

Detailed results of cloudy conditions (“A” and “B” in Fig. 6) are given in Fig. 7. The reference current decreased from 35A to 22A in the cloudy condition “A”. As seen in Fig. 7(a), inverter currents are successfully regulated to the reference by the MPC algorithm. Similar control actions are seen also for “B” condition in Fig. 7(b). Current tracking results show the combined control algorithms successfully track the MPP not only in varying irradiation but also in cloudy conditions.



(a)



(b)

Fig 8. Inverter efficiency results, a: Power results, b: Overall efficiency of the system

Transferred power to grid at the output of the inverter and ideal MPP curves have been compared to analyze the overall efficiency of the proposed system. The power losses between inverter output power and ideal maximum power curve can be seen in Fig 8(a). Especially the power losses are increased around the nominal power. It caused by filter inductance. Even if the losses increased, Fig. 8(b) shows that the minimum system efficiency is approximately 90% for bigger power values than 5kW. Inverter efficiency can be calculated as 92% by using Fig. 5(b) and Fig. 8(b).

IV. Conclusion

The paper proposes a combined control algorithm for PV systems. The proposed control approach consists of MPPT and MPC algorithms. Thanks to the fast and sensitive control capability of MPC, the combined algorithm offered effective tracking under both varying irradiation and cloudy conditions. Besides the combined algorithm performance tests, it is seen from the step-change tests that the MPC algorithm has a superior current control capability. Efficiency analysis has been performed for both control and power structures. The control efficiency of the MPPT method is 98% and inverter efficiency is 92%. The overall system efficiency for both control algorithms and inverter is approximately 90%.

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