Comprehensive performance analysis of model predictive current control based on-grid photovoltaic inverters

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Abstract: A considerable amount of energy is lost by utilizing the traditional pulse width modulation (PWM) based inverters in an on-grid PV system. Therefore, a model predictive current control (MPCC) based control strategy is proposed in this research work. The controller works based on a predefined cost function. The cost function includes deviation of current from its reference and a switching frequency term to reduce the average switching frequency. All the possible control actions i.e. inverter switching states are tested against the cost function. The state which yields minimum cost is selected as an optimal control action for the inverter. Simulation results show that the proposed controller tracks the reference current accurately with a mean absolute error of 2.5% which is 30% for the PI-PWM based controller. The MPCC based inverter yields low current THD of 2.07%, whereas in traditional PI-PWM based inverter the current THD is 7.26%. The energy efficient operation of the MPCC based inverter is also verified by doing loss analysis. It is shown that conduction, switching, and harmonic losses of the inverter are reduced by 36.8%, 50%, and 91.9%, respectively, in comparison with the PI-PWM based inverter.

Keywords: Model predictive, photovoltaic, inverters, on-grid, harmonic, loss

1. Introduction

People all over the world firmly believe that the renewable energy sources, especially solar energy will bring a positive impact against the growing demands of electricity. Solar energy also contributes to the overall energy production. However, the energy produced from the solar energy contains harmonic components due to improper controlling of the on-grid inverter, which makes it less efficient for the system. Traditional proportional integral-pulse width modulation (PI-PWM) controller generates a significant amount of harmonic component, and a filter is utilized to remove the effect of the harmonic component [1]. An LCL-filter is well-known in this regard as it provides preferable features of reducing harmonic component over the conventional series inductors and provides a switching frequency reduction for medium-voltage while maintaining the standard limit of harmonic content [2]. However, the capacitance of LCL-filter engenders a deferral between the converter and grid, and making it hard to control the grid-side quantities [3]. Therefore, the power industry is continually looking toward the development and redesigned advancements. Researchers are continually endeavouring to discover a perfect solution to various issues which takes the power industry in a new era. For a similar reason, this research work has been done to expel the scourge of harmonics from the power system especially, from the power converter. A model predictive current controller (MPCC) is presented in the paper to lessen the total harmonic distortion (THD) of the output current, current tracking error and overall inverter power loss of the on-grid PV system.

MPCC provides flexibility of using any kind of algorithm that utilizes a model of the system to foresee its future behaviour and chooses the most suitable control activity dependent on the cost.
function of the optimization [4, 5, 6]. However, the MPCC requires a high number of calculations than the classic controller. Thanks to the high-speed microprocessors, that can handle the high number of calculations in a specified time frame [7]. By lessening a preset cost function in every sampling time, an optimized cost function is selected by the proposed MPCC. The cost function is designed for reducing the current tracking error and the average switching frequency. Accurate current tracking will improve the current THD, and lower average switching frequency will lessen the switching loss. The aforementioned two control objectives are combined with a weighting factor in the cost function. The value of the weighting factor is selected by trading-off the average switching frequency and current THD, as they are inversely related. Therefore, the specific objectives of the proposed research work are:

- to develop an MPCC based on-grid photovoltaic (PV) inverter controller that reduces the harmonics of the injected grid current and also complies the IEEE and IEC current THD standards [8];
- to design, develop, and evaluate the on-grid PV system utilizing the proposed controller in MATLAB/SIMULINK platform;
- to analyze the performance of the controller in terms of current tracking accuracy, steady-state and transient responses, current THD, inverter power loss and also to compare the performance with the traditional PI-PWM controller.

2. System Modelling
The block diagram of the designed system as shown in figure 1 consists of a PV system, a dc/dc converter, MPCC based inverter, R-L line filter and the grid.

![Block diagram of proposed MPCC based on-grid PV system.](image)

**PV array modelling**
For modeling a PV array, numerous PV modules are utilized in various combinations [9]. For getting the required amount of voltage and current, the modules are connected in series-parallel combination. The aggregate PV output current can be expressed in Eqn. 1 [10]

\[
I_{PV} = N_P (I_{ph} - I_0) \left[ \exp \left( \frac{q(V_{PV} + R_s I_{PV})}{N_s A K T} \right) - 1 \right] - \frac{V_{PV} + R_s I_{PV}}{N_s R_P}
\]  

(1)

where, \( I_{PV} \) and \( V_{PV} \) are the output current and voltage, \( R_s \) is the series and \( R_P \) is the parallel resistances, \( N_P \) and \( N_s \) are the number of PV cells in a PV module which are connected in parallel and in series, respectively, \( A \) is the ideality factor of p-n junction, \( K \) is the Boltzmann’s constant, \( T \) is the temperature in Kelvin, \( q \) is the charge of electron [8], and \( I_{ph} \) is the produced photocurrent. With \( V_{PV} \) and the simplified, \( I_{PV} \), the power produced by the PV module is represented as [10],

In the research work, the proposed MPCC based inverter consists of a 39kW PV array, which is designed with 168 modules, each having a maximum power rating of 235W.

DC/DC Boost Converter Modelling
A dc-dc converter performs an indispensable role in the solar PV system. To change over the unregulated dc voltage into a directed dc voltage is the utmost function of it. Without the dc/dc converter, structuring an inverter control will be entangled. The dc voltage contribution to the inverter will not be consistent and will differ due to the inverter switching. It will be hard to control the power stream. In this work, a consistent 850V dc voltage is provided to the inverter by a closed loop dc/dc boost converter.

Three-Phase Two-Level Inverter Modelling
The two-level voltage source inverter (VSI) has been chosen since it is a standout amongst the most utilized converter topologies in the industrial sectors. Insulated Gate Bipolar Transistor (IGBT) switches are used in the inverter. For two level three phase converter, eight possible voltage vectors are available as presented in Table 1. It is seen that \( v_0 = v_7 \) which results in seven different voltage vectors in the complex plane and the states will generate different configurations of the three-phase load connected to the dc source.

| \( v_n \) | \( S = [S_a S_b S_c] \) | \( v = v_a + jv_b \) |
|----------|-----------------|-----------------|
| \( V_0 \) | 0 0 0 | 0 |
| \( V_1 \) | 1 0 0 | \( 2/3V_{dc} \) |
| \( V_2 \) | 1 1 0 | \( 1/3V_{dc} + j\sqrt{3}/3V_{dc} \) |
| \( V_3 \) | 0 1 0 | \( -1/3V_{dc} + j\sqrt{3}/3V_{dc} \) |
| \( V_4 \) | 0 1 1 | \( -2/3V_{dc} \) |
| \( V_5 \) | 0 0 1 | \( -1/3V_{dc} - j\sqrt{3}/3V_{dc} \) |
| \( V_6 \) | 1 0 1 | \( 1/3V_{dc} - j\sqrt{3}/3V_{dc} \) |
| \( V_7 \) | 1 1 1 | 0 |

Three Phase Active Load Model
For each phase of three-phase VSI, the load current dynamic expression can be written as [11-12]

\[
v = Ri + L \frac{di}{dt} + e_g
\]  

(3)

where, \( v \) is the inverter voltage vector is indicated by \( v \), injected current is represented by \( i \) and \( e_g \) is the grid voltage vector. For simulation, a constant amplitude grid voltage is assumed with a constant frequency. Hence, the injected current derivative \( dt/dt \) is replaced by a forward Euler approximation can be expressed as [13]

\[
\frac{dt}{dt} \approx \frac{t(k+1) - t(k)}{\tau_s}
\]  

(4)

Now placing the Eqn. (4) in Eqn. (3) to obtain the following expression that allows prediction of the future load current at the time \( (k + 1) \), for each one of the seven values of voltage vector \( \nu(k) \) generated by the inverter.

\[
i^p(k + 1) = \left(1 - \frac{RT_A}{L} \right) i(k) + \frac{\tau_s}{L} \left( \nu(k) - e_g(k) \right)
\]  

(5)

where, \( e_g(k) \) denotes the grid voltage. The superscript \( p \) denotes the predicted variables.
Power loss expression

The overall losses in the devices include the addition of conduction, switching and harmonic losses. Collector-emitter voltage and collector-current influence the conduction loss. The reduction of conduction loss requires the decreasing of the collector-emitter voltage during the conduction time, which can only be altered by the manufacturer of the device. The mathematical expression for determining the average and instantaneous conduction loss of an IGBT can be expressed as [14-15]

\[ P_{\text{con}} = \left( \frac{1}{T_0} \right) \int_0^{T_0} (V_{\text{ceo}} + I_x(t) * R_{ce} ) * I_x(t) * \tau(t) \, dt \]  

(6)

\[ P_{\text{con instantaneous}} = (V_{\text{ceo}} + I_x(t) * R_{ce} ) * I_x(t) * \tau(t) \, dt \]  

(7)

where, \( V_{\text{ceo}} \) is the turn-on / threshold voltage of the IGBT, \( R_{ce} \) is the differential resistance of the IGBT and \( I_x(t) \) represents the arm current through the upper IGBT. The value of \( V_{\text{ceo}} \) and \( R_{ce} \) is taken from a manufacturer datasheet at a specified temperature [14]. The mathematical expression of \( I_x(t) \) and \( R_{ce} \) are as follows.

\[ I_x(t) = (I_{dc}/3) + (I_{ac}/2) \]  

(8)

\[ R_{ce} = \frac{V_{\text{ceo}} - V_{\text{cet}}}{I_{ce} - I_{cet}} \]  

(9)

The term \( \tau(t) \) is related to the modulation index \( m \) of the controlling method. For PWM only, duty cycle \( \tau(t) \) is present and its expression is

\[ \tau(t) = \left( \frac{1}{2} \right) * (1 + m * \sin(2\pi * f_0 * t)) \]  

(10)

where, the output frequency is indicated by \( f_0 \). In case of MPCC, there is no need of modulation index. Therefore, in this case this term is neglected.

The switching loss occurs during the turn-on and turn-off condition of IGBT. The dc link voltages, the output load current, the transient parameters of the IGBTs influence the switching loss. The switching loss is also dependent on the junction temperature of the device and the gate driver circuit resistance. This loss can be reduced by using various soft switching techniques. The mathematical expressions for determining the average and instantaneous switching losses are as follows [14-15]

\[ P_{\text{sw}} = \left( \frac{1}{T_0} \right) \int_0^{T_0/2} f_{\text{sw}} * (E_{on} + E_{off}) * \left( \frac{V_{dc}}{V_{\text{ccon}}\text{nom}} \right) * \left( \frac{I_x(t)}{I_{\text{ccon}}\text{nom}} \right) \, dt \]  

(11)

\[ P_{\text{sw instantaneous}} = f_{\text{sw}} * (E_{on} + E_{off}) * \left( \frac{V_{dc}}{V_{\text{ccon}}\text{nom}} \right) * \left( \frac{I_x(t)}{I_{\text{ccon}}\text{nom}} \right) \, dt \]  

(12)

where the switching frequency is presented by \( f_{\text{sw}} \), \( V_{dc} \) is the dc link voltage and \( V_{\text{ccon}}\text{nom} \) and \( I_{\text{ccon}}\text{nom} \) are the voltage across the collector-emitter terminal of IGBT and the collector current during the test, respectively. The values of \( V_{\text{ccon}}\text{nom} \) and \( I_{\text{ccon}}\text{nom} \) are taken from the manufacturer datasheet. The values of turn-on and turn-off energy \( E_{on} \) and \( E_{off} \), respectively, are also taken from the datasheet [16].

The presence of the harmonic component in the injected grid current also causes power loss which decreases the penetration of power to the grid. The presence of the harmonic component is expressed by the term THD. The total harmonic losses due to the harmonic components are determined by the following expression [17].

\[ P_{\text{harmonic}} = 3R_L I_L^2 = 3R_L \left( I_T^2 + \sum_{n=2}^\infty I_n^2 \right) = R_L I_T^2 \left( 1 + THD_I^2 \right) \]  

(13)
where, $I_1, I_n$ and $THD_i$ are the fundamental current, current due to harmonic component and amount of current THD, respectively, and $R_L$ is the per phase resistance.

3. Model Predictive Current Control (MPCC) Strategy

MPCC is an optimization method in which a cost function is minimized for a pre-defined time horizon, subject to the system constraints and model. The outcome is a succession of optimizing the cost function. The algorithm developed for the proposed controller is presented in figure 2. The algorithm consists of five sections: (i) measurement, (ii) estimation, (iii) prediction, (iv) optimization, and (v) application of the optimal voltage vector $V_{opt}$. The cost function for the proposed on-grid PV inverter can be expressed as \[ g = |i^*_a(k + 1) - i^P_a(k + 1)| + |i^*_b(k + 1) - i^P_b(k + 1)| + \lambda n_{sw} \] (14)

where, $i_a$ and $i_b$ are the real and imaginary components of current vector $i$, respectively, and $i^*_a$, $i^*_b$, $i^P_a$, and $i^P_b$ are the real and imaginary components of the reference and predictive current vector, $i^*$, and $i^P$, respectively. $n_{sw}$ is the number of commutations of the power semiconductor devices, which is included in the cost function in order to evaluate the reduction of the average switching frequency. The preferred switching state will be the one that provides less number of commutations of the switch. The two cost function terms i.e. reference current tracking and switching frequency reduction are handled by a weighting factors $\lambda$. The switching frequency reduction will be given priority if the value of $\lambda$ is greater. The overall strategy of the control is executed using the following steps.

Step 1: The injected current $i(k)$, grid voltage $\bar{e}_g(k)$, and dc link voltage $V_{dc}$ are measured.
Step 2: For the immediate next sampling instant, the future load current $i^P(k + 1)$ and number of switching transitions $n_{sw}(k + 1)$ are predicted for all the possible switching states.
Step 3: The designed cost function $g$ is estimated for each of the prediction.
Step 4: For the minimized cost function $g_{opt}$, an optimal switching state $S(j_{opt})$ is selected.
Step 5: The newly selected switching state $S(j_{opt})$ is then applied to the next sampling instant.

![Figure 2. Block representation of the algorithm utilized in MPCC controller](image)

4. Simulation Results

The whole simulations are carried out by using MATLAB/Simulink tool. The parameters utilized in the simulation are shown in Table 2. The features of the proposed MPCC based on-grid inverter system are compared with the existing PI-PWM controllers for the same parameters. The results of the comparison are given below.
Table 2. Parameters for the simulated systems

| Parameter         | Value |
|-------------------|-------|
| Inverter voltage  | 850V  |
| Reference current | 96A   |
| Reference frequency | 50Hz |
| Load resistance   | 3.44Ω |
| Load inductance   | 70mH  |
| Grid voltage      | 120V  |
| Grid frequency    | 50Hz  |

**Transient Analysis**

In order to test the dynamic performance of the controllers, transient analysis is done. A step reduction is done in the amplitude of the real component of the reference current $I_α^*$ from 96A to 48A at time 0.015sec, while the imaginary component of the reference current $I_β^*$ is kept constant at 96A for all the aforementioned controllers. The results of the analysis are presented below.

The transient responses of the measured injected current in $αβ$ frame and voltage in phase ‘a’ for the PI-PWM controller are shown in figure 3. It is seen that the controller tracks the change in reference current, but does not provide the decoupled control of load current $(I_α, I_β)$. This means that a change in one component $I_α^*$ affects another component ($I_β^*$) while to settle down the change.

For realizing the transient behaviour of the proposed controller, a step reduction (from 96A to 48A) of the real component ($I_α^*$) of the reference current is also done at time 0.015s. The response of the injected current in $αβ$ frame and voltage in phase ‘a’ for the proposed MPCC based controller under transient conditions are shown in figure 4. It is seen that the controller provides decoupled control of injected current $(I_α, I_β)$. This means that a change in one component ($I_α^*$) does not affect the other($I_β^*$).

![Figure 3](image)

**Figure 3.** Transient phase voltage in phase a and currents ($I_α, I_β$) in $αβ$ frame for PI-PWM controller

After analysing the aforementioned transient analysis, it is clearly seen that the proposed MPCC based controller provides better transient response than the existing PI-PWM controller.

**Reference Current Tracking**

Appropriate tracking of the reference current is an important feature for any controller. The reference tracking performance of the proposed controller and the existing PI-PWM controller is presented below. For the PI-PWM controller, the measured phase current waveform in $αβ$ frame is shown in figure 5 (a), which shows that the currents contain harmonic components and become distorted. The reference current tracking accuracy of the controller is poor as shown in figure 5(a). Figure 5(b) shows the mean absolute current tracking error is 0.3 (30%) for the PI-PWM controller.
Figure 4. Transient phase voltage in phase a and currents (I_α, I_β) in αβ frame using proposed controller

Figure 5. (a) Reference current tracking response and (b) mean absolute current tracking error for PI-PWM control.

The current tracking accuracy of the MPCC at steady-state condition is shown in figure 6(a). It can be seen that the controller tracks the reference current properly. The mean tracking absolute error at steady-state is 0.025 (i.e. 2.5 %) as shown in figure 6 (b).

Figure 6. The current (I_α, I_β) tracking performance under steady-state condition and Mean tracking absolute error between the reference and measured current in MPCC
From figure 5(a), it is seen that the output current of the inverter contains severe amount of harmonic component. Therefore, Fast Fourier Transform (FFT) analysis is done to understand the amount of THD of the current as well as the amount of individual harmonic component of the current for the PI-PWM controller, which is shown in figure 7(a). The current THD is found to be 7.26% for the PI-PWM controller. The result from the FFT analysis for the proposed MPCC controller is shown in figure 7(b). It is seen that the current THD for the proposed controller is 2.07%, which is better than the existing PI-PWM controller.

![FFT Analysis](image)

**Figure 7.** Steady-state grid current THD response for the (a) PWM and (b) proposed MPCC controller.

In summary, if the performance of the described existing PI-PWM controller is compared to the proposed controller in terms of tracking accuracy, harmonic content in the output injected grid current, the proposed one shows the better performance. The individual harmonic components up to 13th harmonic component exist in the output inverter current/the injected grid current by the controllers is shown in figure 8, which shows that the proposed controller performs better than the PI-PWM controller.

![Harmonic Component THD](image)

**Figure 8.** Comparison of individual harmonic component THD values for the PI-PWM and the proposed controller.

The standards of IEC 61727 and IEEE 929-2000 infers that the current THD of the injected current to the grid ought to be under 5% and the odd harmonic component from third to ninth and eleventh to nineteenth ought to have THD under 4% and 2%, individually. Along these lines, the PI-PWM controller indicates higher current THD than the proposed controller.

**Loss analysis**

Power loss analysis is done for the proposed control strategy and compared with the conventional PWM strategy. The parameters used in the analysis are shown in Table 3 and the related expressions
are already presented in Section 2.

The instantaneous conduction and switching losses of MPCC is calculated using the Eqns. (7) and (12), respectively, and are shown in figure 9(a). Figure 9(b) shows the instantaneous conduction and switching losses of IGBT for PI-PWM. Comparing the current and loss curve, it can be said that, MPCC yields smooth switching, whereas PWM yields distorted switching.

![Figure 9](image_url)

**Figure 9.** Instantaneous conduction and switching losses in (a) MPCC and (b) PI-PWM controller

| Parameters                  | Value       | Parameters                  | Value       |
|-----------------------------|-------------|-----------------------------|-------------|
| Switching frequency, $f_{sw}$ | 3.54 kHz   | DC link voltage, $V_{dc}$   | 850 V       |
| Turn-On energy, $E_{on}$    | 1.4 mJ     | Turn-on/Threshold voltage of IGBT, $V_{ce0}$ | 1.5 V |
| Turn-off Energy, $E_{off}$  | 2.0 mJ     | Output frequency, $f_o$     | 50 Hz       |
| Voltage across $V_{ce}$ during Test, $V_{ccnom}$ | 400 V   | Modulation Index, $m$       | 0.95        |
| Collector Current during Test, $I_{cnom}$ | 50 A   | IGBT differential resistance, $R_{ce}$ | 0.01467 Ω |

As mentioned earlier, the chosen reference current is 96A. Now, for further analysis, the reference current is varied from 91 to 100A for both the controller as shown in figure 10. It is seen that both the conduction and switching loss of MPCC are greater than PI-PWM during the variation of reference current.

![Figure 10](image_url)

**Figure 10.** Comparison of conduction and switching losses between MPCC and PWM

After determining the switching and conduction losses, another loss due to the harmonic component in the output current i.e. the harmonic loss is calculated using the Eqn. (13). As mentioned before, for
determining the harmonic loss, the rms value of the output current and its THD percentage due to the harmonic component are required. Using the data found from the FFT analysis, the harmonic loss is calculated for both the PI-PWM and MPCC controller. The per-phase continuous harmonic loss for MPCC is 6.79W which is 83.59W for PI-PWM. For three-phase, it will be multiplied by 3, hence, for MPCC it is 20.38W, and for PWM it is 250.78W. Therefore, it can be said that in MPCC, 91.87% harmonic loss is reduced. A comparison of conduction, switching, and harmonic losses between MPC and PWM is shown by a bar graph in figure 11. It is seen that the overall per phase conduction, switching and harmonic losses for MPCC is 42.59W, and for PI-PWM, it is 142.75W. Therefore, 70.16% (100.16W) power loss is reduced due to the use of MPCC rather than the traditional PWM method. The results found from the analysis ensures the proposed controller as energy efficient one.

![Comparison of conduction, switching and harmonic loss for MPCC and PWM](image)

**Figure 11.** Comparison of conduction, switching and harmonic loss for MPCC and PWM

5. Conclusion
To maximize the power penetration, an MPCC based on-grid PV inverter system is designed and the performance is analysed and compared with the traditional PI-PWM controller in this research work. The mean absolute current tracking errors and current THDs for the PI-PWM are 30% and 7.26%, respectively, while the error and THD are only 2.5% and 2.07%, respectively, for the proposed MPCC. The proposed controller also meets the IEEE/IEC standards. It is shown that the PI-PWM and MPCC based controllers provide the continuous overall per phase loss of 142.75W and 42.59W, respectively. This means that a reduction of 70.16% (100.16W) power loss is achieved due to the use of MPCC rather than the traditional PI-PWM method, which makes the proposed controller energy efficient. Therefore, to enhance the present power generating PV system by reducing current THD and power loss, the designed model can be an optimum solution to establish a greener world for the future generation.

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