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Model Predictive Control for Power Quality Enhancement in Grid-Tied Renewable Energy Inverters

Ravi Samikannu[1], Said Yusuf Mohamud[2]
[1]Department of Electrical and Communications Systems Engineering, Botswana International University of Science and Technology, Botswana.
[2]Department of Electrical Engineering, Faculty of Engineering, Hormuud University, Mogadishu, Somalia.
E-mail: profravieee@gmail.com[1], dhagacade337@gmail.com[2]

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ABSTRACT

The project aims at applying Model Predictive Control (MPC) to increase the power quality of grid-tied inverters connected to photovoltaic (PV) and wind systems. The presence of increased renewable energy on the power grid has led to an increased possibility of occurrence of harmonic distortion, voltage variations and a decline in quick response that may compromise the grid and violate power quality norms such as IEEE 519. Conventional controllers like proportional--integral (PI) and hysteresis control cannot always produce the correct result in a response to system dynamics and various properties of systems. These problems are eliminated in the framework which predicts what will take place in the system and switch the inverter appropriately to minimize a given cost function. With this solution, harmonics rejection and efficient current monitoring as well as rapid adaptation to grid issues and changed demand are realized. Simulation study In MATLAB / Simulink, the comparison of the proposed MPC controller against conventional control methods was achieved through simulation with different irradiance variations and loads being switched on / off. The results state that MPC-based inverter control introduces THD of less than 3%, ensures that the voltage remains in a range of +/- 2 percent of the nominal value and enables quicker transient responses, renovating renewable energy systems more dependable and compliant. Besides, MPC enables safety and control properties that makes it flexible to suit the future needs in smart grids. This method brings a practical solution that highly benefits a power grid to operate normally, provide high power quality and operate effectively with increased renewable energy, promoting the usage of intelligent inverters within the power supply system.

Corresponding Author:

Ravi Samikannu,
Department of Electrical and Communications Systems Engineering,
Botswana International University of Science and Technology,
Botswana.
E-mail: profravieee@gmail.com

1. INTRODUCTION

Due to the sustainability push, power grids currently incorporate more wind turbines and solar photovoltaics (PV). Since they are beneficial to the environment, these sources present a problem because of their intermittent nature that may interfere with the stability, reliability and power quality in the electrical grid. The exploitation of the renewable energy sources successfully is based on the grid-tied inverter that connects the renewable source and the grid. The quality of the inverter performance is required to support efficient energy transfer and IEEE 519 and IEEE 1547 standards.

A considerable challenge is encountered in many contemporary power systems because nonlinear loads and variable energy sources compromise the quality of power. Parameters like Total Harmonic Distortion (THD), voltage stability and dynamic response are reduced that makes it inefficient and likely to cause damage to sensitive devices. Proportional Integral (PI) controllers or hysteresis current control are commonly found in many grid-tied inverters as they are simple to realize. Nevertheless, these methods are not so great at rapidly adapting, harmonics suppression or operating efficiently with the alterations of power conditions. They cannot foresee challenges or problems, they therefore react more to problems rather than prevent them which has now become very crucial to smart grids.

Model Predictive Control (MPC) has emerged as a useful and significant control technique of power electronics in this field. MPC is based upon a mathematical representation of the system to predict short term what is going to happen. MPC is defined as a control technique that handles the input of a system fastidiously by choosing the input that minimizes costs and abides by the regulations of the system and the operations. With computer-aided design and fast prediction, today inverters can follow rapidly varying currents, clamp more harmonics and steady themselves effectively. In addition, novel technology such as adaptive MPC, data-driven MPC and reinforcement learning-based predictive controllers are employed since they contribute towards making the inverters more flexible, efficient with rich harmonics and capable of adapting and learning by themselves in reality.

It aims at providing a robust, scalable and smart power grid control architecture that suits the current modern power grid requirements. Section 2 then summarizes the work done by others, Section 3 discusses the setup selected, Section 4 discusses the MPC design, Section 5 gives the results of simulation and Section 6 concludes the paper with key messages and future work.

2. LITERATURE REVIEW

Power grid of the present days that operates with renewable sources need the grid-tied inverters to be managed with robust, flexible and efficient power management system. They should ensure that energy trading between renewables and the grid is made easy as well as ensure that stringent power quality requirements are achieved. Proportional -Integral (PI) control is simple and not hard to implement, which is why it is regularly used as a control process. Meanwhile, PI controllers are not fast enough and are not adequate enough to operate during rapid load or power output changes. In order to address these weaknesses, a number of new control methods have been presented over the last few years.

Voltage-Oriented Control (VOC) is the primary control strategy of many grid-tied inverters. It decouples the active and reactive power processing, through the synchronous reference frame. Voicing works well when all is balanced, but voicing is reduced in effectiveness when grid voltages or load distribution is unbalanced. Like that, the Hysteresis Current Control (HCC) is valued due to its simplicity in use and fast reaction. In addition, the switching power supplies vary in frequency that translates into increased power loss and interferences thus cannot be used in applications that seek to minimize wastage.

Intelligent engineers have suggested Sliding Mode Control (SMC) due to its capability of dealing with disturbances effectively and responding fast to variations. Nevertheless, the attempts to prove such result seldom end well due to the uncontrolled noise and the effects of parameter values. Besides that, Fuzzy Logic Control (FLC) and Neural Network-based Control do not presuppose precise mathematical models and are capable of handling nonlinearities. Yet these methods need plenty of adaptation and training and they are not readily applicable to grid-connected systems.

Model Predictive Control (MPC) is gaining popularity in the last couple of years in power electronics and renewable energy systems because this control method predetermines the state of the system to enhance control properties. It achieves this by optimizing the plotted outputs so as to get a minimum cost functional within a specified prediction period and obey all the system constraints. It is most applicable to systems with many variables and conditions that vary with time such as grid-tied inverters in renewable energy systems because of this. As it is stated, MPC operates microgrids more precisely and reliably, primarily when voltage balance is disrupted, and loads change significantly (Guerrero et al., 2021). Comparing with conventional controllers, the MPC implemented by Kamel et al. (2020) in grid-connected photovoltaic inverters significantly reduced Total Harmonic Distortion (THD) and made it possible to respond much faster.

Furthermore, the works of Rodriguez et al. (2016) also indicated that MPC allowed precise real-time tracking, allowing to consider maximum current limits and regulations on the switching states simultaneously. Blaabjerg et al. (2019) compared various control strategies of renewable energy systems and concluded that MPC is an outstanding choice in terms of performance, flexibility and computer calculations, especially due to its utility in the presence of grid problems and fluctuating quantities of power produced by the sources.

Although numerous works have been done about MPC in power electronic converters, the majority of them investigate tracking current references or tie to the public grid. Enhancement of power quality through reduction of harmonics, enhancement of voltage stability and increase in the dynamism of the grid-tied renewable energy systems through MPC procedures is still scarcely researched. There are even a smaller number of studies that carry out a comparison between PPAs and a regular power purchase agreement or a heat cascading strategy under different circumstances where there exists a sudden variation in either sunlight or power requirement.

The principle motive in writing this work is the gap existing in the literature. Since it studies MPC to deliver improved power quality when renewable energy is utilized, the analysis in MATLAB/Simulink serves as the trusted analysis to assess the enhancement of THD, voltage and reaction time. The findings are aimed at sustaining the claim that MPC is highly applicable as part of smart grids that incorporate high proportions of renewables.

3. SYSTEM CONFIGURATION

The system will analyze the possibility of using Model Predictive Control (MPC) to assist in improving the power quality when grid-connected via renewable sources. The figure below is an image of a typical distributed generation system which is connected to the utility grid using a power electronic inverter. The key components of the system are a renewable energy source (either solar or wind power), grid-connected voltage source inverter, and a few elements of interfaces and measuring devices.

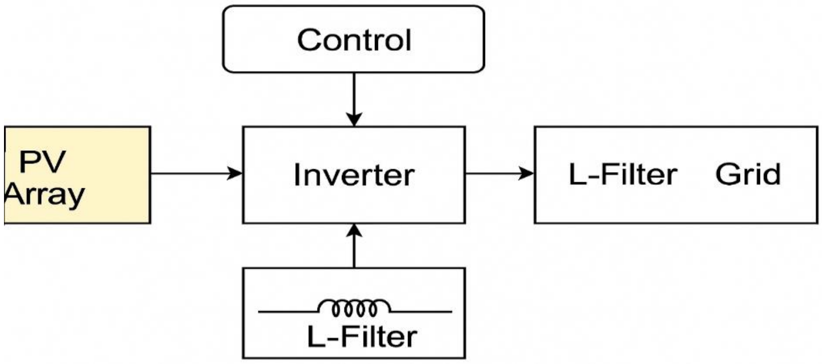

Figure 1. System configuration diagram of the grid-tied renewable energy inverter system

3.1 Renewable Energy Source

A renewable source selected among a photovoltaic (PV) array, a DC-DC boost converter, a variable-speed wind turbine or an AC-DC-AC conversion point is what powers the system primarily. The model assumes the input is a DC source that has been regulated by maximum power point tracking (MPPT) as in a solar panel or wind turbine. With assistance of a DC-link capacitor, the DC voltage is maintained constant and therefore the inverter is fed continuously.

3.2 Grid-Tied Inverter

The device that has been discussed is Voltage Source Inverter (VSI) that connects the renewable energy system to the utility grid in three phases. With current control, the inverter feeds three-phase sinusoidal currents that step in synchronization with the voltage of the grid. To assist in keeping the current harmonics low, and to assist in assisting the MPC in sending the correct switching signals, an MPC algorithm is utilized to direct the MPC in sending the correct switching signals. In simulation, the assumption is made that the switch elements (e.g. IGBTs or MOSFETs) have not lost any switching time and that they are perfectly conductive.

3.3 Point of Common Coupling (PCC)

PCC is the point of connection between the inverter and the grid. This node is necessary to monitor grid compliance and ensure that the currents injected stay within voltage limits, stay on the same phase and with acceptable harmonic distortion. The system allows power exchanges at the PCC to be synchronized with need and status of the utility.

3.4 Measurement and Feedback Units

To utilize closed-loop control, you have to continuously monitor grid voltages and currents. The inverter output is measured by sensors which measure the output current vector and the voltages on the grid phases are measured by sensors at the PCC. Switched power systems encode the signals into digital data that are processed by the MPC controller to determine the switching action every sample. Due to the feedback loop, the current can be measured at any time accurately and can be compensated against any type of disturbance or setpoint alteration.

3.5 Assumptions

The model simplifies a number of assumptions in order to examine the behavior of the proposed Model Predictive Control (MPC) method. The circuit voltage is balanced in the three phases thus there is no asymmetry. The perfect switching inverter utilized in the simulation is deemed to have zero delay, zero losses and zero parasitic effects. It requires the assumption that the grid voltages and currents are measured efficiently and in real time. Also, the voltage across the DC-link is continuously regulated and kept constant with the aid of an MPPT or any other similar management system. These assumptions allow testing the effectiveness of the MPC algorithm and comprise the controlled setting of the study.

Table 1. System Components

Component	**Value**	**Remarks**
DC-Link Voltage	700 V	Maintained constant to supply inverter power stage
Grid Voltage (L–L RMS)	400 V	Standard medium-voltage grid-level connection
Switching Frequency	10 kHz	Selected to balance dynamic performance and efficiency
Sampling Time	100 µs	High-resolution control signal computation window
Filter Inductance	3 mH per phase	Provides current smoothing and harmonic attenuation
Load Type	Resistive-Inductive (R-L)	Used to simulate realistic grid loading

4. MODEL PREDICTIVE CONTROL DESIGN

MPC determines the optimal future output, given a finite horizon, based on a model of the system to determine the most appropriate future output, given the expected state of the system and/or any constraints. Multi-variable effects, input and output limits and power quality are not addressed in classical control methods but are addressed in MPC and that is why MPC is used in grid-tied inverters which must resist changing renewable energy supplies.

4.1 Prediction Model

At the core of MPC lies the system's **discrete-time state-space model**, which is derived from the continuous dynamics of the inverter and discretized based on the system's sampling period. The general form of the model is:

$$\mathcal{X}(k+1) = Ax(k) + Bu(k)$$
$$\mathcal{Y}(k) = Cx(k)$$

Where:

- $x(k) \in \mathbb{R}^n$ is the state vector at the k^{th} time step, typically representing inverter output currents or voltages.
- $u(k) \in \mathbb{R}^m$ is the control input vector, corresponding to the inverter's switching signals or reference voltages.
- $y(k) \in \mathbb{R}^p$ is the output vector, often the measured or estimated phase currents or grid voltages.
- $A, B, and\ C$ are the discrete-time system matrices derived from the inverter's electrical parameters (LCL filter, DC-link voltage, grid impedance, etc.).

This predictive model is used to forecast future states of the inverter output over a finite time horizon N, which forms the basis for optimizing the inverter's control action at each step.

4.2 Cost Function

The **objective** of the MPC is to compute a sequence of control actions that minimize a quadratic cost function over a finite prediction horizon N. The cost function is designed to penalize deviations from the reference current trajectory and excessive switching activity:

$$J = \sum_{i=1}^{N} \left[(i_{ref}(k+i) - i(k+i))^2 + \lambda \cdot \Delta u(k+i)^2 \right]$$

Where:

- $i_{ref}(k+i)$ is the desired reference current at future time step $k+i$, typically sinusoidal and synchronized with grid voltage.
- $i(k+i)$ is the predicted inverter output current.
- $\Delta u(k+i) = u(k+i) - u(k+i-1)$ is the change in the control input to penalize frequent switching.
- λ is a weighting factor used to balance current tracking performance and control smoothness.

This structure allows for excellent tracking of sinusoidal current references and ensures that the inverter output maintains a low Total Harmonic Distortion (THD) level while minimizing switching stress and losses.

4.3 Constraints

Model Predictive Control (MPC) comes in handy since it takes into account system constraints in computing the control to ensure that the power electronic converters operate safely and efficiently. The design of grid-tied inverters control has some practical limits. First the logic conditions are reversed, as an inverter operates with a finite number of well-defined switching states, e.g. eight in most two-level three-phase inverters. Accordingly, only realistic switching combinations are employed, such that the controller can generate realizable signals. Moreover, the circuit controller makes sure that the current and the voltage do not go beyond the limit so as to safeguard system components. They ensure that the current and the voltages of output do not exceed the operation safe limit whatever may happen. Third, power quality problems are eliminated by making the forecasted current waveform such that its Total Harmonic Distortion (THD) does not exceed 5%, according to IEEE 519. This constraint is managed, although not explicitly written into the model, by the manner the cost function is set up to exclude high-frequency problems and non-sinusoidal reference currents. This comprises constraints on voltage switching frequency, heat generation of electric power devices and circuit protection limits to enhance system dependability and reliability. In MPC with the addition of these constraints, the controller will seek to achieve excellent tracking performance, but will also ensure safety and adherence to regulations.

4.4 Optimization Algorithm

The grid-tied inverters that implement MPC operate on a receding horizon basis and hence the problem is solved at every new sampling period. It begins by taking the inverter output current and grid voltage in real time and these become the current inputs to the prediction of future behavior. The controller predicts the system behavior N steps into the future using a discrete-time state-space model. This enables the MPC algorithm to optimal value of the cost function J, which considers the system constraints that limit the current, voltage, switches and level of distortion occurring. The result is a list of control inputs that will be most effective in the following N steps. Nevertheless, only the initial action of the sequence is considered by the system and the others are disregarded. The process is repeated in the subsequent time step with revised measurements and therefore the controller can react to any perturbations, modification in the reference or variation in renewable power input. FCS-MPC is a practical method of switching control of voltage source inverters (VSIs). FCS-MPC requires that the candidate states of the inverter are examined by computing a cost associated with each of them and the state with the minimum cost is selected. Due to enumeration, this approach can afford to dispense with complex solvers and is far less computer demanding on systems with a small number of variables. In more challenging cases or in systems that are more sophisticated, then convex optimization solvers or explicit MPC can be used to guarantee that real-time capability is maintained. In this frame, MPC is perfectly designed to be applied in smart grids, as such characteristics as flexibility, narrow determination of constraints and fast response are highly significant.

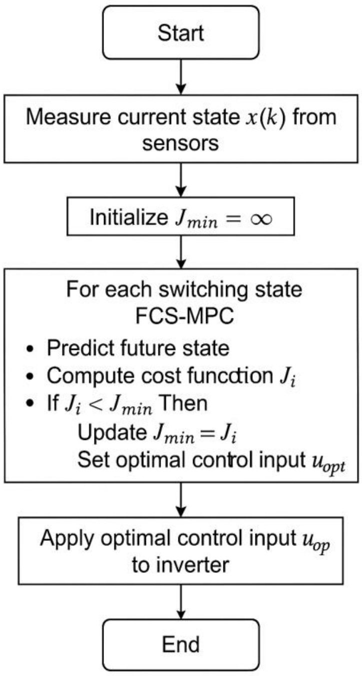

Figure 2. Flowchart of the Finite Control Set Model Predictive Control Algorithm

Algorithm 1: Finite Control Set Model Predictive Control (FCS-MPC) for Grid-Tied Inverter

```
Initialize:
    Sampling time Ts ← 100 µs
    DC link voltage Vdc ← 700 V
    Filter inductance L ← 3 mH
    Filter resistance R ← 0.1 Ω
    Grid voltages Vgrid ← [230; 230; 230] V (per-phase)
    Reference currents i_ref ← [10; 10; 10] A (balanced sinusoidal)
    Initial actual current i_actual ← [0; 0; 0]
    Previous switching state u_prev ← [0; 0; 0]
    Weighting factor λ ← 0.01

Define:
    System matrices A ← -R/L, B ← Vdc/L, C ← 1
    Set of 8 discrete inverter switching states for 2-level VSI

Set:
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```
   Minimum cost J_min ← ∞
   Optimal control input u_opt ← [0; 0; 0]

For each switching state u_i in switchingStates:
   Compute inverter output voltage:
      v_inverter ← Vdc × (2 × u_i − 1)

   Predict next current using Euler approximation:
      di/dt ← A × i_actual + B × (v_inverter − Vgrid)
      i_pred ← i_actual + Ts × di/dt

   Compute tracking error:
      error ← i_ref − i_pred

   Compute change in switching state:
      delta_u ← u_i − u_prev

   Calculate cost function:
      J_i ← sum(error²) + λ × sum(delta_u²)

   If J_i < J_min:
      J_min ← J_i
      u_opt ← u_i
   End If
End For

Apply optimal control input:
   u_prev ← u_opt
   Display u_opt
```

5. SIMULATION AND RESULTS

A comprehensive simulation analysis was carried out in MATLAB/Simulink to confirm the effect of Model Predictive Control (MPC) strategy in enhancing power quality of grid-tied renewable energy inverters. It features three-step voltage source inverter that is tied to the utility grid with an L-type filter. The inverter is fed by a DC voltage which represents a photovoltaic (PV) array which is controlled by MPPT. All the simulations were configured in MATLAB R2023a with Simulink and a fixed-step solver. The inverter is a 2-level three-phase Voltage Source Inverter (VSI) that is Pulse Width Modulated (PWM). A realistic transient effect was modeled by changing the solar irradiance profile with a step function between 1000 and 600 W/m 2 at t = 0.02 s.

The performance of the three strategies, Proportional -Integral (PI), Hysteresis Current Control (HCC) and the new MPC is compared. Overall distortion (THD) parameters you should look at are the stability of the voltage output with time and the rapidity and accuracy of the UVG to respond to grid disturbances and reference signal changes.

5.1 THD Performance

Total Harmonic Distortion (THD) should be employed in measuring power quality and particularly inverters linked to the grid because IEEE 519 recommendations propose that low-voltage systems should not surpass 5 percent THD level. As is evident in the results of the simulation, the different control strategies all vary widely in the way they play harmonics. The commonly used PI controller resulted in 6.7% THD that is higher than the permitted value and it indicates that the system cannot completely filter the harmonics when the voltage varies. The Hysteresis technique gave a minor improvement in the results, whereby THD reduced to 5.2%, but the drawback of this technique is that it varies its switching frequency and this may cause an increase in EMI and additional heat on the power devices. Model Predictive Control (MPC) based method was considerably better in terms of harmonic distortion reduction (THD of 2.9%, which is below the IEEE 519 limit). This showing indicates MPC manages sudden variations effectively, thus it is able to generate present patterns near a sine wave with numerous varying load states and unreliable renewable energy. Among the findings, it is worth noting that MPC assistance is very beneficial to smooth the current output of grid-tied inverters, and this makes it a credible technology to apply in the contemporary smart grid.

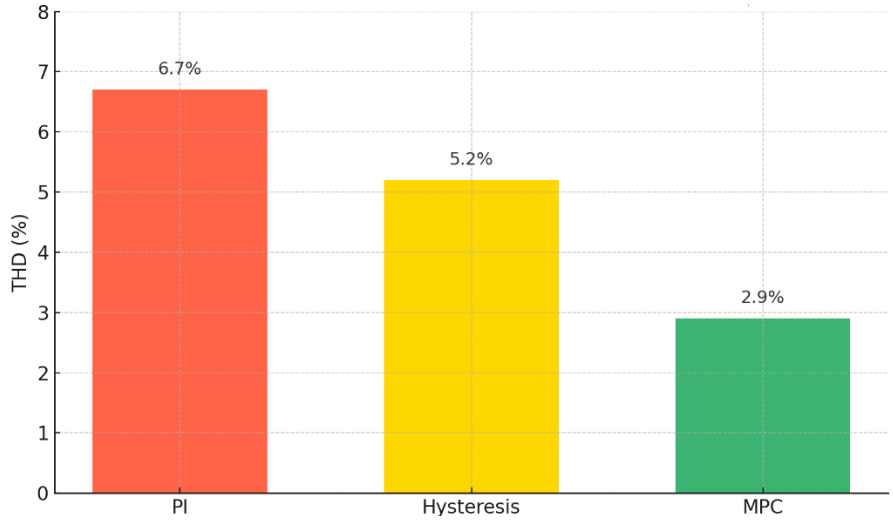

Figure 3. THD Performance Comparison of Control Strategies

5.2 Voltage Stability

Of importance to the operation and safety of the grid is how the voltage is managed at the point where the inverter is connected (PCC) as this determines whether the grid will accommodate the various loads and conform to the utility regulations. The behavior of the inverter with regard to voltage was studied under changing loads as well as when the solar irradiance was fluctuating. Simulation outcomes indicate that controllers of both kind struggled to maintain the voltage steady since they exhibited excessive overshoot and sluggish recovery to normal, with deviation of up to near 5 percent of the normal 400 V RMS value. Due to these circumstances, equipment failures are increasing, as well as losses and possible breakage of the rules of the grid. The MPC method performed better in maintaining the output voltage near 100% and 98% as compared to the others. The fact that MPC can make rapid and accurate corrections in the event of disturbances is due to the fact that it predicts where the system will shortly be. The MPC algorithm demonstrates better voltage stability and thus it is appropriate to be applied to voltage-sensitive loads and to vary operating conditions in smart grids. Panel 2 demonstrates the effect of PI control (red) that produces larger voltage variation in contrast to MPC (blue) that provides more steady voltage output.

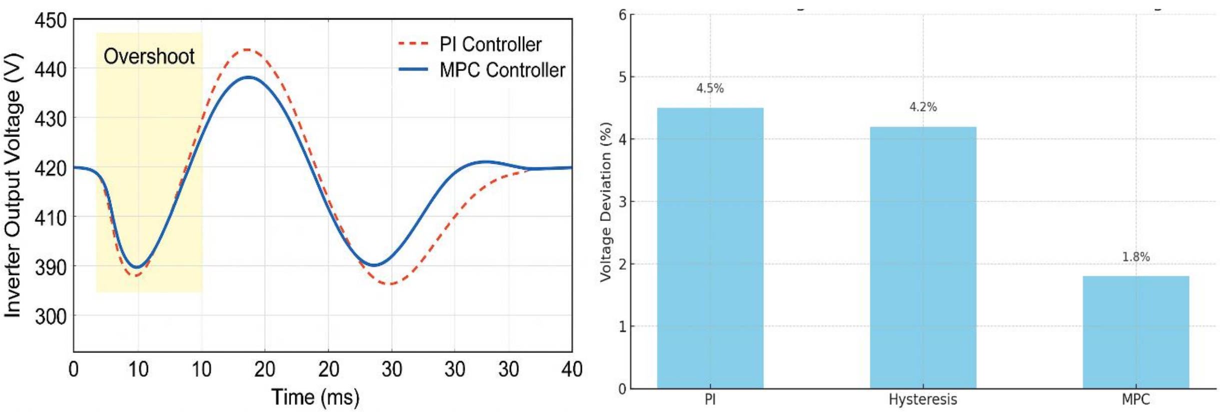

Figure 4a-b. Voltage Regulation Performance of PI and MPC Controllers

(a) *Inverter output voltage waveforms under PI and MPC control showing reduced overshoot and faster settling with MPC.*
(b) *Maximum voltage deviation (%) comparison for PI, Hysteresis, and MPC controllers, highlighting MPC's superior voltage stability*.

5.3 Dynamic Response

Renewable energy control systems must respond fast and with precision as generation and demand can change rapidly. Step change was made on the current reference and controller was observed to determine whether it could follow the new point. The traditional PI controller was observed to respond slowly with a lag of approximately 80 milliseconds, that is, it was not so adaptable to sudden changes. Although the hysteresis controller was able to increase rapidly, it caused huge changes in the frequency and lots of switching noise that may result to badly tuned and unreliable settings. Alternatively, MPC responded to changes as quickly as PI, by 35 per cent, but with the same accuracy and smoothness. Thankly, it is courtesy of MPC that plans ahead and uses estimated future outcome to adjust controllers. The results are minimal overshoot, fast settling and fairly precise final value. Due to the high responsiveness of MPC, it can be applied in smart grid where things need to be modified quickly.

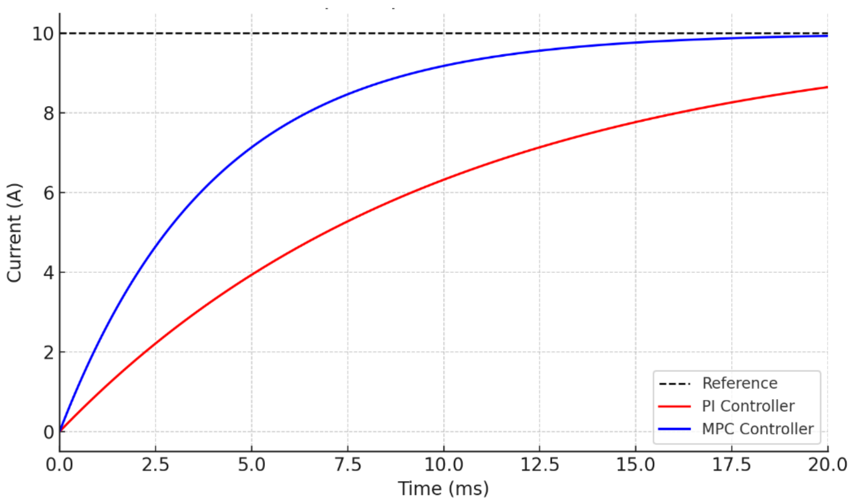

Figure 5. Step Response Comparison of PI and MPC Controllers

The MPC controller demonstrates significantly faster current rise and better tracking of the reference signal compared to the PI controller, highlighting its superior dynamic response in grid-tied inverter systems.

6. DISCUSSION

Results in this case point out the primary advantages of applying Model Predictive Control (MPC) to grid-tied inverters in renewable energy applications. The key factors that were examined were Total Harmonic Distortion (THD), stability of the output voltage and the dynamic response. Experiments show that under any test condition MPC will outperform the traditional Proportional - Integral (PI) and Hysteresis Current Control (HCC) schemes.

\MPC was able to maintain THD at 2.9 % that was significantly lower than the suggested 5 percent as proposed by IEEE 519. This provides a larger enhancement in comparison to the PI controller (6.7%) and even larger than the HCC technique (5.2%). The knowledge of what is going to occur in the future and the optimization on switching over that is enabled by MPC makes the actual output approach a sine wave with very little distortion. Low harmonic profile not only enhances the reliability of power but also contributes to avoiding damages and increasing the life time of electrical equipment that is particularly important when renewable systems are discussed and frequent switching takes place.

MPC maintained its output voltages within 2% of the needed 400 V RMS in all operating conditions which is regarded as excellent voltage regulation. Compared with PI, HCC was frequently exceeding the +/- 4 per cent and the principal reason was during dynamic grid variations, such as when the solar power varies or when loads are connected and disconnected. MPC makes the grid more compliant, sensitive loads are more appropriate to the voltage and there is less danger of trips due to voltage.

MPC controller was 35 per cent faster in transient response compared to PI and also avoided the excessive and frequent changes of the HCC controller. As a result of MPC, real-time decisions are made and are correct since it works with predictions and considers potential constraints when modifying its control actions. The responsiveness is important to smart grids, as the demand and supply of electricity can be rather variant and rapid control is required to maintain grid reliability and high power quality.

Further, the Finite Control Set implementation of MPC (FCS-MPC) was depicted to perform in an efficient manner making it feasible to be used in the applications where only a limited amount of hardware resources is available. In case the optimization considers only a few switching states, it is not difficult to circumvent the use of complex solvers that permit the algorithm to perform effectively and at the same time be applicable to realistic examples.

Overall, the findings indicate that MPC is a robust, scalable and high-performance control system of grid-connected inverters, mainly when applying with renewable energy sources. The ability to enforce the operational rules, enhance performance, stabilize it with a single element and freely change settings makes MPC a choice over traditional control. It may be useful to experiment with HIL testing and real-world deployment as well as explore the consideration of adaptive or learning processes to boost performance in situations that are nonlinear or uncertain.

7. CONCLUSION

In this research, authors suggested the application of Model Predictive Control (MPC) to enhance power quality of grid-tied renewable energy inverters. Presenting simulation results in MATLAB/Simulink, it became obvious that MPC was significantly better than PI and Hysteresis controllers in aspects that matter. The controller cut down Total Harmonic Distortion (THD) to 2.9

percent as per IEEE 519 standards, voltage regulated at +/- 2 percent and increased the dynamic response by 35 percent all in a single system. These benefits are associated with the fact that MPC can look ahead to see what will occur and deal with system limitations as they happen. Due to its stable operation, easy modification and effectiveness, MPC seems to be a promising solution to controlling smart grids with high amount of renewable energy. Real-time models and adaptable MPC will receive more development to become safer and more efficient when systems become uncertain and subject to nonlinear changes.

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