Research on Strategies to Improve the Dynamic Response Capability of Photovoltaic Inverters Based on Model Predictive Systems

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Abstract. While electronic technology has facilitated production and daily life, it has also brought certain issues, with leakage current being one of the most typical problems. Excessive leakage current can damage electrical equipment and even threaten the safety of personnel. Achieving maximum electrical safety has become a research hotspot in recent years. This paper, based on photovoltaic power generation systems, aims to improve the dynamic response capability of photovoltaic inverters through the establishment of predictive systems. The paper first analyzes the working principle and existing problems of model prediction, then lists the principles of three optimization schemes, including the introduction of virtual voltage, the two-step prediction method, and the recursive least squares method. It also analyzes the advantages and disadvantages of these three schemes and finally proposes the future development direction of using model prediction to suppress leakage current issues.

Keywords: Leakage current, finite set model prediction, virtual voltage, two-step prediction method, parameter correction.

1. Introduction

In the context of China's continuously improving economic level and the rapid development of science and technology, the field of electrical engineering and automation has provided a favorable development environment. Nevertheless, there are specific issues in the application, with leakage current being a typical concern. In photovoltaic power generation systems, excessive leakage current poses significant safety hazards to the power generation equipment and maintenance personnel. Common methods to suppress leakage current include optimizing inverter topology, using sliding mode variable structure control, and establishing predictive systems.

The most widely used and mature method is optimizing inverter topology, which stabilizes the common-mode voltage by adding clamping circuits or adopting a common-ground topology to short-circuit parasitic capacitances. While common-ground inverter topology can eliminate leakage current, it has poor dynamic response capabilities and generally requires additional control components. Sliding mode variable structure control designs sliding mode surface functions and controls the system using the conditions of reaching or approaching the sliding surface. Its main advantages are robustness, fast tracking speed, high precision, and strong anti-interference capability, but it has chattering issues and cannot eliminate leakage current. Establishing a predictive system involves building model predictions to forecast the next moment's current or voltage and choosing the control scheme that minimizes the difference from the prediction. This method can enhance the system's dynamic response and anti-interference abilities but also cannot eliminate leakage current issues. Therefore, this paper focuses on enhancing dynamic response capabilities by adding a model predictive system control to topologies that already suppress some leakage current under ideal conditions, so as to deal with undesirable external distractions, exploring the working principles of model predictive systems, optimization schemes, and potential future developments.

2. Principle of Model Prediction

Model Predictive Control (MPC) is a closed-loop optimization control strategy based on a model that uses the system's discrete-time model to predict future changes in control variables. The appropriate switching control signal is selected based on the set optimization criteria. MPC strategies are mainly divided into continuous set model prediction and finite set model prediction. The latter is more commonly used due to the high computational demand of the former. The main working principle is shown in Figure 1.

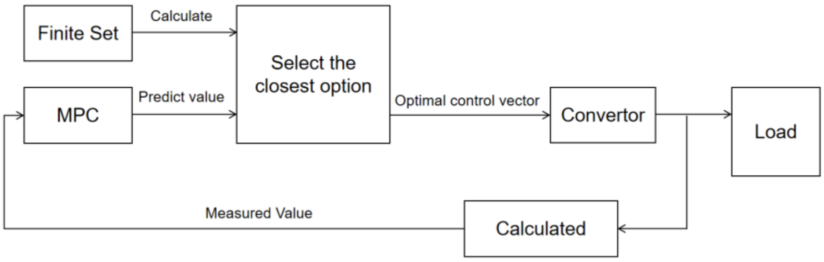


Figure 1. Inverter Finite Set Predictive Control Strategy Flowchart [1].

Based on the relationship between the switching function S, system control objectives x, and the system's state equation is established and discretized to obtain the system's discrete model. Then, the switching state Si and the measured value of the control objective x (k) at moment k are substituted into the discrete model to predict all possible values of x (k+1). Subsequently, x(k+1) is calculated using the prediction model, and the control vector closest to the reference value is chosen from the finite set as the optimal control vector for the current moment k[1-2]. The schematic of the finite set optimization strategy is shown in Figure 2.

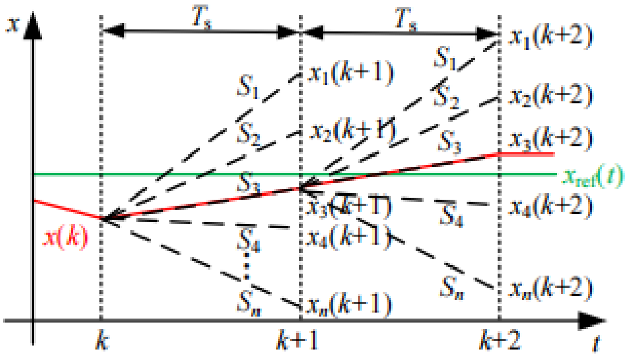


Figure 2. Finite Set Optimization Schematic [1].

3. Errors and Causes in Finite Set Model Predictive Control

Finite set model predictive control systems can reduce the impact of environmental and external changes on inverters during operation, thereby enhancing their dynamic response and anti-interference capabilities. However, certain errors are inherent, mainly due to insufficient prediction accuracy, response delays, and parameter mismatches. The issue of insufficient prediction accuracy mainly arises from the use of finite set model prediction, which limits the choice to the closest option hence the prediction accuracy depends on the number of control voltage sets within the finite set. The response delay issue is due to the assumption that the predictive control system operates under ideal conditions with nearly zero computation time. In reality, computation takes a certain amount of time, during which some delay occurs, causing a deviation between the output prediction and the actual value. Parameter mismatches are primarily caused by the possibility of non-ideal working conditions, such as measurement errors, component tolerances, sudden changes in external conditions, and delays in computation feedback, all of which can affect the accuracy of model predictions.

4. Proposed Improvement Schemes for Finite Set Predictive Model

4.1. Introduction of Virtual Voltage to Improve Prediction Accuracy

Literature [3] bases its study on the Heric inverter topology and introduces 8 virtual voltages in addition to the three basic output voltages. This expansion increases the finite set in the MPC algorithm from 3 to 11, enhancing the freedom in selecting control voltages and effectively improving the calculation accuracy of grid-connected current predictions.

Based on the principle of volt-second balance, each cycle is divided into two durations, each corresponding to one of two basic voltages. By changing the combination of these durations and basic voltages, virtual voltages are synthesized, as detailed in Table 1.

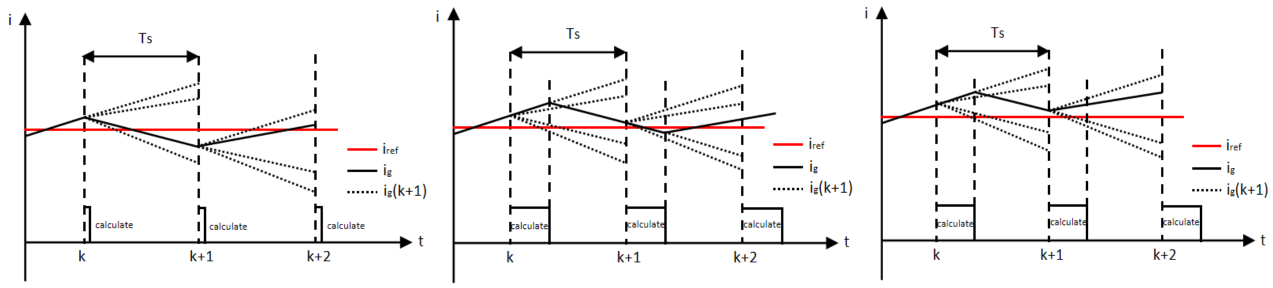
Table 1. Virtual Voltage and Corresponding Modes Table.

Voltage Number	Td	Mode during Td	T0	Mode during T0	Vinv
V5	1/5 Ts	Mode 1 (V1)	4/5 Ts	Mode 4 (V4)	1/5 Vdc
V6	2/5 Ts	Mode 1 (V1)	3/5 Ts	Mode 4 (V4)	2/5 Vdc
V7	3/5 Ts	Mode 1 (V1)	2/5 Ts	Mode 4 (V4)	3/5 Vdc
V8	4/5 Ts	Mode 1 (V1)	1/5 Ts	Mode 4 (V4)	4/5 Vdc
V9	1/5 Ts	Mode 3 (V3)	4/5 Ts	Mode 2 (V2)	-1/5 Vdc
V10	2/5 Ts	Mode 3 (V3)	3/5 Ts	Mode 2 (V2)	-2/5 Vdc
V11	3/5 Ts	Mode 3 (V3)	2/5 Ts	Mode 2 (V2)	-3/5 Vdc
V12	4/5 Ts	Mode 3 (V3)	1/5 Ts	Mode 2 (V2)	-4/5 Vdc

By generating composite modes from basic modes and expanding the number of voltages in the finite set, if the optimization function finally selects a basic voltage, the corresponding switch state of that basic voltage is applied directly within that sampling period. If the optimization result is a virtual voltage, the optimal output corresponding to the voltage in the finite set is determined, and the combination of modes corresponding to that voltage is selected, thereby completing the optimal switch selection and improving prediction accuracy.

4.2. Two-Step Prediction Method to Increase Response Speed

The ideal optimization strategy of a model predictive control system is shown in Figure 3(a). However, in actual operation, due to response delays, the optimization result is as shown in Figure 3(b). Based on the principle of model prediction, literature [4] proposes the use of a two-step prediction method. In each prediction calculation, two computations are performed simultaneously, predicting the forecast currents for T (k+1) and T (k+2) moments. The optimal switch control state for T (k+1) is then determined through optimization within the finite set. At T (k+1), the forecast current value for T (k+2) can be used directly, avoiding computational time deficiencies and preparing for the next round of prediction. The optimized state after delay compensation is shown in Figure 3(c). With this optimization, the controller can make optimal selections at each sampling point from the moment (k+1) onwards, and the tracking effect of the grid-connected current is enhanced.



(a) (b) (c)

Figure 3. (a) Ideal State [3]. (b) Actual State [3]. (c) Optimized State [3].

4.3. Using Recursive Least Squares Method for Model Parameter Correction and Error Compensation

Addressing issues such as measurement errors, component tolerances, sudden environmental changes, and response delays in model predictive control systems, literature [5-6] suggests using the Recursive Least Squares (RLS) method for real-time model parameter correction, thereby compensating for errors. The principle involves analyzing the difference between predicted and actual currents to identify factors affecting current prediction errors. It proposes the use of online RLS for real-time model parameter correction. The RLS algorithm can identify both inductance and resistance parameters and computes quickly. Based on this, a two-step current prediction error minimization delay compensation algorithm is used to select the optimal switch state for the next moment, effectively eliminating the effects of sampling and computation delays. The workflow of the RLS method for correcting predictive model parameters is illustrated in Figure 4.

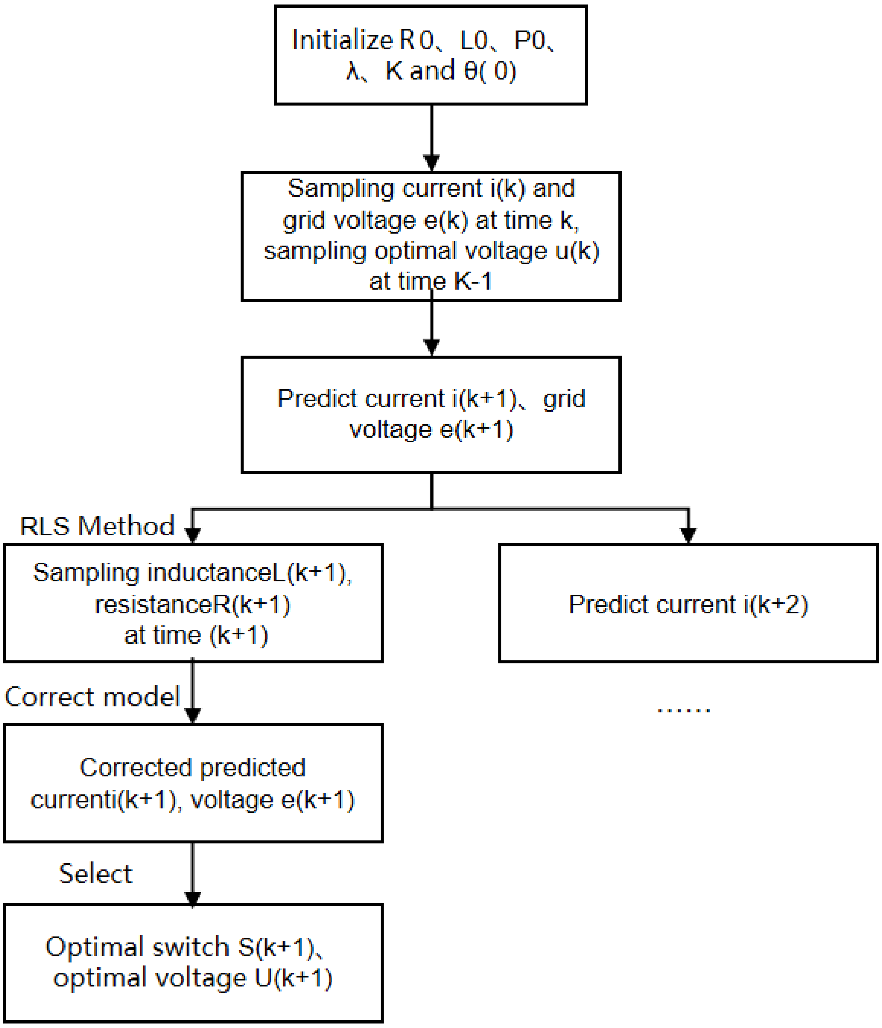


Figure 4. Simplified Flowchart of RLS Correction of Predictive Model Parameters.

Using the recursive least squares method for real-time model parameter correction can reduce the prediction variance caused by measurement errors, environmental influences, and computation delays.

5. Comparative Analysis of Optimization Schemes

The introduction of the virtual voltage concept, the use of the two-step prediction method, and the application of the online RLS for correction all significantly improve the control performance of the model predictive control system. A comparison of the principles, advantages, and disadvantages of these three schemes is shown in Table 2.

Table 2. Comparison of Model Prediction Optimization Schemes

Optimization Method	Summary of Principle	Advantages	Disadvantages
Introduction of Virtual Voltage Concept	Based on the volt-second balance principle, the period is divided into two durations corresponding to two basic voltages. The combination of these durations and voltages creates virtual voltages, expanding the range of options within the finite set.	Refines virtual voltages to improve prediction accuracy and reduce deviation.	Increases computational load during optimization.
Two-Step Prediction Method	Performs two calculations in each prediction cycle to shorten the time for the next prediction.	Shortens response time.	Increases computational load for each calculation.
Online RLS Correction	Real-time correction of model parameters using the recursive least squares method to reduce prediction errors caused by measurement inaccuracies, environmental influences, and computation delays.	Corrects the predictive model in real-time, reducing deviation.	The selection of correction parameters and forgetting factors relies mainly on empirical values.

While introducing virtual voltage increases the number of options in the finite set for higher prediction accuracy, it also increases computational load during optimization. The two-step prediction method, by performing two calculations simultaneously, shortens the waiting time for computation, thereby increasing response speed and reducing errors, but it also increases computational load per calculation. Incorporating recursive least squares into the predictive model allows real-time model correction, beneficial in reducing inaccuracies due to measurement errors, environmental disturbances, and response delays. However, the method's correction parameters and forgetting factors are largely based on empirical values, lacking a solid theoretical foundation.

6. Conclusion

This article opts for a finite set model predictive control method to enhance the dynamic response capability of inverters, thereby stabilizing grid current and voltage and to some extent suppressing leakage current issues. It analyzes the basic principles of model prediction and simultaneously examines the working principles of three optimization schemes: the introduction of the virtual voltage concept, the use of a two-step prediction method, and the application of the recursive least squares method, summarizing their effects. The introduction of the virtual voltage concept primarily addresses prediction deviations caused by insufficient precision in the finite set; the two-step prediction method mainly tackles prediction errors due to computational delays; while the use of the recursive least squares method focuses more on correcting model parameters to address prediction discrepancies arising from non-ideal states encountered during prediction, such as component tolerances, measurement errors, environmental factors, and computational delays. All three methods employ a rolling optimization pattern, continuously updating the prediction model, and can effectively achieve dynamic response without additional components. However, each method increases the computational load and because of the computation time, prediction errors cannot be eliminated.

Since model predictive systems are based on function calculations in various ways to obtain predictive values, and these calculations require time, enhancing computational speed will be one of the future directions for deepening model predictive control systems. Specific potential areas of focus might include: integrating developments in information technology, introducing more powerful intelligent computing technologies, or using mathematical models with lesser computational demands. Furthermore, at this stage, the weighting factors in the predictive model, among others, are largely based on empirical values with no theoretical fixed values, and how to make their selection more scientific could become one of the main research directions.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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