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Optimization of Grid-Connected Inverter Performance in Photovoltaic Systems with Model Predictive Direct Power Control

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Abstract

Model Predictive Control (MPC) is of great interest due to its ability to solve the constraints of nonlinear systems. In this article, the Model Predictive Direct Power Control (MPDPC) method is proposed for a two-level inverter grid-connected in a photovoltaic system. First, a predictive direct power model is determined, and then a cost function consisting of two parts of power quality regulation and switching frequency optimization by adjusting the system parameters, is used to select the optimal voltage vectors to improve the inverter performance. The simulation results in MATLAB software show the appropriate efficiency of the proposed control method in two modes of permanent and dynamic system operation, such that the harmonic reduction of the output currents from 8.98% to 1.11% is visible. The switching in the power electronic elements of the inverter was also optimized, and the switching frequency was reduced from 12650 Hz to 8700 Hz, which will reduce losses and also increase the life of the inverter.

Keywords

Inverter; Flexible active power; Photovoltaic; Switching frequency; Model Predictive Direct Power Control;

1. Introduction

The use of power electronics equipment as converters to connect renewable energy sources—such as photovoltaic systems, wind turbines, and fuel cells—to the grid gives rise to certain power quality issues. Various solutions exist to mitigate harmonics caused by power electronics and non-linear loads, as well as to enhance efficiency and power quality in these systems. One such solution involves employing an appropriate control strategy for the inverter [1, 2].

In recent decades, the use of advanced microcontrollers and digital signal processors with high computational capabilities has enabled the implementation of smarter control approaches [3]. The most common among these are hysteresis control, linear control, sliding mode control, predictive control, and artificial intelligence methods [4]. In hysteresis control, the hysteresis band and system nonlinearity result in a variable switching frequency. This phenomenon leads to resonance issues in certain applications and gives rise to a wide range of problems [5–7]. Linear control approaches involving a modulation stage often require coordinate transformations [8]. Among the various control methods, predictive control stands out as one of the most attractive strategies for controlling power converters. The common principle underlying all predictive controllers is the use of a system model to predict the future behavior of controlled variables and the application of an optimization criterion to select the appropriate actuation [7–9]. Model Predictive Direct Power Control (MPDPC) in rectifiers aims to reduce switching losses in switches subjected to stresses such as thermal stress; by applying an offset voltage at sampling instants $(k+1)$, the voltage vector applied to the specific switch is limited as much as possible, thereby extending the lifespan of the rectifier switches. However, focusing on a switch in a specific phase leads to an increase in the Total Harmonic Distortion (THD) of the currents [10]. In [11], a multi-vector-based MPDPC strategy is combined with switching frequency reduction—achieved by incorporating a penalty term into the cost function—within a Doubly Fed Induction Generator (DFIG) system; voltage vectors are generated by simultaneously minimizing the voltage vector error and the switching frequency within the cost function. Consequently, an optimal and controllable switching frequency of 2 kHz is achieved, and the stator current THD is reduced from 8.36% to 5.79%. The primary difference between [11] and the proposed paper lies in the specific implementation of the multi-vector MPDPC control combined with switching frequency reduction via a cost-function penalty term within a DFIG system, where voltage vectors are generated through the simultaneous minimization of voltage vector error and switching frequency. In this paper, by combining the cost functions for active and reactive power optimization (g_1) and switching frequency optimization via commutation reduction (g_2)—and by integrating penalties into both functions to form a new cost function $g(K)$ for optimal voltage vector selection—we achieved high power quality and output currents with lower THD (1.1%) compared to the reference [12]. In this paper, the effectiveness of the Model Predictive Direct Power Control (MPDPC) strategy is evaluated—using a practical implementation on a grid-connected,

two-level, three-phase inverter within a photovoltaic system—across two dimensions: switching frequency optimization and flexible active power regulation. This evaluation is conducted in MATLAB Simulink under various scenarios, including steady-state and dynamic system conditions, as well as system short-circuit fault events. The fundamental concept of this paper was developed by examining studies such as [13, 22] regarding active power regulation and [14, 18] concerning switching frequency optimization. By aggregating the cost functions from these two areas, a new, practical, and tunable cost function—incorporating penalty terms—was defined and utilized to determine the optimal voltage vectors for the inverter.

2. Proposed Predictive Direct Power Control Structure

Figure 1 illustrates the Model Predictive Direct Active Power Control (MPDPC) strategy for a grid-connected inverter system designed for flexible active power regulation. Active power $P(k)$ and reactive power $Q(k)$ are calculated by measuring line current and grid voltage. Using the system's predictive model, the values of $P(k+1)$ and $Q(k+1)$ can be predicted for all possible voltage vectors at each sampling instant. To select the optimal voltage vector, the predicted power values are evaluated using cost function g_1 . Finally, the voltage vector that minimizes the cost function is selected for the next sampling instant. Since active and reactive powers hold equal priority in flexible power regulation, the cost function defined in Equation (1) is employed to minimize power error.

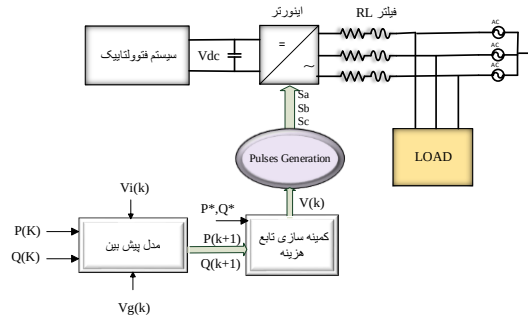


Figure 1: Block diagram of the predictive direct active power controller.

$$g_1 = (P^* - P(K + 1))^2 + \lambda_Q (Q^* - Q(K + 1))^2 \quad (1)$$

3. Results and Discussion

The proposed control strategy is tested using MATLAB/Simulink simulations. First, active and reactive powers are measured, and their future values are calculated. Predictions of active and reactive power are generated for each of the seven possible voltage vectors produced by the inverter, and each prediction is evaluated using a cost function. The cost function, $g(k)$, then minimizes reactive power error and regulates the active power to match the reference value. An RL load with 2 kW of active power and 100 VAR of reactive power is applied to the system. Optimal active power regulation can be achieved by adjusting the weighting factor λ_Q (the reactive power control coefficient).

Initially, when the weighting factors λ_{Q-} and λ_{sw} are omitted—meaning the effects of reactive power and switching frequency are not taken into account—output current distortion is significant. As the value of the weighting factor λ_Q is gradually increased from zero, the output current THD initially decreases, reaching an optimal level within a certain range, before subsequently rising. Figure 2 shows the active power before and after optimization, and Figure 3 displays the reactive power before and after optimization. Both active and reactive powers track their references without deviation, except at the initial instant—specifically at $t = 0.01$ s—due to the presence of the DC-link capacitor. It should be noted that the higher the DC-link capacitance, the greater the initial deviation.

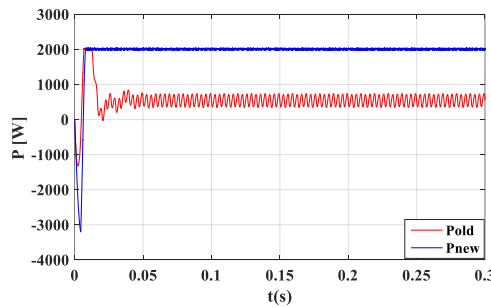


Figure 2: (Pold) active power before optimization and (Popt) optimized active power

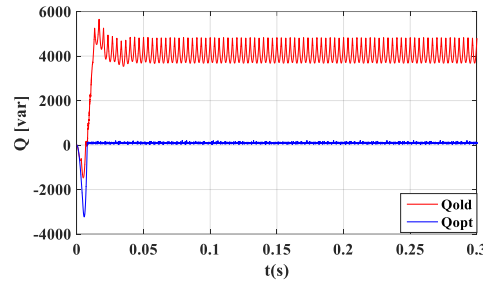


Figure 3: (Qold) active power before optimization and (Qopt) optimized active power

Figure 4 illustrates the inverter voltage and switching frequency during the transient state. It can be observed that the proposed MPDPC strategy provides a satisfactory dynamic response, as the powers track their reference values without current overshoot.

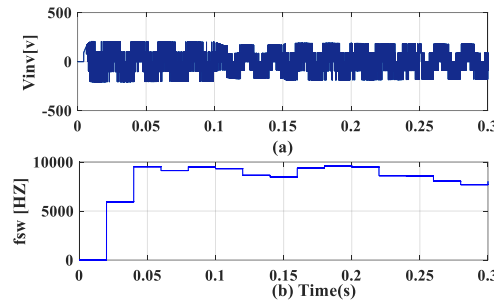


Figure 4: Dynamic response of the system with (a) inverter voltage (b) switching frequency

4. Conclusions

In this paper, the effectiveness of the MPDPC (Model Predictive Direct Power Control) strategy in a grid-connected inverter system is evaluated through MATLAB simulations, focusing on two aspects: switching frequency optimization and flexible active power regulation. By adjusting the weighting factors λ_Q and λ_{sw} , favorable results were achieved, characterized by high power quality and low output current THD (1.11%) and switching frequency. It should be noted, however, that other studies utilizing multilevel inverters with various control methods have achieved even lower THD values under optimal conditions. Regarding the system's dynamic response, the outputs exhibit a rapid response, effectively tracking their reference values. In the event of a system fault, the desired output power is rapidly injected into the grid once the fault is cleared, based on the input power supplied by the PV source. Overall, the proposed controller not only reduces harmonics in the grid-connected load's output voltages and currents and enables flexible active power regulation but also optimizes the switching of the inverter's power electronic components. Specifically, the output current THD decreased from 8.98% to 1.11%, and the switching frequency dropped from 12,650 Hz to 8,700 Hz; these improvements lead to reduced power losses and an extended lifespan for the inverter.

5. References

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