Postprint: Grid-Connected Peak Shaving Control of Micro Photovoltaic Energy Storage Systems

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Abstract

This paper investigates distributed photovoltaic grid-connected systems in renewable energy generation, focusing on the core inverter component of grid-connected power generation systems. A novel two-stage grid-connected inverter integrated with an energy storage device is designed. Building upon this inverter design, and addressing power peak-valley problems caused by load demand variations in distribution networks, the control strategy for peak shaving and valley filling in distribution networks using distributed photovoltaic grid-connected systems with energy storage devices is further studied. A peak regulation control strategy based on grid-connection point voltage compensation is proposed. The parameter design of the entire system is completed, and the rationality of the designed two-stage grid-connected inverter is verified through both software simulation and hardware experimental platforms. This enhances the operational efficiency of photovoltaic grid-connected systems, effectively solves peak regulation and stable grid-connected operation issues, and provides a technical reference for the design of distributed photovoltaic grid-connected power generation systems.

Full Text

Research on Grid-Connected Peak Shaving Control for Micro Photovoltaic Energy Storage Systems

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Abstract

This paper investigates distributed photovoltaic (PV) grid-connected systems for new energy power generation, focusing on the core inverter component. A novel two-stage grid-connected inverter with integrated energy storage is designed. Based on this new inverter topology, a peak shaving control strategy is proposed for distributed PV grid-connected systems with energy storage devices to address power peak-valley issues caused by load demand variations in distribution networks. The strategy employs point of common coupling (PCC) voltage compensation-based control. The complete system parameter design is accomplished, and the rationality of the proposed two-stage grid-connected inverter is verified through both software simulation and hardware experimentation. The results demonstrate improved operational efficiency of the PV grid-connected system, effective solution to peak shaving and stable grid operation problems, providing a technical reference for designing distributed PV grid-connected power generation systems.

Keywords: Distributed photovoltaic, Flyback inverter, Soft switching, Battery energy storage system, Peak load shaving

1 Introduction

Photovoltaic power generation has experienced rapid development in recent years as a crucial component of new energy generation. Distributed PV generation, characterized by its flexibility and high efficiency, has emerged as a promising energy utilization approach with expanding construction and application scope, becoming a research hotspot in new energy grid integration. As the core component for power conversion in grid-connected generation, the inverter represents a key research direction in PV systems. Current inverter research and design primarily focus on improving inversion efficiency and safe, stable system operation, with key technologies including optimized inverter topology design, impact of different circuit operating modes on efficient system operation, soft switching technology, and control algorithm optimization [1-3].

Since solar energy is an intermittent power source, PV system output power exhibits instability and unpredictability, which affects power quality and safe, stable operation of the power system. Additionally, increasing user loads and their volatility lead to large peak-valley differences in power demand [4]. To ensure stable grid operation and balance between power supply and consumption, corresponding peak shaving and valley filling measures must be implemented. Battery Energy Storage Systems (BESS) offer advantages such as high energy density, flexible installation, and fast control response [5], providing significant application potential in new energy grid-connected systems [6-8]. Energy storage systems can not only smooth power fluctuations from intermittent sources like PV and wind [9-10], but also conveniently regulate grid peak-valley from the load side. Peak shaving control through BESS can reduce investment in generation, transmission, and distribution equipment on the grid side, improve equipment utilization, decrease line losses, and yield considerable economic benefits, representing an effective approach to solving power peak-valley problems [11].

This paper designs a novel two-stage micro-inverter topology with batteries connected to the intermediate DC bus. The front-stage Boost converter controls PV panel output to achieve maximum power point tracking, improving solar energy utilization. The rear stage employs a flyback inverter with an active clamp circuit integrated into the topology to achieve soft switching of the main switch, reducing switching losses. The control strategy enables battery charge/discharge control and grid-connected inversion, maintaining the inverter in high-power operation state, improving grid-connected system operational efficiency, and achieving grid peak shaving and stable operation.

2 PV Grid-Connected System Structure and Control Strategy

To achieve stable and efficient operation of the PV grid-connected system, a 200W micro PV inverter is designed. The two-stage micro inverter system topology is shown in [Figure 1: see original paper].

The two-stage micro inverter consists of a Boost converter, interleaved flyback circuit, active clamp circuit, full-bridge inverter circuit, and LC filter circuit. The Boost converter output connects to the battery energy storage device, achieving distribution network peak shaving functionality through battery charge/discharge control. The two-stage micro inverter design parameters are shown in .

The flyback inverter topology offers prominent advantages [12], and the interleaved parallel connection of two flyback transformers [13-14] doubles the output power at the same voltage level, improves efficiency, and ensures the PV grid-connected inverter system efficiently outputs high-quality, low-harmonic sinusoidal grid current synchronized with the grid frequency and phase.

The two-stage flyback inverter converts the DC output from the front-stage Boost circuit into quasi-sinusoidal half-wave current through a high-frequency transformer, then outputs AC power synchronized with grid frequency and phase through full-bridge inversion and filtering before feeding into the grid.

The flyback inverter operates in Continuous Conduction Mode (CCM). Under CCM, the relationship between flyback inverter output voltage V_{out} and DC-side input voltage V_{in} can be derived from the volt-second balance of the excitation inductance over a switching period:

$$V_{out} = n \cdot D \cdot V_{in}$$

where $n = N_s/N_p$ is the turns ratio of the flyback transformer secondary to primary winding, and D is the steady-state duty cycle. The inverter output voltage V_{out} equals the sum of filter circuit voltage drop $Z_L i_{ac}$ and grid voltage V_{grid}, so the steady-state duty cycle D is:

$$D = \frac{V_{grid}\sin\omega t + Z_L i_{ac}}{V_{grid}\sin\omega t + Z_L i_{ac} + nV_{in}}$$

where i_{ac} is the grid-connected current and Z_L is the filter impedance. Equation (2) can be divided into two parts, represented by D_{feed} and Δd:

$$D = D_{feed} + \Delta d$$

$$D_{feed} = \frac{V_{grid}\sin\omega t}{V_{grid}\sin\omega t + Z_L i_{ac} + nV_{in}}$$

The advantage of adding feedforward compensation is that it reduces the impact of grid disturbances on the control system, improving control stability and accuracy. The system control block diagram is shown in [Figure 2: see original paper].

In [Figure 2: see original paper], the current reference amplitude I_{ref} combines with grid phase information obtained from the PLL to generate the grid current reference value I^*. After PI regulation, this produces a dynamic duty cycle adjustment signal Δd, which is then superimposed with the voltage feedforward compensation D_{feed} to obtain the steady-state duty cycle D. The resulting modulation wave undergoes high-frequency modulation to generate the switching tube drive signals for circuit control.

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3 Simulation Analysis

Based on analysis of the two-stage micro inverter topology and operating principles, along with parameter design and control strategy, a system model is built in Matlab software to verify design rationality through simulation.

The designed flyback inverter circuit operates in continuous current mode. The flyback output side current is shown in [Figure 3: see original paper], demonstrating quasi-sinusoidal half-wave current output. Zooming in on the quasi-sinusoidal half-wave current reveals that the circuit operates in CCM mode.

As mentioned previously, to improve PV system inversion efficiency, an active clamp circuit [15] is added to the flyback topology to achieve zero-voltage switching of the main switch while eliminating voltage spikes caused by resonance between the high-frequency transformer leakage inductance and main switch parasitic capacitance. The clamp circuit can absorb and recover leakage energy, improving inversion efficiency.

[Figure 4: see original paper] shows the simulated waveforms of the complementary active clamp soft switching implementation, where V_{ds} is the main switch tube voltage, I_p is the main switch tube current, and the clamp tube drive signal is inverted. At the main switch turn-on moment, its terminal voltage is zero, achieving zero-voltage turn-on.

The final system grid-connected operation simulation waveforms are shown in [Figure 5: see original paper]. The two waveforms represent grid voltage and grid-connected current. Since the micro inverter rated power is 200W with a grid-connected rated current of 0.91A, the current signal is amplified 50 times for convenient comparison with grid voltage.

The simulation results for each component and the grid-connected operation demonstrate consistency with theoretical design, meeting expected requirements and proving the rationality of the inverter design and correctness of the control method from a simulation perspective.

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4 Peak Shaving Control Strategy Research

When the PV generation system connects to the distribution network for grid operation [16-17], its equivalent circuit model is shown in [Figure 6: see original paper]. In the diagram, U_S is the distribution network voltage, typically considered an infinite bus with essentially constant voltage amplitude; $Z = R + jX$ is the distribution network line impedance, where R is the resistive component and X is the reactive component; P and Q are the active and reactive power transmitted from the grid to local loads; U_{PCC} is the point of common coupling voltage; P_L and Q_L are the active and reactive power of local loads at PCC; P_G is the active power output from the PV generation system (generally controlled at unity power factor, outputting only active power).

From the equivalent circuit of the grid-connected PV system in [Figure 6: see original paper], the power transmitted between the distribution network and PV system at the PCC is:

$$S = P + jQ$$

Therefore, the voltage difference between distribution network bus voltage U_S and PCC voltage U_{PCC} is:

$$\Delta U = (R + jX)\frac{P + jQ}{U^*_{PCC}}$$

where $*$ denotes complex conjugate. Setting U_{PCC} as the reference voltage, equation (8) can be separated into real and imaginary parts:

$$\Delta U = \frac{RP + XQ}{U_{PCC}} + j\frac{XP - RQ}{U_{PCC}}$$

where $P = -P_G + P_L$ and $Q = -Q_G + Q_L$. Since the resistive and reactive components in line impedance are comparable, the imaginary part in equation (9) is much smaller than the real part and can be neglected, yielding:

$$U_{PCC} \approx U_S + \frac{R(P_G - P_L) + X(Q_G - Q_L)}{U_{PCC}}$$

After distributed energy resources connect to the distribution network, system power flow exhibits three scenarios: (1) When DER output exceeds local load demand, the surplus power flows to the distribution network to participate in power flow distribution; (2) When DER output equals local load demand, the grid requires no power supply due to supply-demand balance; (3) When DER output is less than local load demand, DER output is directly consumed by local loads while the distribution network simultaneously supplies power to loads [18].

When distributed PV power supply and load demand are mismatched, power load peak conditions occur, affecting power system reliability. The peak shaving control research in this paper addresses this situation. A key advantage of the two-stage PV grid-connected system is that the integrated BESS can regulate peak-valley issues through its energy storage characteristics, buffering supply-demand mismatches and significantly improving distribution network power supply stability.

In the system control strategy, equation (10) shows that due to line impedance, power transmission between the PV generation system and distribution network causes PCC voltage variations. By monitoring PCC voltage, grid load changes can be determined. Consequently, controlling PCC voltage stability through BESS charge/discharge can balance supply and demand, achieving peak shaving. The peak shaving control strategy employs PCC voltage control based on droop characteristics. The output power and voltage amplitude characteristics of the inverter unit can be expressed as:

$$P_{out} = P_{ref} - m(U_{pcc} - U_{ref})$$

where U_{ref} is the PCC voltage reference value, P_{ref} is the active power reference corresponding to U_{ref}, m is the active power droop coefficient, and P_{out} is the actual active power output obtained through droop control.

The control diagram for BESS participating in peak shaving operation is shown in [Figure 7: see original paper]. In [Figure 7: see original paper], I_{bat}^* is the battery charge/discharge reference current (corresponding to the actual required output active power), I_{bat} is the real-time battery current, I_{ref}^* is the inverter active current reference, and I_{ac} is the PV inverter output current. The system controls battery charge/discharge power to track P_{out}, enabling system supply power to follow load power and achieving peak shaving.

5 Experimental Analysis

This paper verifies system design feasibility through experimentation on a built two-stage PV grid-connected inverter hardware platform. The flyback micro inverter uses DSP as the control core, with the experimental platform integrating power supply circuits, control circuits, flyback main circuits, high-frequency transformers, driver sampling circuits, and filter circuits. The flyback operating frequency is 100kHz. For software design, a model-based design approach is adopted. With the hardware platform and software design completed, each part of the micro inverter is experimentally verified.

The drive signals for the primary main switch tube and clamp switch tube during inverter flyback circuit operation are shown in [Figure 8: see original paper]. Channels 1 and 3 show the interleaved main switch tube drives at 12V; channels 2 and 4 show the clamp switch tube drive signals. A 300ns dead time exists between main switch tube drive and clamp switch tube drive.

First, the effectiveness of the active clamp soft switching circuit is verified by comparing the main switch tube voltage and current waveforms before and after adding the active clamp circuit. [Figure 9: see original paper] and [Figure 10: see original paper] show the main switch tube voltage and current waveforms without and with the clamp circuit, respectively. Without the active clamp circuit, the main switch exhibits large voltage spikes detrimental to operation. With the clamp circuit added, the main switch voltage spikes are significantly reduced at the same power and voltage level due to the clamp circuit's resonance action, which absorbs and recovers leakage inductance energy. A short-duration negative current exists during resonance, absorbing the main switch parasitic capacitance energy and achieving zero-voltage turn-on.

After verifying circuit operation and correct soft switching implementation, grid-connected experiments are conducted. [Figure 11: see original paper] shows the grid voltage and grid-connected current waveforms. During grid connection, the current is fed into the grid through a voltage regulator. Channel 1 shows 220V voltage, with some fluctuations in regulator output voltage due to inverter interference. Channel 3 shows the grid-connected current with an RMS value of 0.907A and grid-connected power of 200W, meeting rated power design requirements. The output grid-connected current is synchronized in frequency and phase with grid voltage. Experimental results align with theoretical analysis, achieving expected outcomes and verifying the correctness and feasibility of the designed grid-connected inverter.

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6 Conclusion

This paper investigates distributed PV grid-connected power generation systems, primarily designing a novel PV grid-connected inverter. The analysis covers the entire system structure and principles, with detailed examination of each component. The inverter operating mode is selected as continuous conduction mode. Active clamp circuit technology is introduced to achieve soft switching, eliminating voltage spikes caused by resonance between high-frequency transformer leakage inductance and main switch parasitic capacitance, achieving zero-voltage turn-on of the main switch. The clamp circuit absorbs and recovers leakage energy, improving inversion efficiency.

Based on the micro inverter design, the control strategy and application of distributed PV grid-connected systems with energy storage devices for distribution network peak shaving are further studied. A peak shaving control strategy based on PCC voltage compensation control is proposed for power peak-valley problems caused by distribution network load demand variations, providing a reference for energy storage system peak shaving control research and design.

Finally, the PV inverter is verified through simulation and experimentation, with sequential analysis of each experimental result validating the selected circuit operating mode, technical feasibility of active clamp circuit soft switching implementation, and stable operation of the micro inverter in grid-connected mode.

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Note: Figure translations are in progress. See original paper for figures.