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Two-Stage Power Decoupling for a Single-Phase Photovoltaic Inverter by Controlling the DC-Link Voltage Ripple in the DQ Frame

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***Abstract*— The input voltage and current are DC and its maximum power is desired to be a constant value. However, in the single-phase PV inverter, the sinusoidal voltage and current waveform makes the output power pulsated with double frequency, which results in the power mismatch between the input and the output. Therefore, it is necessary to use energy buffer to balance the power, i.e., the power decoupling. In this work, a power decoupling method first is developed in d-q rotation frame and is optimized so that the energy buffer can be minimized. The power decoupling controller designed in the d-q frame has the superiority of simplicity so that the traditional proportional integral (PI) control can be used. Besides, a composite power decoupling method which includes both DC side passive and AC side active power decoupling is developed. Due to the use of two stage power decoupling, the energy buffer, e.g., capacitance at the DC and AC side, is minimized. Meanwhile, the important functions such as the maximum power point tracking (MPPT) and relatively high power quality are achieved electrolytic capacitor by the film capacitor with high reliability..**

***Keywords*— : two stage single phase inverter; double line frequency ripple; power decoupling and ripple elimination**

I. INTRODUCTION

Due to the growth demand of global energy and adverse effects of conventional energy such as pollution caused by fossil fuel and nuclear fission sources, the exploration of the renewable energy sources (RES) is increased . Renewable energy, as clean and alternative energy, is based on self-renewing energy sources including the solar energy, wind energy, wave energy, tidal energy, ocean thermal energy, hydropower, the geothermal energy, and biomass energy . With increasing concern about the environmental issues, RES are paid more and more attention. The growth rate of renewable power installation has exceeded that of the fossil fuel and nuclear power capacity combined Since the electricity generated from RES is more cost effective than that from the coal-fired power plants , it is cheaper to build new wind or PV plants than utilizing existing coal-fired power plants Besides, renewable also beat new natural gas power 2 station on cost in many locations and has become the cheapest sources of new electricity generation on the earth . Among the clean energy technologies, PV has significantly grown in recent years Not only the efficiencies of the most domestic solar panels are low, i.e., around 10-20%, but the performance of other components such as inverters and batteries are limited as well. Battery, which can provide fast response for balancing the power between the generation and consumption , is becoming a good candidate for the electrical energy storage system (ESS). However, the initial installation costs are still high . Power electronic converters, which regulate voltages from one form to another are compatible with end-use electricity supply, are key elements for renewable energy power generation . Inverters that convert DC to AC voltages is broadly used in solar power conversion. In some applications such as the residence area, a single-phase PV inverter is usually used.

As shown in Figure 1 the PV inverter is usually used for PV system integration. On one hand, it regulates the DC voltage to AC, on the other hand, the maximum solar power is delivered to the grid. Figure 1.5 shows the voltage, current, and power waveforms in PV panel and inverter.

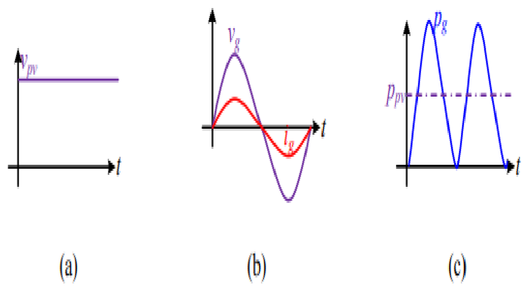

Figure 1.: Voltage and power waveforms. (a) PV voltage; (b) inverter output voltage and current; (c) power of inverter and PV panel. As shown in Figure 1.5, the input PV voltage is a constant value, the output voltage and current of the inverter is sinusoidal waveform with 60 Hz. Then the power of the PV panel (ppv) is constant DC and the output power (pg) pulsated with 120 Hz. Since the power needs to be balanced anytime, it is necessary to use the energy storage device remove the pulsated power, i.e., when the input solar power is larger than the output power, the surplus power is absorbed; when the solar power is less than the output, the energy storage device provides the deficient power. Therefore, the 120 Hz ripple power is removed. The focus of this thesis is to design and control PV inverter to achieve the power decoupling capacitors.

II. LITERATURE SURVEY

Johan [1] O. Ellabban, H. Abu-Rub, and F. Blaabjerg, “Renewable energy resources: Current status, future prospects and their enabling technology,” Renewable and Sustainable Energy Reviews, vol. 39, pp. 748-764, Nov. 2014

Accordingly, this paper presents how renewable energy resources are currently being used, scientific developments to improve their use, their future prospects, and their deployment. Additionally, the paper represents the impact of power electronics and smart grid technologies that can enable the proportionate share of renewable energy resources.

[2] P. Sampaio and M. González, “Photovoltaic solar energy: Conceptual framework,” Renewable and Sustainable Energy Reviews, vol. 74, pp. 590-601, July 2017.

The analysis result of this research shows that studies about photovoltaic energy are rising and may perform an important role in reaching a high-energy demand around the world. To increase the participation of photovoltaic energy in the renewable energy market requires, first, to raise awareness regarding its benefits; to increase the research and development of new technologies; to implement public policies a programs that will encourage photovoltaic energy generation. Although crystal silicon

solar cells were predominant, other types of cells have been developed, which can compete, both in terms of cost reduction of production, or in terms of greater efficiency.

[3] N. Abas, A. Kalair, and N. Khan, “Review of fossil fuels and future energy technologies,” Futures, vol. 69 , pp. 31-49, May 2015.

Perhaps CO2 and H2O based fuel systems would facilitate climate change and grand energy transition. An energy mix consisting of fossil fuels, hydrogen, bio-fuels, and renewable energy sources seems to be a good initiative. This paper reviews evidence of hydrocarbons decline scenarios and timelines of future energy technologies.

[4] E. Kabir, P. Kumar, S. Kumar, A. Adelodun, and K. Kim, “Solar energy: Potential and future prospects,” Renewable and Sustainable Energy Reviews, vol. 82, pp. 894-900, Feb. 2018.

The merits and demerits of solar energy technologies are both discussed in this article. A number of technical problems affecting renewable energy research are also highlighted, along with beneficial interactions between regulation policy frameworks and their future prospects.

[5] S. Bull, “Renewable energy today and tomorrow,” Proc. IEEE, vol. 89, no. 8, pp. 1216-1226, Aug. 2001.

Each of the renewable energy technologies is in a different stage of research, development, and commercialization, and all have differences in current and future expected costs, current industrial base, resource availability, and potential impact on greenhouse gas emissions. The technical status, cost, and applications of major renewable energy technologies and implications for increased adoption of renewables will be reviewed.

[6] S. Harb, H. Hu, N. Kutkut, I. Batarseh, and Z. Shen, “A three-port photovoltaic (PV) micro-inverter with power decoupling capability,” in Proc. IEEE Appl. Power Electron. Conf. Expo., Fort Worth, TX, Mar. 2011, pp. 203-208.

presents a new micro-inverter topology that is intended for single-phase grid-connected PV systems. The features of the proposed topology are: (1) eliminating the double-frequency power ripple using small film capacitor; (2) improving the maximumpower-point tracking (MPPT) performance; (3) using long life-time film capacitors, which will improve the reliability of the inverter; and (4) requiring no additional circuitry to manage the transformer leakage energy.

[7] T. Shimizu, K. Wada, and N. Nakamura, “Flyback-type single-phase utility interactive inverter with power pulsation decoupling on the DC input for an AC photovoltaic module system,” IEEE Trans. Power Electron., vol. 21, no. 5, pp. 1264-1272, Sept. 2006.

paper proposes a novel flyback-type utility interactive inverter circuit topology suitable for ac module systems when its lifetime under high atmospheric temperature is taken into account. A most distinctive feature of the proposed system is that the decoupling of power pulsation is executed by an additional circuit that enables employment of film capacitors with small capacitance not only for the dc input line but also for the decoupling circuit, and hence the additional circuit is expected to extend the lifetime of the inverter. The proposed inverter circuit also enables realization of small volume, lightweight, and stable ac current injection into the utility line. A control method suitable for the proposed inverter is also proposed. The effectiveness of the proposed inverter is verified thorough P-SIM simulation and experiments on a 100-W prototype.

[8] C. Liao, W. Lin, Y. Chen, and C. Chou, “A PV micro-inverter with PV current decoupling strategy,” IEEE Trans. Power Electron., vol. 32, no. 8, pp. 6544-6557, Aug. 2017.

to propose a novel photovoltaic (PV) micro-inverter with PV current decoupling (PVCD) strategy to achieve maximum power point tracking (MPPT) performance without using large electrolytic capacitors. Conventionally, the grid-connected PV micro-inverter needs a large PV-side electrolytic capacitor to suppress the double-line frequency voltage ripple, which is caused by the injected ac grid power, to achieve the desired MPPT performance. However, the short lifetime electrolytic capacitor will reduce the PV micro-inverter's reliability dramatically. Therefore, different active power decoupling circuits (APDCs) have been proposed in published papers to reduce the required input capacitance so that the long lifetime film capacitor can be used to replace the electrolytic capacitor

[9] S. Kjaer, J. Pedersen, and F. Blaabjerg, “A review of single-phase gridconnected inverters for photovoltaic modules,” IEEE Trans. Ind. Appl., vol. 41, no. 5, pp. 1292-1306, Sept./Oct. 2005.

focuses on inverter technologies for connecting photovoltaic (PV) modules to a single-phase grid. The inverters are categorized into four classifications: 1) the number of power processing stages in cascade; 2) the type of power decoupling between the PV module(s) and the single-phase grid; 3) whether they utilizes a transformer (either line or high frequency) or not; and 4) the type of grid-connected power stage. Various inverter topologies are presented, compared, and evaluated against demands, lifetime, component ratings, and cost. Finally, some of the topologies are pointed out as the best candidates for either single PV module or multiple PV module applications.

[10] H. Hu, S. Harb, N. Kutkut, I. Batarseh, and Z. Shen, “A review of power decoupling techniques for microinverters with three different decoupling capacitor locations in PV systems,” IEEE Trans. Power Electron., vol. 28, no. 6, pp. 2711-2726, June. 2013.

reliability of the microinverter is a very important feature that will determine the reliability of the ac-module photovoltaic (PV) system. Recently, many topologies and techniques have been proposed to improve its reliability. This paper presents a thorough study for different power decoupling techniques in singlephase microinverters for grid-tie PV applications. These power decoupling techniques are categorized into three groups in terms of the decoupling capacitor locations: 1) PV-side decoupling; 2) dc-link decoupling; and 3) ac-side decoupling. Various techniques and topologies are presented, compared, and scrutinized in scope of the size of decoupling capacitor, efficiency, and control complexity. Also, a systematic performance comparison is presented for potential power decoupling topologies and techniques;

III. Operating Principles of Single-Phase Power Decoupling Techniques

The During the integration of these distributed PV arrays to the power system, single-phase inverters play an important role in the energy conversion as well as voltage regulation. However, due to the doubleline-frequency issue of the single-phase inverter, i.e., there is voltage/current ripple generated at the dc-link [Such voltage ripple degrades system performance such as the maximum power point tracking (MPPT) efficiency of the PV system [15]. Taking the view of the issue from the perspective of power. The instantaneous power of the single-phase inverter can be expressed as follow

$$p(t) = v_g \cdot i_g = \sqrt{2} \cdot V_g \sin(\omega t) \cdot \sqrt{2} \cdot I_g \sin(\omega t - \varphi)$$
$$= \underbrace{S \cdot \cos\varphi}_{P} - \underbrace{S \cdot \cos(2\omega t - \varphi)}_{\tilde{p}}$$

where S and p ~ represents the apparent power and AC component (or pulsating power component) of the instantaneous power, respectively; Vg and Ig are the root mean square (RMS) values of vg and ig on the AC side, φ is the phase angle difference between vg and ig. Equation (2.1) shows that p is composed of a constant component (P) and an oscillation component (p ~) at double load/grid frequency. Therefore, the output power of the inverter is pulsated with double line frequency. However, the input solar power is desired to be constant.

The pulsating power is transferred to the dc side, which generates a second order ripple on the dc voltage/current. The undesirable ripple results from power mismatch. Therefore, extra energy storage system (ESS) is required to be placed between the PV and output of the inverter to eliminate the pulsating power, which is also called power decoupling For example, when po > ppv, EES provides the deficient power; otherwise, ESS stores the surplus power. Then the solar power can be harvested as much as possible. po ppv (t) Stored Energy t Released Energy

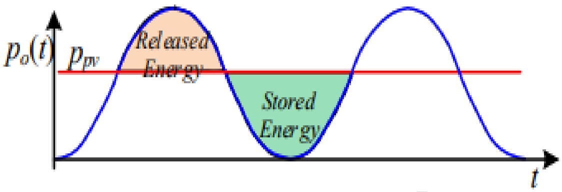

Fig.2. Power decoupling of the PV system with the ESS.

The power decoupling technology can be generally divided into control and topology parts, which means that modification of the control strategy or the topology with additional components can eliminate (or suppress) the double frequency ripple [19]. Then the power decoupling method can be classified as passive power decoupling method, active decoupling method and hybrid power decoupling method.

As we mentioned before, equation above shows that the instantaneous power of the converter is composed of a continuous component (P) and an oscillation component (p ~) at twice the load/grid frequency. This chapter is to model and design controllers of an inverter with smaller capacitance to achieve power decoupling on both DC and AC sides. The amount of decoupling power on the DC side can be calculated as follows:

$$p_{dc} = 2 \cdot \omega \cdot C_{dc} \cdot V_{dc} \cdot \Delta v_{dc}$$

where ω is the angular frequency of the grid; Vdc and Δvdc are the DC and AC components of vdc, respectively. As indicated in equation a large value of Cdc is needed if power is decoupled on the DC side only. Such large capacitance requires to use an electrolytic capacitor which has lower reliability than the film capacitor.

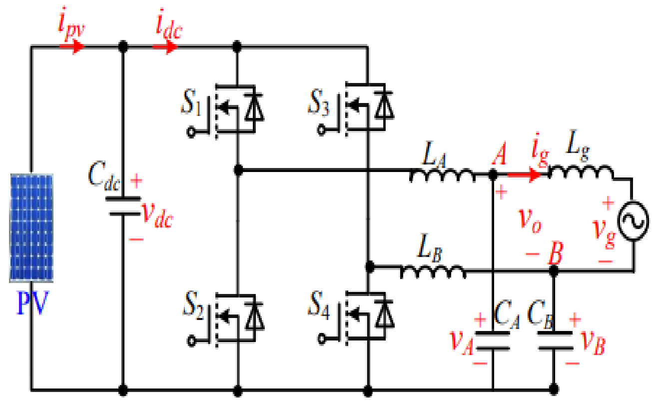

Fig 3 Two-stage power decoupling PV inverter.

On the AC side, to remove the pulsating power with small capacitance, two capacitors, CA and CB are added on a H-bridge inverter as shown in Figure 3.1. On one hand, the voltage difference between vA and vB is controlled to be vg; on the other hand, two capacitors CA and CB are used for absorbing the pulsating power component on the AC side. For simplicity purposes, the voltage drop on the inductors LA and

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LB will be neglected in the analysis for the calculation of the voltage of the CA and CB . Then the pulsating power on the AC side is decoupled by the capacitors CA and CB. Since vo is sinusoidal waveform, vAB can be solved as follows:

$$v_{AB} = \sqrt{\frac{P_{ac} \cdot \sin(2\omega t)}{2\omega \cdot C_2} + V_{c0}^2 - \frac{v_o^2}{4}} \pm \frac{v_o}{2}$$

(where Pac represents the power decoupled on the AC side; Vc0 is the initial voltage of CA and CB; CA = CB = C2. Figure 3.2 Ideal waveforms of the inverter. Figure 3.2 shows the ideal waveforms of vA, vB, and vo, as shown in Figure 3. vA and vB are DC voltages while its difference vo is AC voltage with sinusoidal waveform.

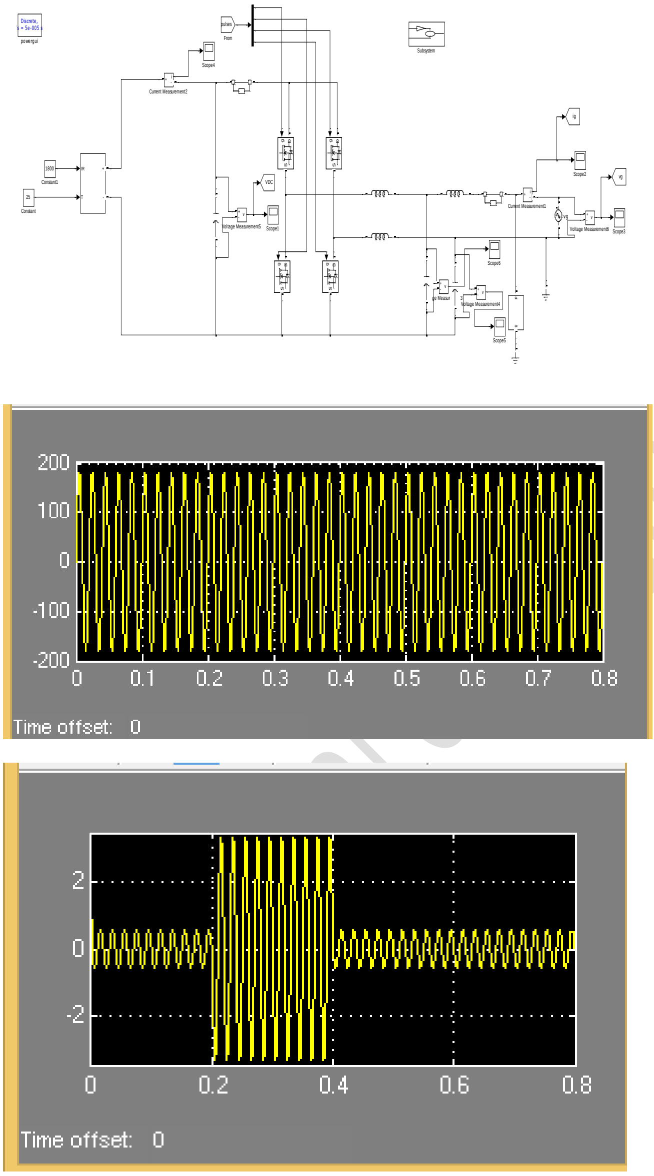

Fig 4 Modeling and waveform .

show the voltage and current waveforms of the single-phase bridge inverter with and without activating the power decoupling control under rated power. The input DC voltage is set at 100V, and the two-stage single-phase bridge inverter is operated under rated power. The DC-link voltage is successfully boosted to around 200V, the decoupling capacitor voltage is around 300V, and the output AC voltage is a pure sinusoidal waveform with a peak value around 156V. In Fig4 without power decoupling control, the input DC current contains a visible second-order component, which has almost the same amplitude as the DC component of the input DC current, i.e. 4A, and the highorder harmonics from switching are filtered out by a low-pass filter with the cutoff frequency at 1kHz. The output filtering inductor current is a sinusoidal waveform with high-order harmonics due to switching actions, and the peak value of the fundamental component is around 4.5A. In Fig. 4 the AC component of the DC-link voltage has a higher amplitude because of the power decoupling control. The AC component at the DC link does not affect the output AC voltage because the AC component is being taken into consideration in hybrid modulation. The input DC current is around 4A, and the second order component has almost been eliminated. The fundamental component of the output 116 filtering inductor current has a peak value around 5A. With addition of power decoupling control, the DC-link voltage stress increases nearly 20V, but the current stress decreases nearly 50%. As shown in the zoomed-in part of the output inductor current, the bridge inverter is operating under DCM around the zero-crossing point and under CCM around the peak and troug

IV. CONCLUSION

This modeling and control of a two-stage power decoupled PV inverter. The power decoupling can be achieved on both DC and AC sides, then the film capacitors with smaller capacitance can be used on DC-link. Besides, by modeling the inverter in the d-q frame, the conventional PI controllers can be designed to remove the pulsating power. The experimental results showed the capacitor at DC bus can be significantly reduced from 900 µF to 68 µF while maintaining the same voltage ripple. The use of film capacitors will further increase the life span and the reliability of the PV inverter.

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