

Comparative study on power decoupling technology based on double frequency disturbance suppression of single-phase photovoltaic inverter

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Abstract. During the grid connection process, single-phase photovoltaic inverters frequently encounter the issue of instantaneous power imbalance between the AC and DC sides. This results in twice the line frequency disturbance power being transmitted to the DC side, severely affecting the system's stability and performance, especially maximum power point tracking efficiency. To address this problem, research in photovoltaic grid-connected technology is now focusing on power decoupling technology to suppress double-frequency disturbances, referred to as power decoupling. This article covers the three main approaches to power decoupling—passive, active, and composite—and focuses on analyzing the circuit topology of the latter two approaches applied to single-phase photovoltaic inverters. The advantages and disadvantages of different power decoupling circuit topologies are discussed in detail, and a comparison is made in this article. Detailed discussions on current power decoupling technology trends and potential future directions, as well as recommendations for further refining grid-connected PV technology, are provided.

Keywords: Single-phase photovoltaic inverter, power decoupling, circuit topology.

1. Introduction

The global reliance on fossil fuels for electricity, such as petroleum, and the resulting environmental damage, have garnered significant attention in recent years. This has hastened the development of renewable energy technologies, particularly solar energy. As a clean energy option, solar energy has seen increasing use in power generation. This is especially true for small-scale photovoltaic power plants, where reliable and effective grid connection is crucial. The single-phase photovoltaic inverter plays a vital role in connecting the solar system to the electricity grid. Its stability and efficiency directly impact the overall performance of the system. When the photovoltaic system is linked to the grid, an instantaneous power imbalance between the AC and DC sides causes a disruption of twice the line frequency, affecting the system's ability for maximum power point tracking (MPPT) [1]. Although adding an electrolytic capacitor can reduce the disturbance, it may shorten the PV system's lifespan [2]. Consequently, international academics have extensively studied power decoupling technologies. These studies primarily focus on three strategies: passive, active, and composite power decoupling. This article aims to review the topologies of these power decoupling schemes, compare their pros and cons, and discuss potential future development paths and technological challenges. It intends to provide a reference for the further advancement of photovoltaic grid-connected technology.

2. Single phase inverter passive power decoupling strategy

In prior related studies, single-phase systems achieve active or passive power decoupling, classified by whether they depend on the use of power semiconductor devices. Among these, the passive power decoupling strategy often involves increasing capacitance on the DC side or designing LC resonance to suppress the second frequency disturbance. For example, LC is specifically constructed after harmonic analysis to allow harmonics to flow into the DC-link, facilitating power decoupling [3]. However, due to the inductor-capacitor characteristics, especially when components

aging the parameters of the device are changed, this approach may reduce power decoupling performance.

Figure 1 shows a typical passive power decoupling circuit. The circuit features a typical boost converter, which necessitates the use of large-capacity electrolytic capacitors due to its high voltage requirements. Alternatively, power decoupling is managed in [1] by employing parallel capacitors; however, this strategy requires a larger energy buffer, necessitating the use of large-capacity electrolytic capacitors with reduced reliability. Therefore, the passive power decoupling method using parallel capacitors not only affects the overall lifespan of the system but also presents problems such as higher cost and larger volume in practical applications.

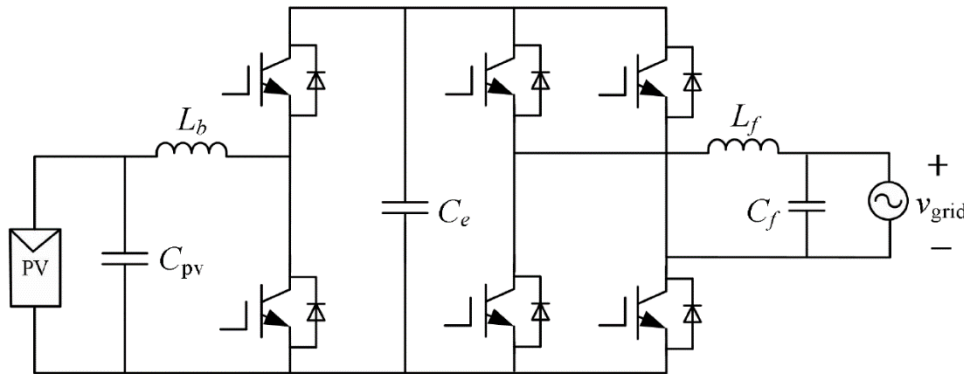


Figure 1. Typical passive power decoupling circuit [4].

3. Power decoupling circuit topology for single-phase photovoltaic systems

In an effort to increase the lifetime of single-phase PV systems, it is necessary to reduce the system's reliance on electrolytic capacitors. The primary focus of research is on active power decoupling and composite passive and active power decoupling methods. These methods achieve power decoupling by constructing circuits that utilize power switching devices to direct disturbed power to be absorbed by the energy storage device.

3.1. Active power decoupling

The majority of active power decoupling strategies increase the circuit's voltage or current stress due to the addition of more bidirectional converters or the utilization of sophisticated power decoupling control strategies [5]. In [6], a Boost-based power decoupled single-phase inverter topology is proposed in Figure 2. By utilizing a capacitor C_d and managing four additional switches judiciously, power decoupling is achieved. The energy from the PV panel is transferred to the capacitor in two modes. In mode 1, switch S_1 is on and switch S_2 is off, and the PV panel charges the inductor first; in mode 2, both switch S_1 and switch S_2 are turned on, and the inductor charges the capacitor. This circuit constructs two input voltages through capacitor C_d . When the grid voltage is higher than the capacitor voltage V_{cd} , S_3 is on and S_4 is off, and the output voltage to DC-link is the sum of the input voltages V_{dc} and V_{cd} , then supply power to the grid in the form of SPWM modulation. When the grid voltage is lower than the capacitor voltage V_{cd} , switch S_3 is off and switch S_4 is on, and the output voltage to DC-link is V_{cd} , the power supplied to the grid is in modulation of multilevel input. The circuit constructs a double input voltage, which lowers the AC power on filter inductor L_f , leading to a reduced volume requirement for the inductor and improving power density and operating efficiency of the inverter, meanwhile, the control strategy suppresses the output side LC oscillation, reducing total harmonic distortion and improving power density. It also decreases switching losses and voltage stress on the switches; however, having more switches results in a more complex control strategy and higher cost. Additionally, the decoupling strategy, which connect the input DC part of voltage of the capacitor in series with the DC input voltage to get a higher voltage to DC-link, raising the decoupling capacitor's voltage, requires a higher voltage tolerance on the capacitor.

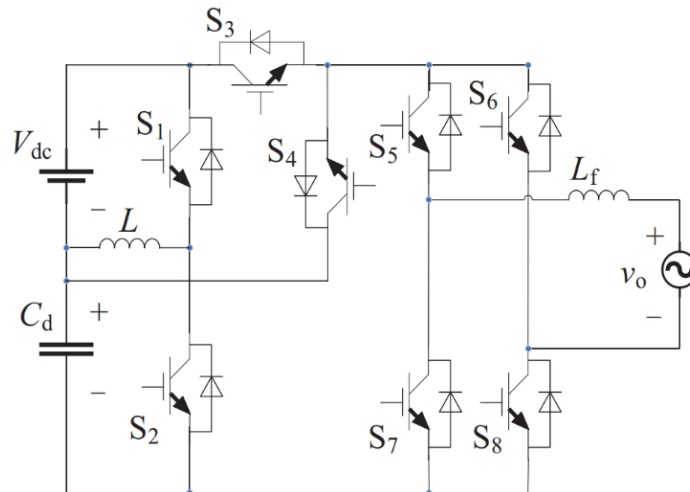


Figure 2. Boost-type power decoupling circuits [6].

As seen in Figure 3, this is a new topology structure. This circuit has five operating modes. In mode 1, the PV panel and capacitor C_{PV} transfer energy to the inductor L_1 , boosting the inductor's current i_{L1} , when S_1 is on and S_2 is off. Meanwhile, during the grids positive half cycle, C_1 transmits energy to L_1 and C_2 transfers' energy to L_2 , and during the remaining half cycle, the direction of energy transfer is reversed. When both S_1 and S_2 are off, it is mode 2, and Energy is supplied from L_1 to C_1 , C_s and L_2 . At this time, the diode connected in reverse parallel with S_2 conducts, so that S_2 realizes zero voltage switching. In mode 3, S_1 is off and S_2 is turned on, during this period, i_{L1} rapidly reduces to 0, and the circuit turns to mode 4, causing diode D to cut off. Due to i_{L1} being zero, the diode connected in reverse parallel with S_2 cuts off when both S_1 and S_2 are turned off, and C_s transfers energy to L_1 and C_1 to let voltage on C_s reduce to zero, causing zero voltage switching of S_1 realized, and this is mode 5. The inductor L_1 is operated in discontinuous current mode (DCM) by controlling the switch. This results in the cycle average of i_{L1} being a constant value, which reduces power fluctuation. The amplitude of the grid-connected current is controlled in real-time by adjusting the fixed value of the sum of the voltages on capacitors C_1 and C_2 , which allows the capacitors to process the power difference between the DC side and AC side. Leakage current is avoided by allowing the PV's negative pole to be connected directly to the AC grid's neutral line. This circuit can output reactive power while decoupling power and achieve zero voltage switching to reduce switching losses by using C_s , only using 2 switches, reducing the controller's and systems structural complexity. However, it needs to add dead time to avoid simultaneous conduction of both switches, which increases the DC bus ripple [7].

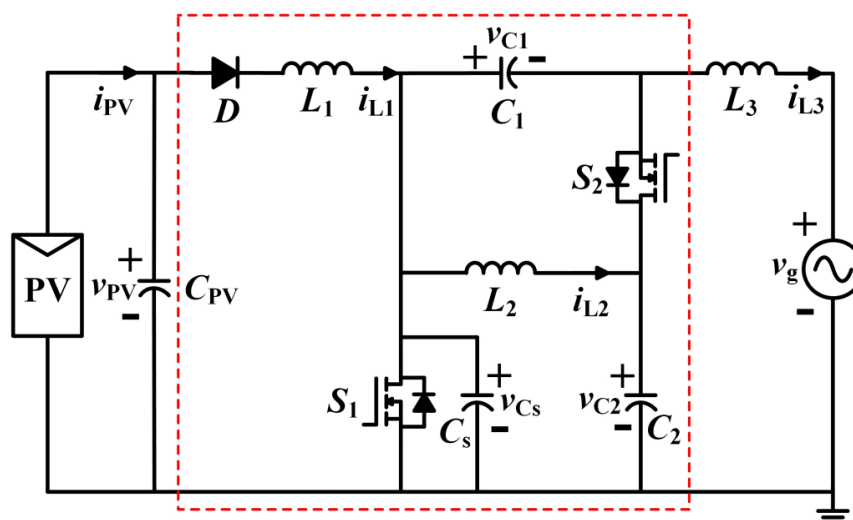


Figure 3. A new power decoupling circuit [7].

An AC side power decoupling circuit topology based on the H-bridge is shown in Figure 4. When C_A and C_B are able to store unbalanced power and modify their voltage difference to equal the inverter's output voltage, power decoupling accomplished on the grid side. This circuit reduces the capacitance value of the DC side, can use high-reliability film capacitors, and has low total harmonic distortion and DC bus voltage ripple. Without changing the H-bridge inverter's original construction, this circuit just adds two capacitors to the AC side and replaces the capacitors on the DC side with film capacitors. However, the control approach is rather complex and requires the employment of three controllers and this makes the circuit less resistant to interference requiring additional processing. Meanwhile, the apparent power will pass through the decoupling part in the system, resulting in higher losses [8].

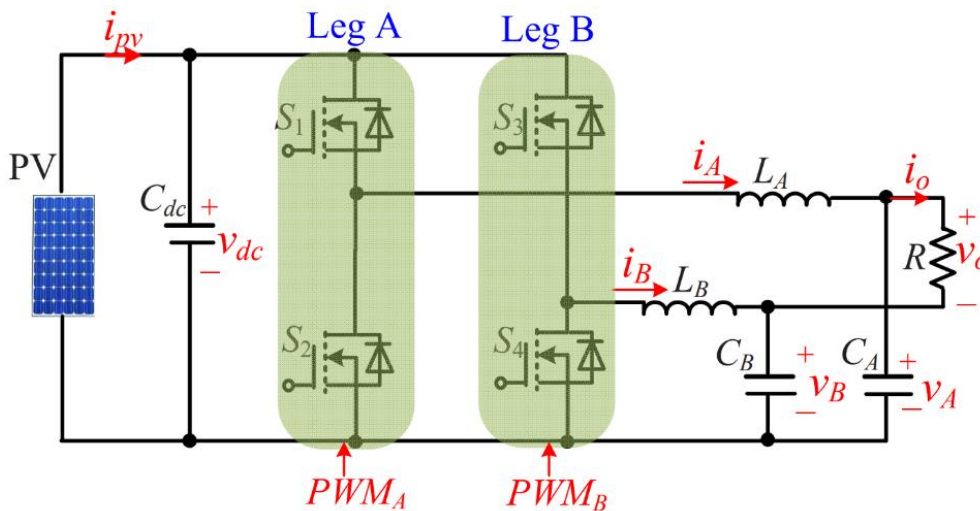


Figure 4. A power decoupling circuit on the AC side [8].

Figure 5 shows a three-port power decoupling topology. This circuit has two modes. The circuit is in mode 1 when the power of the DC side exceeds the power of the AC side. This excess energy from the DC side is stored in the capacitor C_x . Mode 1 is divided into four phases, in the phase 1, only the main switch S_1 is on, and the photovoltaic panels charge the inductor L_1 , and then the switch S_1 is off, the switch S_4 of the decoupling port is on, and the inductor L_1 transmits the energy to the capacitor C_x , and this is the second phase. When it turns to the third stage, the switch S_4 is disconnected, the secondary switch S_2 conducts, and the PV panel supplies energy to the AC side. In the fourth stage, all the switches are off and the circuit is in discontinuous conduction mode, inductor L_1 and capacitor C_x transfer the energy to the grid side through the rear H-bridge inverter circuit until all their energy is transferred to the AC side, and then the circuit enters into Mode 2. Mode 2, like Mode 1, is divided into four stages. Stages 1, 2, and 4 have the same switching state as in mode 1, except that in mode 2, inductor L_1 and capacitor C_x derive their energy from the AC side. In the third stage of mode 2, the main switch S_1 is disconnected, the switch S_3 of the decoupling port is on, and the capacitor C_x transfers energy to the inductor L_1 . A separate port is used to charge and discharge the decoupling capacitor C_x in order to equalize the instantaneous power on the AC and DC sides. The double-frequency disturbance power that was introduced on the DC side is suppressed as a result. This circuit topology separates the power decoupling part as a port, causing less interference to the original circuit, and only adds two switch tubes, making it easy to control. It also uses film capacitors with higher reliability, improving the overall efficiency and stability of the inverter. However, when the circuit is impacted by external disturbances, its ability to decouple will be severely weakened since the circuit is constructed under the premise that the voltage of the decoupling capacitor would remain constant over a switching cycle [9].

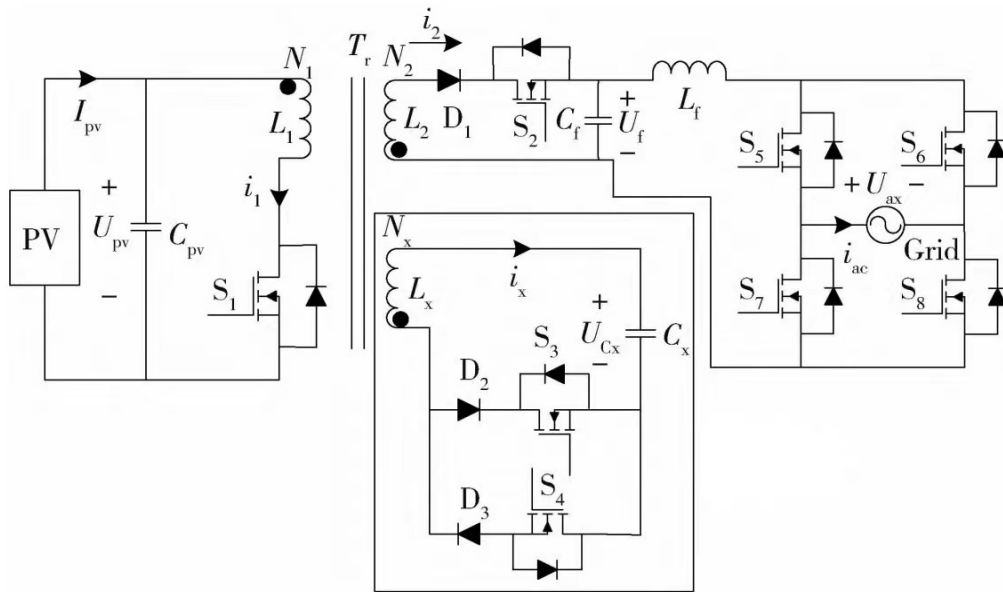


Figure 5. A three-port power decoupling circuit [9].

3.2. Composite power decoupling

A composite power decoupling circuit that optimizes energy buffering is shown in Figure 6. Power decoupling is achieved through C_A and C_B on the AC side and C_{dc} on the PV side. When the DC link voltage ripple over a certain level during startup and in the steady state, the DC side decoupling is engaged to reduce disturbances. The DC side decoupling power is proportional to this ripple. During the startup process, the circuit takes into account the delay of the startup and enables capacitor C_{dc} to decoupe power with maximum efficiency. When there is an abrupt change in power on the PV side, the power decoupling portion on the DC side immediately eliminates. There are no extra semiconductor devices in this circuit. By automatically activating or deactivating passive power decoupling on the DC side, the amount of power decoupling can be dynamically distributed to both sides, reducing power loss. It can adapt to sudden changes in photovoltaic panel power and load, and can maintain an MPPT efficiency of more than 99% on both the DC and AC sides. The requirements for all capacitance values are reduced, and film capacitors with higher reliability can be used [10].

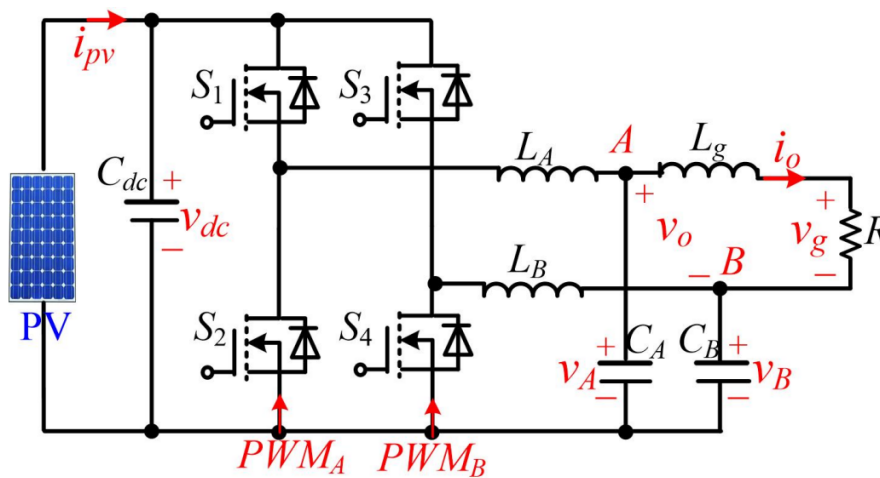


Figure 6. Composite power decoupling circuit based on H-bridge [10].

3.3. Comparison summary

Through the above analysis, active power decoupling needs to reduce the use of additional bidirectional converters and simplifies controlling strategies to lower the stress on the circuit. Using

the method of adding switches and using capacitor to construct double voltages lowers the stress on switches and suppresses the LC oscillation on the AC side while increasing costs and requiring a more complex control strategy. Adding additional capacitors achieves zero voltage switching to reduce switching losses, while dead time would increase ripple. For decoupling on the AC side, when the switching tube is subjected to higher voltage, power loss will increase for apparent power increasing and flows to the decoupling part and reduce the immunity of circuits. Through separating the power decoupling port, a multi-port circuit introduces unbalanced power into separate ports, thereby causing less interference to the original circuit while the decoupling port is less resistant to interference. The composite power decoupling circuit reduces power loss by automatically initiating passive power decoupling or by adjusting the amount of its power decoupling. To lower the voltage of the switches. The circuit topologies proposed in [8] and [10] are very similar, but the one in [10] utilizes the decoupling capability of the capacitor on the DC side more efficiently and flexibly by dynamically adjusting it to the decoupling on the AC side, resulting in better inverter performance. Based on the above analysis, a comparison of different power decoupling circuit topology is provided in Table 1.

Table 1. Comparison of different power decoupling circuit topology.

Circuit	pros	cons
Typical passive power decoupling circuit	lower power of the filter inductor; suppressed LC oscillation on the AC side; improved power density;	more complex control strategy; higher cost; higher capacitor's voltage
A new power decoupling circuit	eliminated leakage current; output reactive power; reduced switching losses	more the DC bus ripple
A power decoupling circuit on the AC side	small capacitance value; low total harmonic distortion and DC bus voltage ripple	a higher power loss
A three-port power decoupling circuit	less interference to the original circuit; easier control strategy	the decoupling port is less resistant to interference
Composite power decoupling circuit based on H-bridge	without additional semiconductor devices; MPPT efficiency of more than 99%; dynamically distributed power decoupling;	

4. Conclusions

This paper delves into the application of power decoupling technology in single-phase photovoltaic inverters and analyzes the circuit topologies of active power decoupling and composite power decoupling in detail. It shows that although both options may share some components in the original circuit and require more complex control strategies, they can still achieve effective cost control, especially the composite power decoupling. As the composite power decoupling circuit can better adjust to abrupt changes in the power and load of solar cells, it demonstrates greater flexibility and dependability in practice.

For further research on photovoltaic inverters, circuits that integrate multi-port power decoupling circuits with composite power decoupling circuits while eliminating leakage current will be a promising direction. This type of composite circuit will enhance the PV inverter's performance as well as the system's stability and efficiency, especially when facing large changes in power and load. Therefore, future research should focus more on the research and optimization of these composite circuits, in particular, the circuit's exposure to sudden power changes on the grid side should be considered, and propose more efficient and reliable power decoupling technologies to further enhance the overall performance of photovoltaic grid-connected systems.

References

- [1] Huang, K. P., Wang, Y. and Wai, R. J., Design of power decoupling strategy for single-phase grid-connected inverter under nonideal power grid, *IEEE Transactions on Power Electronics*, 34(3), 2938-2955 (2018).
- [2] Yang, Z., Zeng, J., Zhang, Q., Zhang, Z. and Winstead, V., Yu, D., A composite power decoupling method for a PV inverter with optimized energy buffer, *IEEE Transactions on Industry Applications*, 57(4), 3877-3887 (2021).
- [3] Hanchao, Z., & Daolian, C. (2017, October). A single-stage isolated charging/discharging DC-AC converter with second harmonic current suppression in distributed generation systems. In *IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society* (pp. 4427-4432). IEEE.
- [4] Liyun, Z., Research on power decoupling based on single-phase photovoltaic grid-connected inverter, <https://link.cnki.net/doi/10.27276/d.cnki.gsdgc.2022.000776> (2022).
- [5] Sun, H., Wang, H., & Qi, W., Automatic power decoupling controller of dependent power decoupling circuit for enhanced transient performance. *IEEE Transactions on Industrial Electronics*, 66(3), 1820-1831 (2018)
- [6] Meiqing, M., Zhenyu, S. and Liuchen, Z., A new power decoupling topology to improve the power density of single-phase photovoltaic grid-connected inverters, *Acta Energiate Solaris Sinica*, 43(6): 33, 2022.
- [7] Jiang, J., Pan, S., Zha, X., & Hao, L. (2019, June). A new single-phase single-stage photovoltaic grid-tied inverter with leakage current eliminating and power decoupling. In *2019 IEEE 10th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)* (pp. 560-564). IEEE.
- [8] Zeng, J., Zhao, J., & Kim, T. (2018, September). Modeling and control for a photovoltaic inverter with power decoupling on the AC side. In *2018 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 991-997). IEEE.
- [9] Kangjie, L., Photovoltaic grid-connected micro-inverter with power decoupling, *Electric Engineering*, (7), 75-78 (2023).
- [10] Yang, Z., Zeng, J., Zhang, Q., Zhang, Z., Winstead, V., & Yu, D. (2021). A composite power decoupling method for a PV inverter with optimized energy buffer. *IEEE Transactions on Industry Applications*, 57(4), 3877-3887.