Remus Teodorescu | Marco Liserre | Pedro Rodriguez

Grid Converters for Photovoltaic and Wind Power Systems

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He has more than 150 papers published in IEEE conferences and transactions, one book and four patents (pending). He is the co-recipient of the Technical Committee Prize Paper Awards at IEEE IAS Annual Meeting 1998. He is a Senior Member of IEEE, Past Associate Editor for *IEEE Power Electronics Letters* and Chair of IEEE Danish Joint IES/PELS/IAS Chapter. His areas of interests include the design and control of grid-connected converters for mainly wind power and photovoltaic systems and for utility applications FACTS/HVDC. Remus Teodorescu is the co-ordinator of the Vestas Power Programme, a five year research programme involving 10 PhD students in the area of power electronics, power systems and storage.

Marco Liserre is engaged in teaching courses of power electronics, industrial electronics and electrical machines. His current research interests include industrial electronics applications to distributed power generation systems based on renewable energies.

He has been a visiting Professor at Aalborg University, Denmark, Alcala de Henares University, Spain, and at Christian-Albrechts University of Kiel, Germany. He has given lectures in different universities and tutorials for many conferences. Dr Liserre is an Associate Editor of the *IEEE Transactions on Industrial Electronics* and *IEEE Transactions on Sustainable Energy*. He is the Founder and the Editor-in-Chief of the *IEEE Industrial Electronics Magazine*, 2007–2009. He is the Founder and the Chairman of the Technical Committee on Renewable Energy Systems of the IEEE Industrial Electronics Society. He received the IES 2009 Early Career Award and is IEEE-IES Vice-President for publications. Dr Liserre was the Co-Chairman of the International Symposium on Industrial Electronics (ISIE 2010), held in Bari in 2010.

Pedro Rodríguez received his M.Sc. and Ph.D. degrees in electrical engineering from the Technical University of Catalonia (UPC-BarcelonaTech), Barcelona, Spain. In 1990 he joined the faculty of UPC as an Assistant Professor, where he is currently an Associate Professor in the Department of Electrical Engineering and the Head of the Research Center on Renewable Electrical Energy Systems (SEER). He was a Visiting Researcher at the Center for Power Electronics Systems, Virginia Polytechnic Institute and State University, (Blacksburg, USA). He stayed as a Postdoctoral Researcher at the Department of Energy Technology (DET), Aalborg University (Denmark). Currently, he is a habitual visiting professor at the DET where he lectures Ph.D. courses and participates as a co-supervisor in the Vestas Power Program at the AAU.

Pedro Rodríguez has coauthored about 100 papers in technical journals and conference proceedings. He is the holder of four licensed patents on wind and photovoltaic systems. He has lectured courses on power converters applied to power systems in many universities around the world. His research activity lies in the field of electronic power processors applied to electrical distributed generation systems, being mainly focused on designing controllers for the grid interactive power processors, designing power electronics based power processors for green energy sources and proposing new technical solutions to improve stability and power quality in electrical networks. Dr. Rodriguez is a Senior Member of the IEEE, an Associate Editor of the *IEEE Transactions on Power Electronics*, and the Chair of the IEEE-IES Student and GOLD Members Activities Committee.

Preface

The penetration of wind- and photovoltaic (PV)-generated electrical energy into the grid system worldwide is increasing exponentially. A limiting factor is the increasingly stringent grid requirements imposed by different grid operators aiming to maintain grid stability. Both wind power (WP) plants and PV power plants are connected to the grid through grid converters which, besides transferring the generated DC power to the AC grid, should now be able to exhibit advanced functions like: dynamic control of active and reactive power; stationary operation within a range of voltage and frequency; voltage ride-through; reactive current injection during faults; participation in a grid balancing act like primary frequency control, etc. Therefore the aim of this book is to explain the topologies, modulation and control of grid converters for both PV and WP applications. In addition to the classical handbooks in power electronics this book shows the PV- or wind turbine (WT)- specific control functions according to the recent grid codes and enhances the classical synchronization and current control strategies with the general case when the grid is unbalanced.

The idea of this book originated in a biannual Industrial/PhD course 'Power Electronics for Renewable Energy Systems' started in May 2005 in Aalborg University, Institute for Energy Technology, and is successfully continued with over 250 PhDs or industry engineer attendees (by the end of 2010). The success of this course was due to the practical aspects involved as more than 40 % of the time was spent in the lab for designing and testing control strategies on real grid converters. Thus, the initiative for writing this book together with Marco Liserre from Politecnico di Bari and Pedro Rodríguez from UPC Barcelona has been taken in order to ensure a unique reference for the course.

The book is intended as a textbook for graduating students with an electrical engineering background wanting to move into areas of the electrical aspects of PV and WT power regenerations, as well as for professionals in the PV or WT industry.

Chapter 1 gives an overview of the latest developments in the PV and WT penetrations in the worldwide power systems as well as the forecast until 2014, which looks very promising despite the economical crisis of 2008–2010. Chapter 2 discusses the various high-efficiency topologies for PV inverters as well as some generic control structures. In Chapter 3 the grid requirements for PV installations are described. Chapter 4 gives a deep analysis of the basic PLL as the preferred tool for synchronization in single-phase systems and discusses different quadrature signal generator methods, while Chapter 5 discusses islanding detection methods. Chapter 6 describes the most typical WT grid converter topologies together with generic control structures. The most recent grid requirements for WT grid connection, the so-called Grid Codes, are explained in Chapter 7. The next chapter extrapolates the knowledge of single-phase PLL structure for three-phase systems. New robust synchronization structures are proposed in order to cope with the unbalance grid or frequency adaptation. In Chapter 9 the most used grid converter control structures for WT are explained while Chapter 10 extrapolates the control issue for the case of grid faults, where new control structures are proposed. In Chapter 11 the issue of designing grid interface filters is discussed along with methods actively used to damp the resonance for LCL filters. Finally, Chapter 12 goes down to basics and advanced methods for controlling the grid current going from linear to more robust nonlinear techniques. The new resonant controllers are introduced and compared with the classical PI. Appendix A familiarizes the reader with the issue of different coordinate transformations in three-phase systems, Appendix B gives the basic principle of instantaneous power theory and Appendix C describes the concept of resonance controllers.

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1

Introduction

In the last few years renewable energies have experienced one of the largest growth areas in percentage of over 30 % per year, compared with the growth of coal and lignite energy.

The goal of the European Community (the EU) is to reach 20 % in 2020, but the EU-27 energy is only 17 % of world energy. The US, with 22 % of energy share, has adopted similar goals under the pressure of public opinion concerned by environmental problems and in order to overcome the economical crisis. However, the policies of Asia and Pacific countries, with 35 % of energy share, will probably be more important in the future energy scenario. In fact, countries like China and India require continuously more energy (China energy share has increased 1 point every year from 2000).

The need for more energy of the emerging countries and the environmental concerns of the US and the EU increases the importance of renewable energy sources in the future energy scenario.

1.1 Wind Power Development

Grid-connected wind systems are being developed very quickly and the penetration of wind power (WP) is increasing.

The driving force in Europe was taken in March 2007, when EU Heads of State adopted a binding target of 20 % of energy generated from renewable sources by 2020. A similar plan for 25 % renewable energy sources until 2025 has been adopted in the US.

According to BTM Consult [1], the cumulative and annual installed wind power worldwide in 2009 is shown in Figure 1.1. Despite the economic crisis, 2009 was a very good year, with a worldwide installed wind power of 38.1 GW (35 % higher than 2008). The biggest markets in 2009 were China, with 36.1 %, and the US, with 26 %. The cumulative worldwide installed wind power by the end of 2009 was 160.1 GW. The average growth for the period 2004–2009 was 36.1 %, while the forecast average growth for the period 2010–2014 is 13.6 % (reduced due to the economic crisis of 2008–2010). The worldwide cumulative installed power forecasted by 2019 is close to 1 TW, leading to a global wind power penetration of 8.4 %.

Wind energy penetration (%) is defined as the total amount of wind energy produced annually (TWh) divided by the gross annual electricity demand (TWh). According to the

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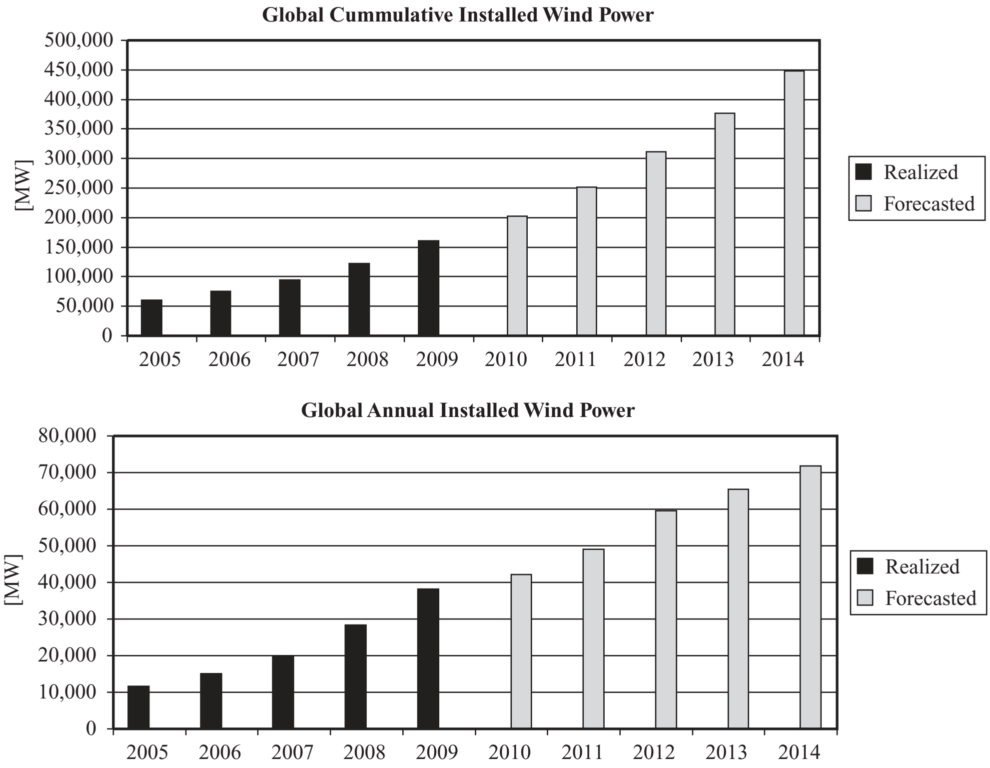

Figure 1.1 Wind power installed worldwide by 2009 and forecast until 2014: cumulative (left) and annual (right). Source: BTM Consult

EWEA (European Wind Energy Association) [2], the approximate wind energy penetration in Europe by 2008 was 3.8 %, with the highest penetration levels of 21 % in Denmark, 12 % in Spain and Portugal, 9 % in Ireland and 7 % in Germany. At the regional level much higher penetration levels were achieved, as, for example, 36 % in Schleswig-Holstein, Germany, and 70 % in Navarra, Spain.

According to the DOE (US Department of Energy) [3], the wind energy penetration level in the US reached 1.9 % by 2008, with highest state levels in Iowa 13.3 %, Minnesota 10.4 % and Texas 5.3 %. The worldwide wind energy penetration by 2008 was 1.5 %.

It is very difficult to define the maximum level of penetration as it is strongly dependent on the particularities of the grid in the considered area in terms of conventional generation, pricing, interconnection capacity, demand management and eventual storage capacity. Typically several regional or national grids are interconnected (as, for example, UCTE and NORDEL) and by agreement certain shared reserve generation and transmission capacity is provided in order to cope with $n - 1$ type contingency. The fluctuating wind power dispatch works also as a 'disturbance' in the system and this reserve capacity can also be successfully used for balancing purposes. Some studies have indicated that 20 % wind penetration may be achieved without major transmission or storage developments. Electrical utilities continue to study

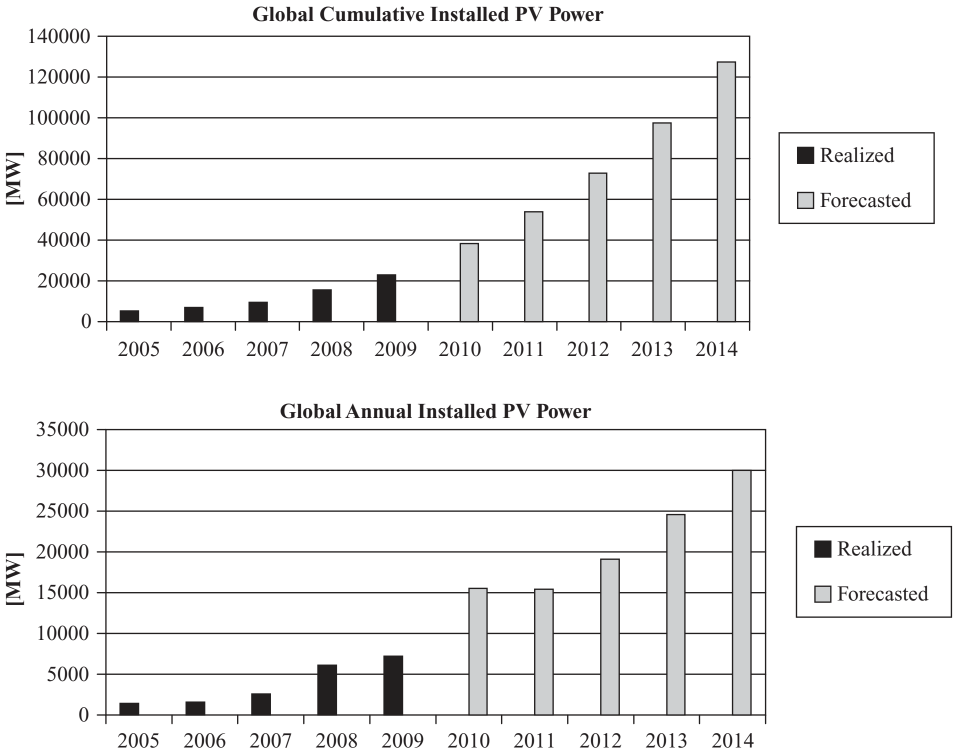

Figure 1.2 PV power installed worldwide by 2009 and forecast until 2014: cumulative (left) and annual (right). Source: EPIA

the effects of large-scale (20 % or more) penetration of wind generation on system stability and economics. Denmark has planned wind penetration of 50 % by 2025 [4]. The Danish grid is strongly interconnected to the European electrical grid through Norway, Germany and Sweden. Almost half of its wind power is exported to Norway, which can easily balance its almost entirely hydro-based power system.

In order to be able to increase the wind energy penetration, new grid interconnection requirements called grid codes have been developed by countries with high penetration.

1.2 Photovoltaic Power Development

The worldwide cumulative and annual photovoltaic (PV) power installed according to EPIA are shown in Figure 1.2 [5].

The year 2009 was also a good year for PV, as 6.4 GW was installed (equivalent to approx one-sixth of wind power installed). From an empirical point of view we can say that PV is growing at approximately the same rate as WP and is just approximately 6 years behind. The forecast for 2014 is 30 GW for PV, close to the 28.7 GW for WP forcast 6 years ago (for 2008). The worldwide cumulative PV power reached 22.8 GW by the end of 2009.

Today, there are several PV parks with installed power > 40 MW in Spain, Germany and Portugal. The PV penetration is quite low now but it is estimated by EPIA that it could be as high as 12 % in 2020.

Another important aspect is that the cost of PV panels have dropped during 2008 by around 40 % to levels under € 2/W for PV. The bulk penetration of the PV system is expected around 2015 when the cost of PV electricity is forecasted to became compatible with the cost of conventional energy.

1.3 The Grid Converter – The Key Element in Grid Integration of WT and PV Systems

Power converters is the technology that enables the efficient and flexible interconnection of different players (renewable energy generation, energy storage, flexible transmission and controllable loads) to the electric power system. Hence it is possible to foresee how the synchronous machine has a central role in the centralized power system and the grid converter, also denoted as the 'synchronous converter', will be a major player in a future power system based on smart grid technologies. While the electromagnetic field has a major role in the synchronous machine, the grid converter is based mainly on semiconductor technology and signal processing but its connection filter, where the inductor is dominant, still has a crucial role to play in transient behaviour.

The increase in the power that needs to be managed by the distributed generation systems leads to the use of more voltage levels, leading to more complex structures based on a single-cell converter (like neutral point clamped multilevel converters) or a multicell converter (like cascaded H-bridge or interleaved converters). In the design and control of the grid converter the challenges and opportunities are related to the need to use a lower switching frequency to manage a higher power level as well as to the availability of a more powerful computational device and of more distributed intelligence (e.g. in the sensors and in the PWM drivers).

The book analyses both basic and advanced issues related to synchronization with the grid, harmonic control and stability, and at the system level in order to detect and manage islanding conditions for PV power systems and control under grid faults for WT power systems. It is intended for both graduate students in electrical engineering as well as practising engineers in the WT and PV industry, with special focus on the design and control of grid converters.

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2

Photovoltaic Inverter Structures

2.1 Introduction

The PV inverter is the key element of grid-connected PV power systems. The main function is to convert the DC power generated by PV panels into grid-synchronized AC power.

Depending on the PV power plant configuration, the PV inverters can be categorized as:

- Module integrated inverters, typically in the 50–400 W range for very small PV plants (one panel).
- String inverters, typically in the 0.4–2 kW range for small roof-top plants with panels connected in one string.
- Multistring inverters, typically in the 1.5–6 kW range for medium large roof-top plants with panels configured in one to two strings.
- Mini central inverters, typically > 6 kW with three-phase topology and modular design for larger roof-tops or smaller power plants in the range of 100 kW and typical unit sizes of 6, 8, 10 and 15 kW.
- Central inverters, typically in the 100–1000 kW range with three-phase topology and modular design for large power plants ranging to tenths of a MW and typical unit sizes of 100, 150, 250, 500 and 1000 kW.

Historically the first grid-connected PV plants were introduced in the 1980s as thyristor-based central inverters. The first series-produced transistor-based PV inverter was PV-WR in 1990 by SMA [1]. Since the mid 1990s, IGBT and MOSFET technology has been extensively used for all types of PV inverters except module-integrated ones, where MOSFET technology is dominating.

Due to the high cost of solar energy, the PV inverter technology has been driven primarily by efficiency. Thus a very large diversity of PV inverter structures can be seen on the market.

In comparison with the motor drive inverters, the PV inverters are more complex in both hardware and functionality. Thus, the need to boost the input voltage, the grid connection filter, grid disconnection relay and DC switch are the most important aspects responsible for increased hardware complexity. Maximum power point tracking, anti-islanding, grid synchronization and data logger are typical functions required for the PV inverters.

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Actually, in contrast with electrical drive industry, which is 20 years older and driven by cost where the full-bridge topology is acknowledged worldwide, new innovative topologies have recently been developed for PV inverters with the main purpose of increasing the efficiency and reducing the manufacturing cost. As the lifetime of PV panels is typically longer than 20 years, efforts to increase the lifetime of PV inverters are also under way. Today, several manufacturers are offering extended service for 20 years.

The first method used to increase the efficiency was to eliminate the galvanic isolation typically provided by high-frequency transformers in the DC–DC boost converter or by a low-frequency transformer on the output. Thus a typical efficiency increase of 1–2 % can be obtained.

As the PV panels are typically built in a sandwich structure involving glass, silicon semiconductor and backplane framed by a grounded metallic frame, a capacitance to earth is appearing, creating a path for leakage current. This can compromise personal safety, which is typically based on a system that monitors the leakage current as an indication of faults, especially in residential applications. This capacitance can vary greatly, depending on construction or weather conditions, and in reference [2] typical values of 10 nF/kW for PV are measured using the full-bridge with unipolar modulation as a well-known source of common mode voltage resulting in leakage current.

Unfortunately, the transformerless structure requires more complex solutions, typically resulting in novel topologies in order to keep the leakage current and DC current injection under control in order to comply with the safety issues.

Another important design issue that is driving the development of new topologies is the ability to exhibit a high efficiency also at partial loads, i.e. during the periods with reduced irradiation levels. Actually a weighted efficiency called ‘European efficiency’ has been defined that takes into consideration the periods for different irradiation levels across Europe.

Today there are many PV inverter manufacturers in the market, such as SMA, Sunways, Conergy, Ingeteam, Danfoss Solar, Refu, etc., offering a wide range of transformerless PV inverters with very high European efficiency (>97 %) and maximum efficiency of up to 98 %.

The topology development for the transformerless PV inverters has been taking the starting point in two ‘well-proven’ converter families:

- H-bridge.
- Neutral point clamped (NPC).

The aim of this chapter is to explain some of the most relevant actual transformerless PV inverter structures as derivatives of these main families. The level of diversity is high as some structures require a boost DC–DC converter with or without isolation. These boost converters are well known and will not be described in detail. Some typical combined boosted inverter structures are presented at the end of this chapter.

For the module-integrated inverters, due to the low power level a very large diversity of new topologies is reported, but due to the very low actual market share of this type of inverter they are not explored in this chapter.

2.2 Inverter Structures Derived from H-Bridge Topology

The H-bridge or full-bridge (FB) converter family, first developed by W. Mcmurray in 1965 [3], has been an important reference in the power electronic converter technology development.

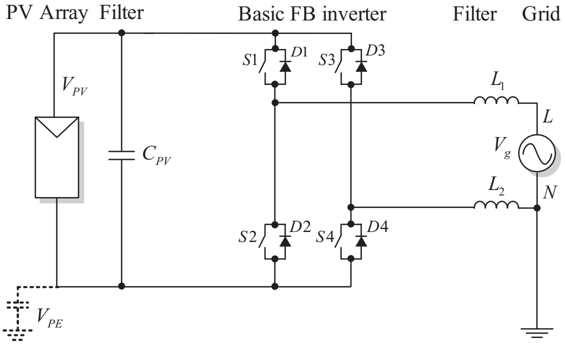


Figure 2.1 Basic FB inverter

It was the first structure able to take advantage of the first available force-commuted semiconductor devices (thyristors). The H-bridge topology is very versatile, being able to be used for both DC–DC and DC–AC conversion and can also be implemented in FB form (with two switching legs) or in half-bridge form (with one switching leg).

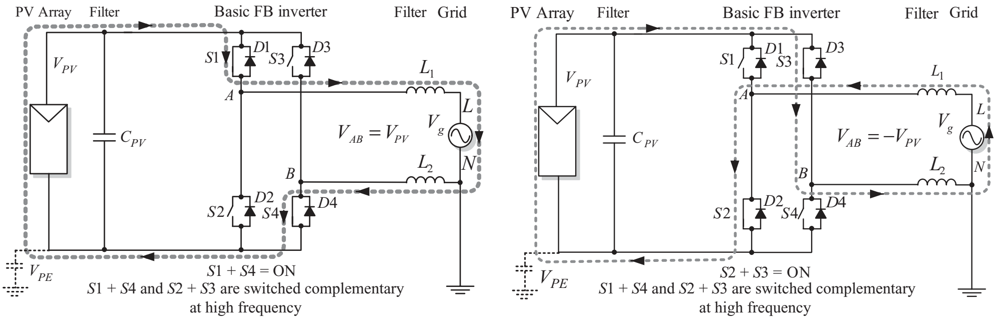
2.2.1 Basic Full-Bridge Inverter

The practical PV inverter topology based on the full-bridge (FB) inverter is shown in Figure 2.1.

Three main modulation strategies can be used:

- Bipolar (BP) modulation.
- Unipolar (UP) modulation.
- Hybrid modulation.

In the case of *bipolar (BP) modulation* the switches are switched in diagonal, i.e. $S1$ synchronous with $S4$ and $S3$ with $S2$. Thus AC voltage can be generated as shown in Figure 2.2(a) and (b) for the positive and negative output currents respectively.



$S1 + S4$ = ON
$S1 + S4$ and $S2 + S3$ are switched complementary at high frequency

$S2 + S3$ = ON
$S1 + S4$ and $S2 + S3$ are switched complementary at high frequency

(a) (b)

Figure 2.2 FB with BP modulation strategy in the case of: (a) positive output current and (b) negative output current

The main features of this converter are:

- Leg A and leg B are switched synchronously in the diagonal ($S1 = S3$ and $S2 = S4$) with high frequency and the same sinusoidal reference.
- No zero output voltage state is possible.

Advantages:

- V_{PE} has only a grid frequency component and no switching frequency components, yielding a very low leakage current and EMI.

Drawbacks:

- The switching ripple in the current equals 1 × switching frequency, yielding higher filtering requirements (no artificial frequency increase in the output!).
- The voltage variation across the filter is bipolar ($+V_{PV} \rightarrow -V_{PV} \rightarrow +V_{PV}$), yielding high core losses.
- Lower efficiency of up to 96.5 % is due to reactive power exchange between $L_{1(2)}$ and C_{PV} during freewheeling and high core losses in the output filter, due to the fact that two switches are simultaneously switched every switching period.

Remark:

> *Despite its low leakage current the FB with BP modulation is not suitable for use in transformerless PV applications due to the reduced efficiency.*

In the case of *unipolar modulation*, each leg is switched according to its own reference. Thus AC current can be generated as shown in Figure 2.3.

The main features of this converter are:

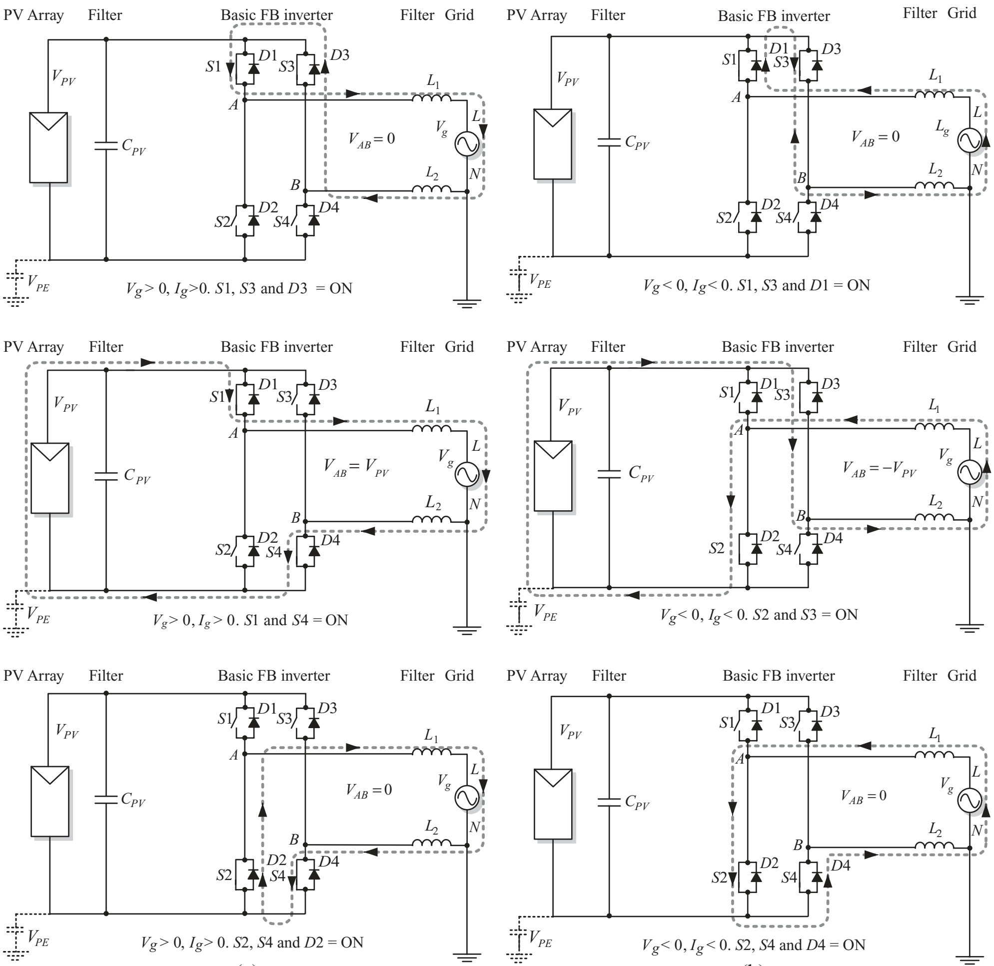
- Leg A and leg B are switched with high frequency with mirrored sinusoidal reference.
- Two zero output voltage states are possible: $S1$, $S3$ = ON and $S2$, $S4$ = ON.

Advantages:

- The switching ripple in the current equals 2 × switching frequency, yielding lower filtering requirements.
- Voltage across the filter is unipolar ($0 \rightarrow +V_{PV} \rightarrow 0 \rightarrow -V_{PV} \rightarrow 0$), yielding lower core losses.
- High efficiency of up to 98 % is due to reduced losses during zero voltage states.

Drawbacks:

- V_{PE} has switching frequency components, yielding high leakage current and EMI.



(a) (b)

Figure 2.3 The switching states of FB with UP modulation in the case of generating: (a) positive current and (b) negative current

Remark:

> *Despite its high efficiency and low filtering requirements FB with UP modulation is not suitable for use in transformerless PV applications due to the high-frequency content of the V_{PE}.*

In the case of *hybrid modulation* [4], one leg is switched at grid frequency and one leg at high frequency. Thus AC current can be generated as shown in Figure 2.4(a) and (b).

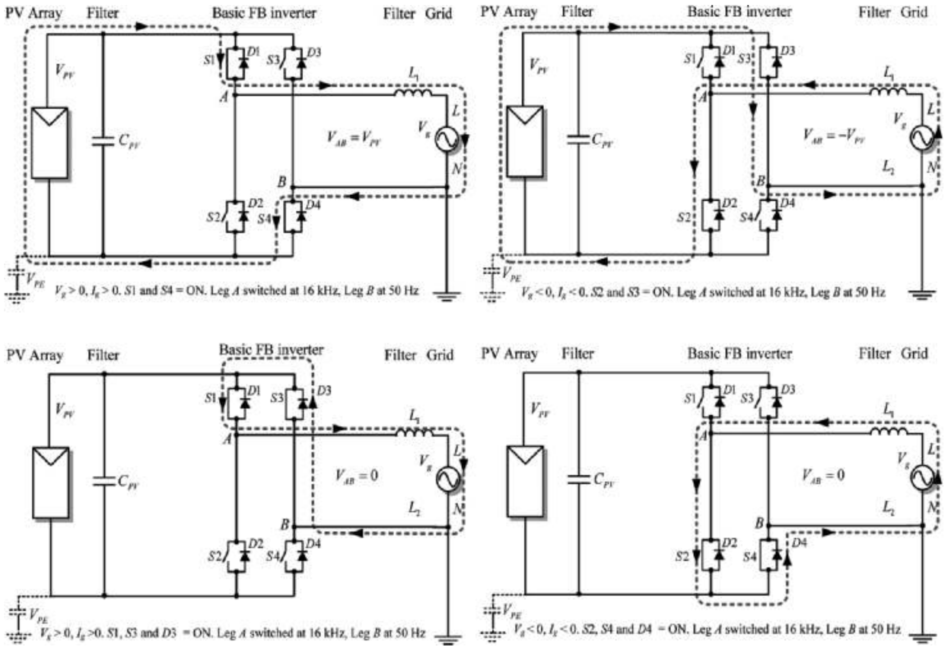


Figure 2.4 The switching states of FB with hybrid modulation in the case of generating: (a) positive current and (b) negative current

The main features of this converter are:

- Leg A is switched with grid low frequency and leg B is switched with high PWM frequency.
- Two zero output voltage states are possible: $S1$, $S2 =$ ON and $S3$, $S4 =$ ON.

Advantages:

- Voltage across the filter is unipolar ($0 \rightarrow +V_{PV} \rightarrow 0 \rightarrow -V_{PV} \rightarrow 0$), yielding lower core losses.
- Higher efficiency of up to 98 % is due to no reactive power exchange between $L_{1(2)}$ and C_{PV} during zero voltage and to lower frequency switching in one leg.

Drawbacks: also a drawback is the fact that this modulation only works for a two quadrant operation.

- The switching ripple in the current equals 1 × switching frequency, yielding higher filtering requirements (no artificial frequency increase in the output!).
- V_{PE} has square wave variation at grid frequency, leading to high leakage current peaks and large EMI filtering requirements.