Power Inverter Topologies for Photovoltaic Modules – A Review

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***Abstract*–This review-paper focuses on the latest development of inverters for photovoltaic AC-Modules. The power range for these inverters is usually within 90 Watt to 500 Watt, which covers the most commercial photovoltaic-modules. Self-commutated inverters have replaced the grid-commutated ones. The same is true for the bulky low-frequency transformers versus the high-frequency transformers, which are used to adapt the voltage level. The AC-Module provides a modular design and a flexible behaviour in various grid conditions. It hereby opens the market for photovoltaic-power for everyone at a low cost due to the plug and play concept, which also makes a further enlargement of the system possible.**

Keywords–photovoltaic; single-phase grid-connected inverter; renewable energy; converter topologies

I. Introduction

Photovoltaic (PV) power supplied to the utility grid is gaining more and more visibility, while the worlds power demand is increasing. Not many PV-systems have so far been put into the grid due to the relatively high cost. The price of the PV-module(s) were in the past the major contribution to the cost of these systems. A downward tendency is now located in the price for the module(s), and for the same reason, the cost of the single-phase grid-connected inverter(s) are becoming more visible in the total cost.

The inverter is needed for two reasons. First, the low DC voltage generated by the module must be amplified to the higher AC level in the grid. Second, the power delivered from the module(s) is very sensitive to the point of operation, and the inverter should therefore incorporate a function for tracking the Maximum Power Point (MPP).

The most common PV-technologies nowadays are the single-crystalline silicon and the multi-crystalline silicon module(s) [1]. The open circuit voltage in such a module is located in two ranges; either from 18 V to 26 V for a module made up of 36 cells or from 38 V to 46 V for a module composed by 72 cells [2]. However, new technologies like the thin-layer silicon, the amorphous-silicon and the Photo Electro Chemical (PEC) are in development [1], [3].

This work was supported in part by the Elkraft System Public Service Obligation – Research & Development (PSO-F&U) program under Grant No. 91.063 (FU1303).

This means that new modules with only one cell may see the light in the future. The voltage range for these cells/modules is located around 0.5 V to 2.0 V [4], [5].

This paper starts with a historical overview. From the past, when large areas of several PV-modules were interfaced to a centralized inverter, into the present time, where decentralized inverters are interfacing a single or few modules and further into the future where inverter only interfaces a single PV-cell to the grid.

Next, an overview of existing power converter topologies for the AC-Module is given. The approaches are further discussed in order to compare the topologies for future applications and finally a conclusion is given.

II. Evolution of Photovoltaic Inverters

A. The Past: Centralized Inverters

The past technology was based on centralized inverters, which was interfaced to a number of modules. The modules were normally connected in both series, called a string, and parallel in order to reach a high voltage and power level. This results in some limitation; such as the necessity of high voltage DC cables between the modules and the inverter, power losses due to a centralized MPP Tracking (MPPT), mismatch between the modules and at last the string diodes.

If one of the modules in a string becomes shadowed, then it will operate as a load with lower power generation as a consequence. On the other hand, if the modules are connected in parallel, the shadowed module is still generating power, but the input voltage to the inverter is inevitable lower due to the parallel connection. A third scheme is given in [6] – [10], where each module is interfaced by a Generation Control Circuit (GCC). Hence, an individual MPPT is assured for every single module, which also lower the possibilities of hot spots.

According to [32], full shadowing of one PV-cell (in a string of 160 cells) causes a temperature raise, inside the cell, of more than 70 ºC above the ambient temperature, whereas the non-shadowed cells only reach 22 ºC above the ambient temperature (for an ambient temperature equal to 12 ºC). This is of great importance, because an overheated cell rapidly decreases the modules lifetime.

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B. The Present: String Inverters and AC-Modules

The present technology, which is a hot research topic in Germany, is the 'string-inverter' [11], [12]. String-inverters use a single string of modules, to obtain a high input voltage to the inverter. However, the high DC voltage requires an examined electrician to perform the interconnections between the modules and the inverter. On the other hand, there are no losses generated by the string diodes and an individual MPPT can be applied for each string. Yet, the risk of a hot-spot inside the string still remains.

The AC-Module, where the inverter is an integrated part of the PV-module, is also an interesting solution [9], [13] – [28]. It removes the losses due to mismatch between modules and inverter, as well as it supports optimal adjustment between the module and the inverter. Moreover, the hot-spot risk is removed. All this together; a better efficiency may be achieved. It also includes the possibility of an easy enlarging of the system, due to the modular structure. The opportunity to become a 'plug and play' device, which can be used by persons without any education in electrical installations, is also an inherent feature.

C. The Future: AC-Modules and AC-Cells

A solution for the future could be the AC-Cell, which is the integration of one great PV-cell and the inverter [3] - [5], [29]. The aim of these cells is to be an integrated part of the climatic-barrier in buildings. The main challenge for the inverter is to amplify the cell' inherent very low voltage up to an appropriate level for the grid-connected inverter and at the same time to reach a high efficiency. For the same reason, entirely new converter technologies are requested.

III. AC-Module Topologies

Inverters for PV-applications have to contain some basic functionalities. The conversion of the low voltage generated at the MPP (typically around 17 V for a 36 cells module and 34 V for a 72 cells module) to a corresponding AC current injected into the grid, must be done with the highest possible efficiency over a wide range of PV-power. This requirement is given due to the irradiation distribution of the sun, which is shown in Fig. 1 for a Danish Reference Year. Fig. 1 shows that most of the power is generated within the range from 200 W/m^2 to 1000 W/m^2 of irradiation.

The grid connected stage in almost all the investigated solutions uses a full-bridge inverter towards the grid, either grid-commutated at twice the grid-frequency [14] – [19], [22] – [26] cf. Fig. 2a), or self-commutated with a high switching frequency [7] – [10], [13], [20] cf. Fig. 2b). The grid-commutated operation is possible if the input-current to the grid-connected stage is modulated to a rectified sinusoidal current. The latter utilises PWM or bang-bang operation. Benefits for the grid-commutated solution are that the switching losses from the stage are completely removed and only the conduction losses remain. This means that the grid

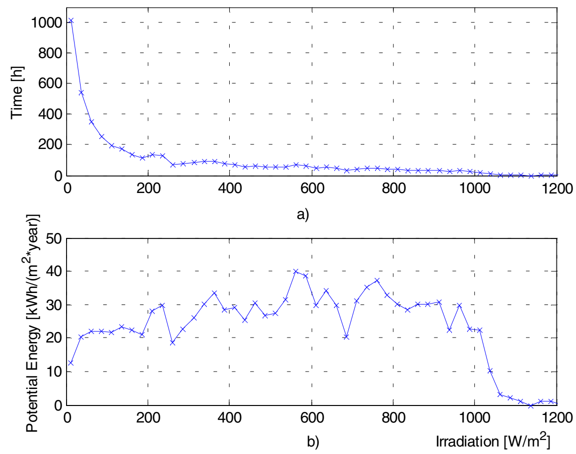

Fig. 1. Meteorological data: a) Irradiation distribution for a Danish Reference Year (DRY). b) Solar energy distribution for a DRY. Total time of irradiation equals 4686 hour per year. Total potential energy is equal to 1154 kWh/(m^2·y) = 132 W/m^2. Courtesy of Danish Technological Institute.

current must be sine-modulated in another sense, e.g. by the DC-DC converter. On the other hand, the switching losses are as a substitute moved to the module-connected converter.

This is on the cost of a reduced power decoupling between the module and the grid (for the dual stage inverter), which makes it more difficult to remove the power fluctuations at the module. The fluctuation comes from the penetration of the instantaneous low frequency power flow to the grid, cf. (1).

Another disadvantage is that both the module-connected converter and the grid-connected inverter must be designed for the peak power and not the average, which leads to larger and hence more expensive components. The peak power is equal to twice the average power, cf. (2), where $\hat{u}_{grid}$ and $\hat{i}_{grid}$ respectively are the grid peak voltage and current, ω_{grid} is the grid frequency, t is the time and PF is the Power-Factor.

$$p_{grid}(t) = \hat{u}_{grid} \cdot \hat{i}_{grid} \cdot \sin^2\left(\omega_{grid} \cdot t\right) \cdot PF \quad (1)$$

$$P_{grid} = \frac{\hat{u}_{grid} \cdot \hat{i}_{grid}}{2} \cdot PF \quad (2)$$

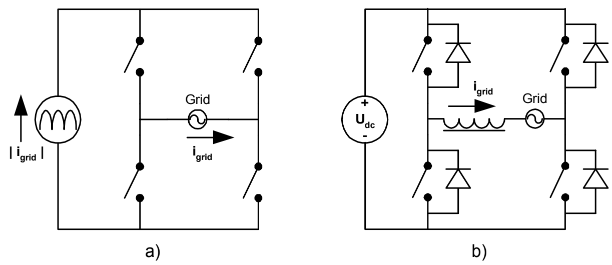

Fig. 2. Grid connected inverters: a) Current-fed, grid-commutated inverter switching at twice the grid frequency. b) Voltage-fed, self-commutated inverter switching at high frequency.

The transformer-included inverters may either utilize a low-frequency [9], [15], [16], [26] or a high-frequency transformer [13], [14], [18] – [20], [22], [24] – [26], [30]. The low-frequency transformer has some shortcoming e.g. the weight while it must somehow be attached to the module without making it mechanical fragile. Another drawback is the prize, while these transformers must be made and mounted manually. Modern inverters tend to use a high-frequency transformer. This results in entire new designs, such as the Printed Circuit Board (PCB) integrated magnetic components [13], even in a core-less version. However, the International Energy Agency-PhotoVoltaic Power Systems (IEA-PVPS) states in their task V [11], that a general requirement for transformer-included topologies is not justified, because small amount of injected DC current to the grid do not affect the local distribution transformers.

The inverter must also include a MPPT in order to optimise the module' point of operation, where it generates the most power (U_{MPP} and I_{MPP}), cf. Fig. 3. Finally, the inverter must be low-cost but simultaneously it should have a lifetime around 25 years [2], which is the common lifetime for a PV-module. This calls for the use of more silicon devices, e.g. MOSFET' and IGBT', which is still decreasing in price, at the expense of fewer capacitors and magnetic devices, which is believed to increase in price.

IV. Single-Step Topologies for the AC-Module

The single step topology must include both the voltage amplification, the MPPT, the DC-AC inversion together with a power decoupling. All in one single inverter. It cannot be made without a transformer and simultaneously achieve a high efficiency, while the requested voltage amplification may reach almost 16 times for European grids.

The topology presented here is the novel Bi-Directional Fly-Back (BDFB) inverter, cf. Fig. 4. It is composed by two bi-directional fly-back converters, hence the name. The voltage-gain, A, is given by (3), in the case where the first converter is operated with a duty cycle equal to D, the second converter is operated with a duty cycle equal to (1-D) and the currents through the transformers are continuous.

$$A = \frac{U_{out}}{U_{in}} = \frac{N_{sec}}{N_{pri}} \cdot \frac{2 \cdot D - 1}{D^2 - D}, \qquad (3)$$

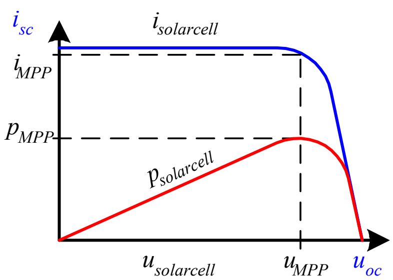

Fig. 3. Typical current and power characteristic for a PV-cell or -module. Short circuit current: i_{sc}, open circuit voltage: u_{oc}, maximum power point voltage, current and power: u_{mpp}, i_{mpp}, p_{mpp}.

where N_{sec} and N_{pri} are the secondary and primary turns numbers. U_{in} is the module voltage and U_{out} is the voltage across the grid and the grid-connected inductor. The converter can always be controlled to operate in Continuous Conduction Mode (CCM) because of the bi-directional current flow capabilities.

The penetration of the 100 Hz power ripple may be rather large compared to the other dual- and multiple-stage inverters. A remedy for removing the ripple is to use an input capacitor, cf. (4). C is the required capacitor in the front of the module in order to obtain a power ratio, defined as $P_{PV,AVG}$ / P_{MPP} , equal to k, where $P_{PV,AVG}$ is the average power delivered from the module, P_{MPP} is the power at the MPP, ω_{grid} is the grid-frequency and U_{MPP} is the maximum power point voltage.

$$C \approx \frac{P_{MPP}}{2 \cdot \omega_{grid} \cdot U_{MPP}^2 \cdot \sqrt{1-k}}, \quad for\ k \approx 1. \qquad (4)$$

For instance, a MPP voltage of 34.0 V (a 72 cell PV-module) with k = 0.99 and for European systems, the requested capacitance would reach 14 µF / W, which is regarded as much compared to the dual- or multiple-step solution, where the required DC-link capacitance equals (partly from [33]):

$$C \approx \frac{P_{grid}}{2 \cdot \omega_{grid} \cdot U_{dc} \cdot \tilde{u}_{dc}}, \qquad (5)$$

where P_{grid} is the power delivered to the grid, U_{dc} is the average DC-link voltage and $\tilde{u}_{dc}$ is the amplitude of the small-signal DC-link voltage. Again, for a European system, with an average DC-link voltage equal to 360 V and a small-signal amplitude of 20 V this correspond to 220 nF / W.

A prototype of the 'Variable Output Bidirectional DC-DC Converter' was tested in [30], with the following specifications: U_{in} = 165 V, U_{out} = 0 V to 250 V, P_{out} = 1 kW and f_{switch} = 100 kHz.

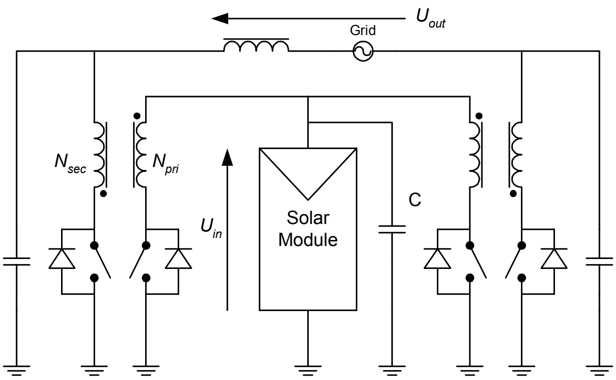

Fig. 4. A novel single-step solution for an AC-Module: the Bi-Directional Fly-Back inverter, based on two 'Variable Output Bidirectional DC-DC Converter' [30].

The specifications for the transformer are $N_{pri} = N_{sec}$ with a magnetizing inductance equal to 100 μH. The converter is in [30] used to drive a piezo-ceramic actuator with an operating frequency ranging from zero to 500 Hz (note that the switching frequency still is 100 kHz).

Another approach is to use a standard full-bridge inverter together with a bulky 50 Hz transformer [6], [15], [16]. However, this is regarded as a poor solution due to the bulky low-frequency transformer and the lack of power decoupling between the module and the grid.

V. DUAL-STEP TOPOLOGIES FOR THE AC-MODULE

The most evident solution for the AC-Module should properly be located amongst the dual step topologies. These topologies offer a good power-decoupling by means of a DC-link capacitor at e.g. 360 V, if the grid-connected inverter is self-commutated. In the case of the self-commutated inverters, the module-connected converter is designed for the average PV-power whereas the grid-connected inverter is designed for a peak power equal to twice the average PV-power, cf. (2). On the contrary, the grid-commutated inverters require that both steps must be designed for twice the average power. A common solution for the AC-Module is based on the resonant DC-DC converter and a self- or grid-commutated grid-connected inverter, cf. Fig. 5.

All commercial inverters in this review (Soladin120 [19], OK4 [18], OK5 [18] and Sunmaster 130 [19] (a three stage inverter)) are based on the resonant principle. In the case of the OK4 inverter the DC-DC converter are used to amplify the voltage but also to modulate the rectified sinusoidal current, which is 'unfolded' in the secondary stage.

The next inverter [20] is based on the series resonant DC-DC converter and a modified full bridge grid-connected inverter, cf. Fig. 6. The inverter is modified in such a way that it cannot operate as a rectifier; hence problems with standby losses are solved. Two additional diodes do this. The DC-DC converter is, as stated before, based on the series resonant converter, where the leakage inductance in the transformer together with the capacitor inserted in the main path forms a resonant-tank. The resonant tank together with the output-capacitances of the switches makes the inverter zero-voltage switching. The DC-DC converter is operated at 100 kHz with a duty-cycle slightly smaller than 50% in order to avoid shoot-through.

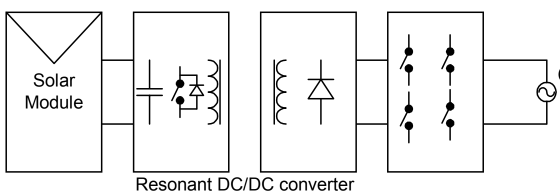

Fig. 5. Block diagram for modern AC-Module inverters with two stages [14, 17-19].

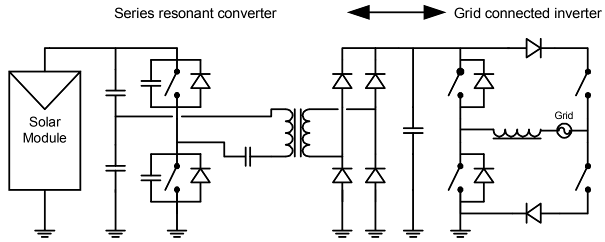

Fig. 6. The inverter proposed in [13, 20]. The series resonant DC-DC converter amplifies the voltage from the PV-Module and the grid connected-inverter generates the sinusoidal grid-current.

The converter runs in this way with a fixed voltage transfer ratio (as a 'DC-transformer') and the MPPT is taken care of by the grid-connected inverter. The switching losses in the DC-DC converter are almost completely avoided but more losses may be expected to appear in the transformer, due to a higher current caused by the resonant principle. The diodes in the rectifier are current-commutated by the use of the series resonant converter, which produces smaller reverse-recovery losses in the diodes. The grid-connected inverter uses both high and low switching frequencies. The leftmost leg in the grid-connected inverter, cf. Fig. 6, is controlled by means of a bang-bang controller. When the absolute error into the controller exceeds a given limit, the left leg makes a switching, which causes the error to decrease. This part of the inverter operates at switching frequencies between 20 kHz and 80 kHz depending on the instantaneous grid voltage and commanded grid-current. The rightmost leg of the inverter is switched according to the polarity of the grid voltage, i.e. at 100 Hz. The switching losses in the grid-connected inverter are in this way reduced by a ratio of two compared to inverters where both legs are switched at high frequencies. However, the non-constant switching frequency may make it more difficult to design a stable EMI filter.

The last dual stage inverter presented here utilises the same layout as in [20], cf. Fig. 6. The inverter given in [13] makes the use of integrated magnetic circuits. This means that all inductors and transformers are incorporated into the PCB by means of planar magnetics. The resonant inductor and transformer for the DC-DC converter are made as one magnetic circuit. This is done in order to increase the efficiency and to decrease the cost and size. Two inductors, each of 500 μH, are used towards the grid. They are also put into the PCB. However, power losses in the grid-connected inductors are increased from 100 mW to 500 mW when changing the technology from an ordinary toroidal core to the more sophisticated planar-magnetics [13]. The DC-DC converter is switching at 500 kHz in a series-resonant configuration and the grid-connected inverter is switching at 100 Hz. This means that the two stages are not decoupled and a large capacitor is required in front of the module in order to attenuate the power ripple, cf. (4). Then again the benefit is the total removal of the switching losses in the inverter and the use of a high frequency transformer.

VI. Multi-Step Topologies for the AC-Module

Due to the three stages (or more) the complexness and cost of the multi-step topology are deemed to be higher than those one- and two-step solutions presented previous. On the other hand, it becomes possible to use an 100 Hz inverter with a belonging rectified-sine modulated DC-DC converter and still obtain a power decoupling between the module and the grid. This results in low switching losses in the grid-connected stage and good MPPT properties.

The last commercial inverter for the AC-Module inverter examined here is the Sunmaster 130S [19], [22], [23], see also Fig. 7. This inverter is radically different than these just presented. For the first, it utilises an auxiliary MPPT circuit and second, it uses three stages. The inverter towards the grid runs at 100 Hz, which again means that the stages are non-decoupled. The second stage is a series resonant converter with a high-frequency transformer and rectifier. The resonant tank is made up around a resonant capacitor, the transformer and the resonant inductor, which is included in the leakage inductance of the transformer. This stage is operated as a 'DC-transformer', which means that it runs with a fixed duty cycle slightly less than 50% and a constant frequency, i.e. without any kind of control. The module-connected converter is based on the buck converter, where the output current is modulated to follow the well-known rectified sine-current. The amplitude of the rectified sinusoidal current is controlled by the MPPT.

Due to the auxiliary MPPT circuit a pi-filter is inserted between the buck converter and the MPPT circuit. The PV-module is disconnected in 200 µs every two seconds. The step-down converter is then fed from the input capacitor, and the MPP voltage is derived from the modules open circuit voltage, U_{oc}, as: $U_{MPP} = 0.8 \cdot U_{oc}$. This is a fast and simple way to perform the MPPT as long as the modules characteristic is known. If they are changed due to a change in e.g. the temperature, then it will not be possible to track the MPP accurately, with reduced power as a consequence.

The next inverter presented is found in [24] and depicted in Fig. 8. A boost converter is used to amplify the module voltage up to approximately 200 V in the DC-link and to track the MPP. Moreover, it is used to supply the auxiliary circuits. This is done by means of a secondary winding on the boost inductor and a matching rectifier. A push-pull converter provides galvanic isolation between the module and the grid. Besides this, it controls the grid-current and the 100 Hz full-bridge inverter is unfolding the rectified sine current, generated by the push-pull converter.

A prototype of this inverter is reported in [24], with the following specifications: U_{in} = 30 V to 170 V, P_{in} = 500 W. The efficiency is reported to be better than 70 % for an input voltage of U_{in} = 45 V and power higher than 90 W. The low efficiency is mainly due to the boost converter. This is not surprising while it must amplify the PV-Module voltage from 45 V to 200 V into the DC-link, or 4.44 times.

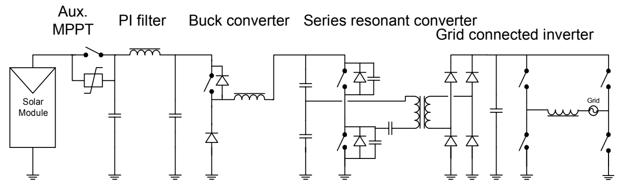

Fig. 7. Schematic for the Sunmaster130S [19]. The buck converter modulates the sinusoidal current. The series resonant converter forms the 'DC-transformer' and the grid connected inverter unfolds the rectified current into the grid.

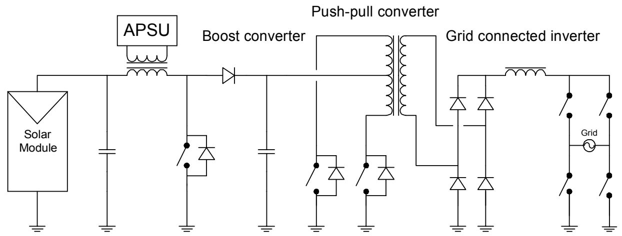

Fig. 8. The proposed topology in [24]. The grid-connected inverter unfolds the rectified-sine current generated by the push-pull converter. The boost converter is used for MPPT. The PV-Module current, and hence voltage, is assured constant by using a boost converter in front of the PV-Module, which acts as a constant current load. The module and the grid become in this way power-decoupled. The auxiliary winding on the boost inductor is used for the Auxiliary Power Supply Unit (APSU).

The efficiency for the boost converter is measured to approximately 80 % at 90 W output power. The efficiency for the grid-connected inverter is always better than 99 %, while in the case of a thyristor-equipped inverter only two times the diode forward-voltage drop and the absolute average grid-current is generating the losses.

Another three-stage inverter is shown in Fig. 9, [25]. A Current Fed Push-Pull (CFPP) converter is used to amplify the module voltage to an appropriate level for the DC-link (app. 400 V). The use of the CFPP converter have some inherent advantages such as a constant input current characteristic which means that none or only a very small capacitor is required in order to stabilise the module voltage around the U_{MPP}. The next stage is the well-known buck converter, which again is used to form the grid-current. The last stage is the 100 Hz inverter, which is build up around thyristors, used to unfold the modulated rectified-sine wave current.

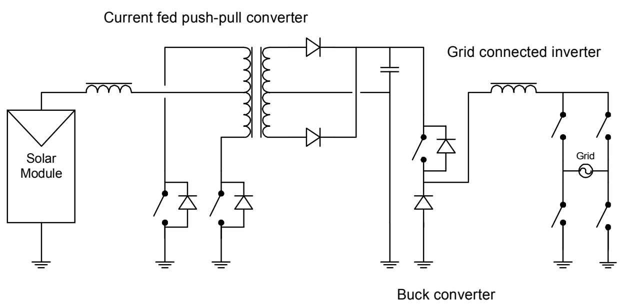

Fig. 9. The proposed topology in [25]. The grid-connected inverter unfolds the rectified-sine current generated by the buck converter. The buck converter is used to generate the rectified sine current and the current fed push-pull converter is used to amplify the module voltage.

A prototype with the following specifications is reported: U_{in} = 14 V, P_{in} = 300 W. An efficiency of 80 % is obtained for the entire system at full load. The relatively low efficiency is due to the low input voltage of only 14 V and could hence be better for a higher module voltage.

VII. Discussion

The solutions for the AC-Module inverter presented in this paper do not include a bulky low frequency transformer but a small high-frequency one. Table I compares the four given topologies, cf. Fig. 4, Fig. 6, Fig. 8 and Fig. 9, regarding nominal power, method of commutation in the grid-connected stage, numbers of components for the power-circuit and power decoupling between the module and grid.

It shows that the three-stage inverters are all grid-commutated. When that is concluded it is also important to emphasize that the three-stage solutions have a higher count of components and hence it is a more expensive solution. It also shows that the single-stage inverter does not offer the power decoupling between the module and the grid and hence a decoupling capacitor must be applied.

The electrolytic capacitors used for the decoupling may be placed at the input of the inverter, where the voltage is low, in the DC-link where the voltage is high and somewhere between.

The required capacitance needed for decoupling in the single-stage inverters is according to (4) inverse proportional to the MPP voltage raised to the second power, whereas for the dual- and multiple-stage inverters it is inverse proportional to the average and small-signal DC-link voltage, cf. (5).

The price index is based on the number of components in the power-stages, their ratings and component prices.

Table II compares the performance among four commercial AC-Module inverters. The evaluation shows that all four inverters accept a wide range of grid voltage. Moreover, the OK5 inverter offers auto-detection of the grid frequency (50 or 60 Hz) and software adjustable voltage range for US, EU and JP grids.

TABLE I
System Comparison of the Different Topologies

Fig.:	4	6	8	9
Nominal PV-power	170 W	250 W	500 W	300 W
Estimated MPP voltage	36 V	53 V	106 V	14 V
DC-link voltage	-	430 V	200 V	400 V
No. of stages	1	2	3	3
Commutation	Self	Self	Grid	Grid
No. of inductors	3	2	3	3
No. of electrolytic capacitors	1	1	1	1
- at voltage level	Module	Grid	Between M/G	Grid
No. of film capacitors	2	3	1	1
No. of switches	4	6	7	7
No. of diodes	0	6	5	3
Decoupling capacitance, app.	2 mF	20 µF	160 µF	50 µF
Power decoupling	No	Yes	Yes	Yes
Price index [pu]	100	109	161	125

TABLE II
Performance Comparison for Commercial AC-Module Inverters

Name:	Soladin120	OK4E	OK5	Sunmaster130S
Nominal power [W]	90	100	500	110
Power density [W/cm^3]	0.15	0.30	0.41	0.09
MPP Voltage [V]	24 – 40	24 - 50	15 – 18	24 - 40
Start-up power [W]	0.4	0.15	0.5	0.95
Grid voltage [V]	207 – 253	190 - 270	190 – 265 98 - 132	203 - 247
Power factor [ ]	0.99	0.99	0.99	0.99
Stand-by power [W]	0.05	0.003	0.05	0.085
EU Efficiency [%] [A]	91.6	90.3	92.9	89.6
%THD$_i$	-	< 3	< 3	-

[A] European efficiency is calculated with the following formula (index value = percent of rated power): $\eta_{EU} = 0.03\eta_5 + 0.06\eta_{10} + 0.13\eta_{20} + 0.10\eta_{30} + 0.48\eta_{50} + 0.20\eta_{100}$ [31].

All the inverters show excellent grid performance in terms of a low THD$_i$ (current Total Harmonic Distortion) and a high power factor. Another important issue is the inverters capability to convert the low irradiation power into electric power. For the reasons given above it is evident that the 'optimum' topology for the AC-Module must be located within the dual stage inverters.

Table II shows that the starting-up power is located in the span from 0.15 W to 0.95 W and at the same time the power consumption during night-time is very low. These entries together with a high efficiency and high power density indicate a high level of knowledge about the design giving parameters.

VIII. Conclusion

This review has covered a few different inverter topologies for photovoltaic applications and particular inverters for the AC-Module. The task for such an inverter is to amplify the photovoltaic-module(s) low voltage up to the higher-level voltage of the grid and to convert it from DC into AC. Seven of these inverters use either a half- or a full-bridge inverter, switching at 100 Hz or in the kHz area. The 100 Hz approach is possible if one of the previous converters in the circuit generates a rectified-sine current. The 100 Hz inverter then unfolds the rectified-sine current to a full-sine. If a high frequency inverter is used towards the grid, the included DC-DC converter(s) just have to amplify the voltage and to track the maximum power point. The latter solutions benefit from a better power de-coupling between the module and the grid; hence a smaller energy-buffer is therefore required. Moreover, the module-connected converter should be designed for the average power and not the peak power, which is the case for the grid-connected inverter. Among the topologies for single and dual step/stage systems the Bi-Directional Fly-Back (BDFB) inverter and the resonant inverters seem to be the most promising.

However, with the BDFB topology measures are necessary to lower the power coupling between the module and the grid. Also further research is required in order to evaluate, whether the BDFB justifies the use of two high-frequency transformers.

The AC-Module is considered as a solution for the future. As a consequence, the next step in the development-phase, of an inverter for the AC-Module, would be to establish some specifications for the inverter. These specifications should be stated in the light of accessible photovoltaic-modules, grid-performance and this overview.

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