Renewable Energy Operation and Conversion Schemes

A Summary of Discussions During the Seminar on Renewable Energy Systems

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Highly reliable and efficient power processing systems allow exploitation of the enormous potential of the renewable sources by transforming the maximum available power into an electrical one, fed into the grid or converted into a high-density energy vector for being stored and used in another place or at another time, when the primary source is not available.

Such topics were discussed at the Seminar on Renewable Energy system (SERENE) held 12–13 June 2009 in Salerno, Italy. The seminar was sponsored by the University of Salerno and the IEEE Industrial Electronics Society (IES) through the Technical Committee on Renewable Energy Systems and Educational Committee.

This article is an attempt at summarizing the most important contributions of SERENE. It is organized as follows: first, the most promising future source of energy, i.e., photovoltaics (PVs), is treated with respect to the maximization of energy extraction, the maximization of efficiency, and reliability with silicon carbide (SiC) devices and power converter structures; then, one of the most challenging energy sources, wave energy, is discussed with reference to the results of the Wave Dragon European project; finally, integration of these sources into the power grid through smart-grid technologies based on the

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grid converter and the use of hydrogen as the main energy vector for stationary power plants are illustrated.

PV Systems

The use of energy coming from the Sun and hitting Earth has been dramatically increasing in the last few years. Apart from the solar thermal plants, the spreading of PV systems is being encouraged by the feed-in tariffs and by the drop in crystalline cells' prices. The latter factor in 2009 has boosted the sales of large PV power plants as well as domestic installations, with a growing trend in 2010, because the pay-back plan benefits of tariffs for the produced energy still remains high with respect to the forecast for future years.

In this scenario, the market has increased the need for power processing systems characterized by high efficiency and low cost, both for low-power (e.g., few kilowatts) and high-power applications. The former figure can be improved by working on conversion efficiency and maximum power point tracking (MPPT) efficiency, whose product results in the total efficiency of the power processing system: SiC devices give a significant contribution in maximizing the electrical conversion efficiency, and an in-depth analysis of the disturbances appearing in grid-connected systems helps in improving the MPPT efficiency. The goal of exploiting several distributed power sources with low-voltage levels or to process high power with lower current can be achieved with multilevel architectures.

As for the cost aspect, current literature indicates that the future of PV-dedicated conversion systems is in the adoption of transformerless topologies, with additional benefits in terms of conversion efficiency. Such aspects have been detailed in the sections that follow.

MPPT Issues

The MPPT is one of the key functions in any PV system, because it ensures that the maximum available electrical power is produced by the PV array at any irradiance and temperature values. As evident from the example reported in Figure 1, the locus of the maximum power points is a large area in the power versus voltage plane.

MPPT performances in steady-state weather conditions as well as during transients in the irradiance level can be heavily penalizing for the total efficiency of the entire PV power processing system, because it is given by the product of MPPT efficiency and electrical efficiency of the conversion chain.

The two most frequently used MPPT algorithms are perturb and observe (P&O) [1] and incremental conductance (IC). Both of them are based on a repeated adjustment of the PV voltage to detect the fulfillment of a proper condition involving the actual values of the PV current, voltage, and power. They are usually implemented in the way described in Figure 2, where it is shown by the PV array, a dc/dc boost converter, the load or another switching converter (e.g., a dc/ac stage) by means of a resistor, and the MPPT block using the measures of PV current and voltage to drive the controlled switch appropriately. The PV field has been described by using its single-diode model [2], the boost converter, usually needed for stepping the PV field voltage up to the level needed by the load or by an inverting stage connected to the ac mains, matches the load to the PV generator so that the latter produces the maximum possible power. The MPPT controller straight forwardly adjusts the duty cycle or does the same by varying the reference voltage in an usual pulse-width modulation (PWM) to ensure that the PV array works at a voltage

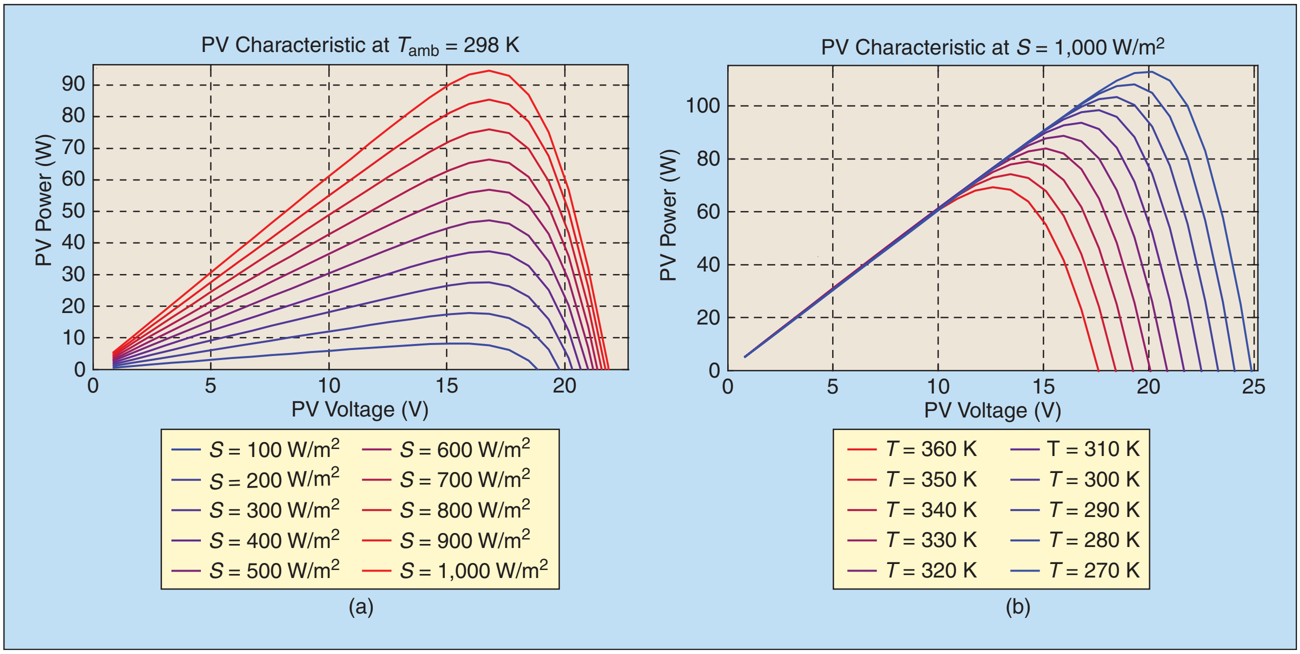

FIGURE 1 – The PV characteristics of a Kyocera KC120 module with varying temperature and irradiance.

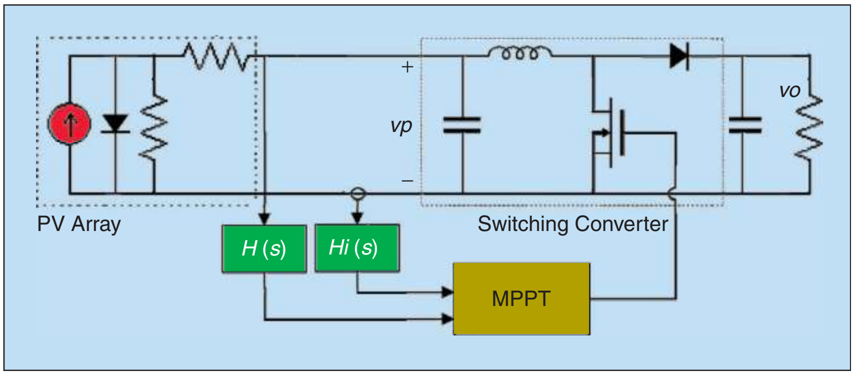

FIGURE 2 – A typical implementation of an MPPT technique.

level resulting in the maximum produced power.

With the same principle, the MPPT technique can be applied to single-stage power processing topologies that do not include the dc/dc converter but employ a dc/ac stage only.

Both P&O and IC MPPT algorithms change the dc/dc converter duty cycle to detect the change of the sign or the null of the derivative of the PV power with respect to the PV voltage [3]. The MPPT efficiency is influenced by a poor parametric design of the algorithm and by the deceiving effect of disturbances originating in the dc/ac stage of the power processing system and propagating backward to the PV array.

As for the first aspect, the amplitude and frequency of the PV voltage perturbations must be designed according to the desired performances at a constant and with a time-varying irradiance. If a too high frequency is settled, the controller might be deceived by the effects of the system's dynamics, but a too low value slows down the MPPT algorithm response to fast irradiance variations. On the other hand, a small amplitude of the perturbations ensures high performances in steady state but worsens them during fast irradiance transients.

A recipe for the optimal design of the MPPT algorithm has been presented in [3], and further measures have been discussed for making the algorithm reliable in single-phase ac applications too. In this case, the performances of any MPPT algorithm, although optimally designed, are deteriorated by a voltage oscillation arising at the dc bus and backpropagating to the PV array. This induces a periodic perturbation of the PV field-operating voltage at twice the ac frequency with a worsened MPPT efficiency. The reason of this phenomenon is explained in Figure 3, where the role of the bulk capacitor in terms of balancing the dc power produced by the PV array and the alternating (at twice the grid frequency) ac power requested by the load or injected into the grid is put into evidence.

Some solutions to this drawback, avoiding any passive filtering and thus preserving the efficiency of the conversion chain, have been presented in the literature. Some solutions are based on a suitable modulation of the dc/dc converter duty cycle to allow the requested oscillation of the bulk voltage and, at the same time, to keep the PV field voltage immune from this disturbance.

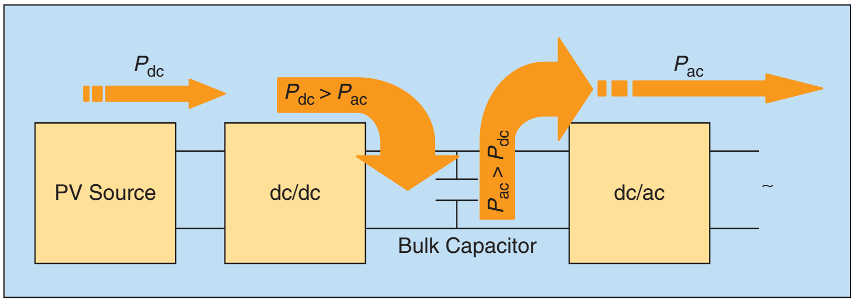

FIGURE 3 – Power fluxes in a two-stage inverter and the source of oscillations at twice the ac frequency.

The increased interest in novel architectures based on the adoption of switching converters employing a PV module-dedicated decentralized MPPT function is giving rise to new challenging problems. The distributed-MPPT (DMPPT) philosophy, which is also stimulating some industries to the production of DMPPT dedicated devices, allows for reducing the impact of the mismatching effect [4], but its implementation requires further studies in terms of interactions among different systems, employing the MPPT function at the same time.

SiC Devices in PV Power Processing Systems

SiC semiconductors have a high potential for enhancements of the electrical conversion efficiency of PV systems. In addition, high switching frequencies inherent to such devices will also enable decrease of weight and cost. Nevertheless, other outstanding characteristics of such components will also play an important role in future developments of other system characteristics such as reliability, maintenance, and life cycle costs, which are of great significance for the further expansion of renewable energy sources (RESs).

The most significant characteristics of SiC is the very high electric breakdown field, allowing thinner and shorter drift layers structures, resulting in very low specific on-state resistance even at higher blocking voltages, as can be observed below for different switch technologies (Figure 4).

The conduction as well as switching losses can be significantly reduced, given the much superior dynamic behavior of SiC devices due to the higher saturated electron drift velocity. Such significant reduction of the overall losses can be translated into additional revenues; for example, increasing the efficiency of a grid-connected PV

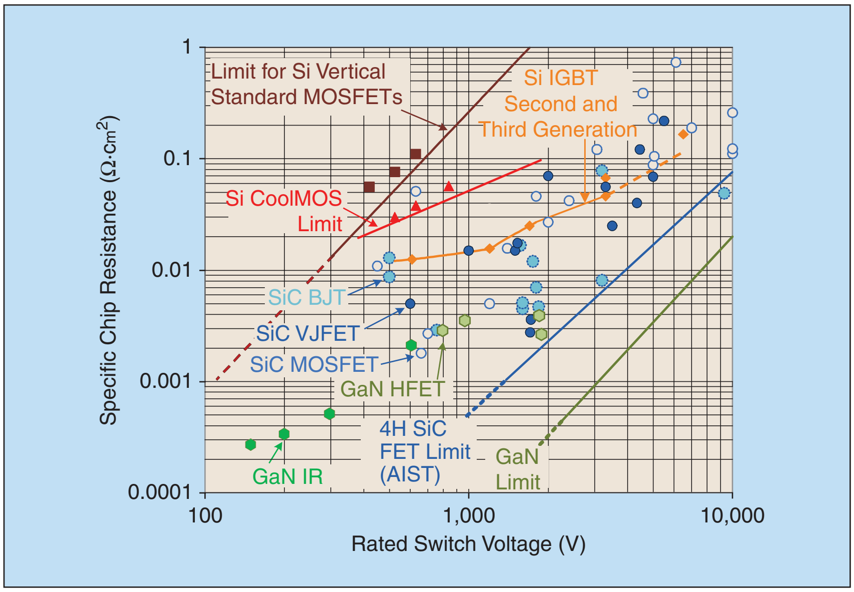

FIGURE 4 – Specific chip resistance for different materials and switch technologies [5].

system in Germany by 1% will return 84€ per installed kW$_{peak}$, considering a lifetime of 20 years. This in turn justifies the use of more expensive devices. Levels of efficiency as high as 99% were already demonstrated in several experimental investigations, though going beyond this level is nevertheless not cost effective so that other features shall also be considered [5], [6] (Figure 5).

The first possibility to be considered is using the high-speed switching capability of SiC devices to increase the switching frequency without much prejudice to the overall losses, allowing a significant reduction of weight and cost of filter inductors. Such characteristic can be observed in Figure 6, where the total losses of a 1,200-V 25-A SiC D-MOSFET and a trench insulated-gate bipolar transistor (IGBT) are compared for a certain current and switching frequency range. A waveform considered here represents the average behavior of a grid-tied inverter with unipolar PWM.

The possibility of operating with reduced losses even at high blocking voltages will allow the use of simplified circuits with fewer semiconductors and power stages. Special characteristics of the switch, for example, normally on behavior depicted by junction field-effect transistors (JFETs), shall also be considered when choosing the optimum circuit for a given application [6].

The referred reduced amount of losses along with higher thermal conductivity and the possibility of operating at very high junction temperatures (inherent to SiC devices only) may also allow a considerable diminution of the heat-sink size and cooling effort, again reducing the weight and cost of the converter.

Transformerless Inverter Topologies

A high-frequency transformer is the key device in classical grid-connected PV power processing systems [7]. It limits the ground current flowing into the grid and ensures that no direct current, which could saturate the distribution transformer, is injected into the grid. Only two parameters have to be considered when selecting the switching converter and its modulation technique: efficiency and line current total harmonic distortion (THD). However, using a transformer increases the weight, size, and cost of the PV system, which in turn reduces

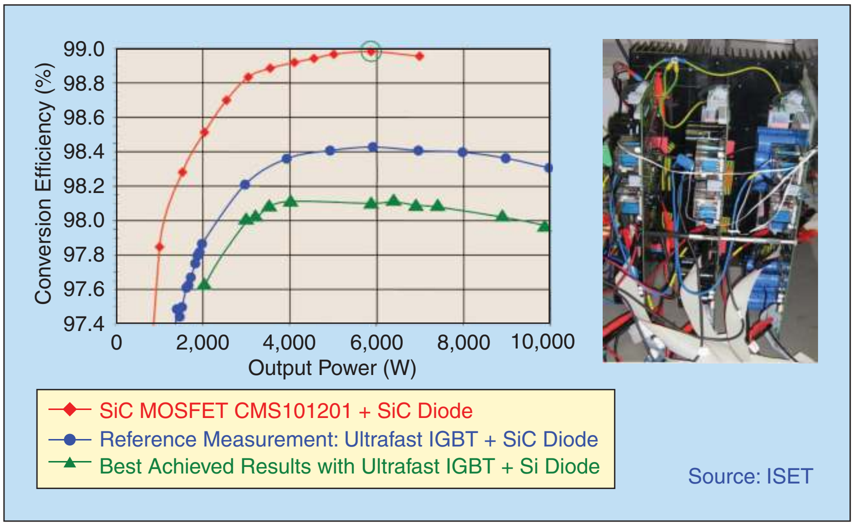

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FIGURE 5 – Measured efficiency curve of a three-phase inverter employing SiC MOSFETs.

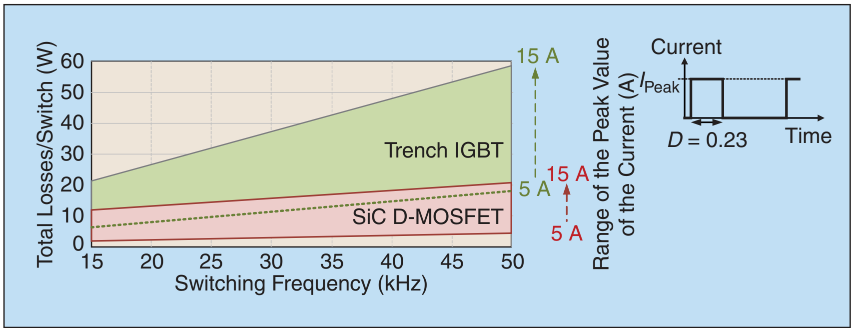


FIGURE 6 – Total losses per switch for a given switching frequency and current range [5].

its efficiency. These drawbacks have motivated researchers to work on transformerless solutions.

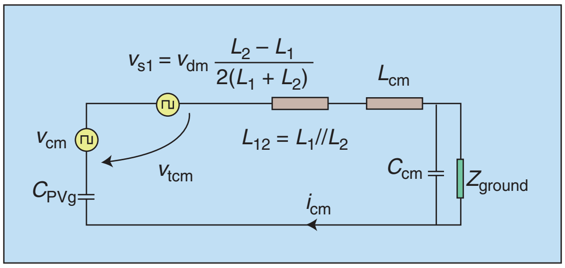
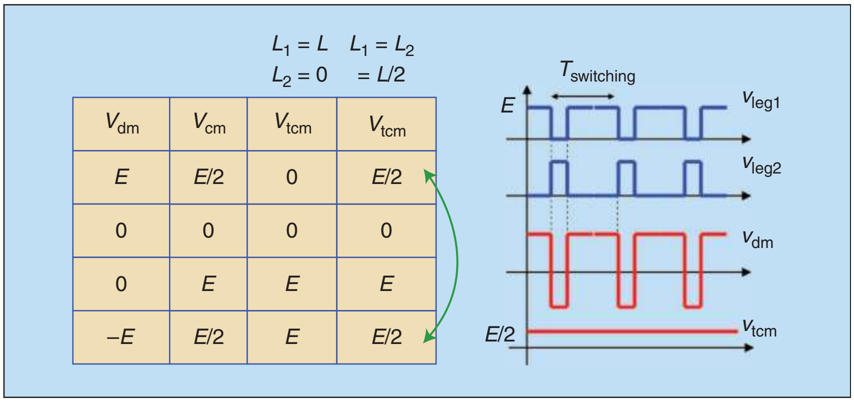


FIGURE 7 – Generalized common-mode model for single-phase transformerless PV systems.

When the transformer is removed from the system, the common-mode behavior has to be carefully considered. The current injected into the ground is only limited by the converter common-mode impedances [mainly due to the electromagnetic compatibility (EMC) filter] and the stray capacitance between the PV generator and ground. This capacitance is high enough to generate strong leakage currents if the inverter impresses a varying voltage across the PV stray capacitance [8]. As a consequence, in PV transformerless systems, the switching converter has to be designed not only for high efficiency and low THD but also to guarantee low ground current injection [9]. Several topologies, apparently based on very different approaches, have been proposed for single-phase transformerless topologies [10]–[12]. Taking into account the general common mode model derived in [8], all the topologies can be systematically analyzed. As a consequence, it is possible to obtain a comprehensive picture of all the different concepts used in those topologies. Additionally, the analysis procedure proposed becomes an useful tool to analyze or derive other solutions.

As a preliminary step, the most significant quality parameters to be evaluated have been described. From the energy generation point of view, the main concern is about efficiency. The main sources of power losses are the converter switching and conduction losses and the energy losses in the output filter. As the operation point of a PV system changes continuously, the efficiency should be obtained considering several operation points. In Europe, the Euro-efficiency coefficient is commonly used for this purpose. From the utility point of view, the main concern is about the line current harmonics, including the dc component, and the current injection into the ground. The line current THD is a function of the inverter output voltage THD. The dc current injection into the grid can be either topologically avoided or controlled by means of a current control loop. Finally, the common-mode current flowing through the ground is a function of the voltage impressed across the stray capacitance of the PV generator to ground. To easily calculate this voltage from any converter topology is very useful to develop a general model of a single-phase PV system for the common mode. This model can be derived considering the switching converter as a two-phase voltage source, with reference to the negative rail of the dc bus, and including the PV to ground (C_{PVg}) and the switches to ground capacitances. The model also has to include the phase and neutral inductors, L_1 and L_2, and the common-mode filter impedances L_{cm}–C_{cm}. The output voltage sources can be expressed in terms of the usual common-mode and differential-mode components. From that model, and after several considerations concerning the frequency range of interest and the relative value of the stray capacitances, the simplified model showed in Figure 1 can be obtained.



V_{dm}	V_{cm}	V_{tcm} ($L_1 = L$, $L_2 = 0$)	V_{tcm} ($L_1 = L_2 = L/2$)
E	E/2	0	E/2
0	0	0	0
0	E	E	E
–E	E/2	E	E/2

FIGURE 8 – Full-bridge analysis for transformerless PV applications.

From the circuit in Figure 7, it is clear that the voltage across C_{PVg} is equal to the total common-mode voltage v_{tcm}, which in turn is a function of the common-mode voltage, the differential-mode voltage, and the line inductors' value. The v_{tcm} has to be kept constant to avoid the current flow into the ground. Because of practical limitations, every PV system topology generates a comparable high-frequency v_{tcm} spectrum, which in turn implies similar values for L_{cm} and C_{cm}, but only in those cases with theoretically constant v_{tcm}, the magnetizing current amplitude would be low enough to achieve a small size for L_{cm}. Ground current spikes of several amperes would appear if L_{cm} saturates.

Once the main quality parameters have been established, they can be easily applied to the analysis of a PV system. For instance, in Figure 8, all the allowable output voltages, v_{dm}, of the full-bridge inverter are listed. Clearly, both requirements, negative and positive output voltages and constant v_{tcm}, are fulfilled only using bipolar modulation and $L_1 = L_2$. But in this case, the output voltage THD is clearly worse, compared with the unipolar modulation, as the zero voltage level is not achievable. A higher switching frequency to improve the current THD negatively affects the system efficiency.

Several modifications to the full-bridge converter have been proposed to generate 0 V in the output terminals at the same time that the v_{tcm} value is kept constant. The goal in all of them is to avoid the connection between the output and the dc bus terminals when the output is short-circuited. Depending on where the additional switches are placed, they could be classified as ac- or dc-bypass inverters. Figure 9 shows two examples. With the help of a table similar to the one depicted in Figure 8, it is possible to systematically derive and justify the modulation technique used in these converters.

A different alternative can be found in the half-bridge topology with no neutral inductance. It provides constant v_{tcm} at the same time that topologically guarantees the noninjection of dc current into the grid. Nevertheless, it generates only two output voltage levels and requires higher dc bus voltage. Multilevel half-bridge converters have been suggested to improve the output voltage THD. On the other hand, only those solutions that do not introduce any additional connection to the capacitor leg would topologically guarantee that no direct current is injected into the grid.

Multilevel Converters

Multilevel PWM converters are gaining popularity in the field of renewable energies because of the need of connecting several distributed power sources, whose power is continuously growing, guaranteeing at the same time good power-quality levels [13]–[20]. They can be used as rectifiers in the case of wind and hydroenergy, where the electricity is generated by ac generators and inverters in the case of wind, solar, hydro, and fuel cell (FC) generation.

There are three basic multilevel topologies: neutral point clamped (NPC), flying capacitor, and cascaded H-bridge (CHB) converters. In the first two topologies, the connected sources cannot be independent; in the case of CHB, the sources can be independent. For this reason, the latter appears very suitable in applications where multiple dc generators are available, typically, solar and FC generation systems. In fact, separate dc sources can be obtained arranging the available sources in distinct groups.

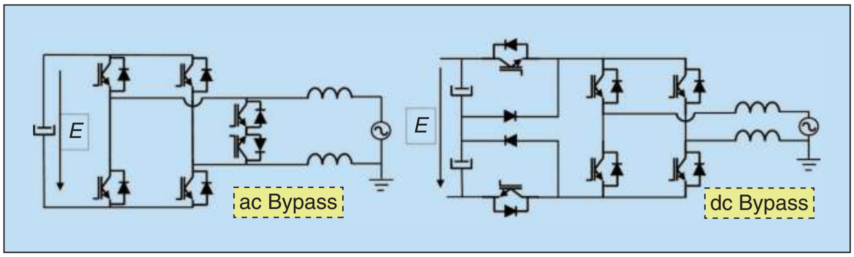


FIGURE 9 – The ac-bypass (highly efficient and reliable inverter concept) and dc-bypass converters.

Multilevel active rectifiers improve the absorbed ac currents, thus reducing generator stress; at the same time, they allow precise output voltage regulation, thus eliminating the need for a dc/dc converter. Furthermore, in the case of multimegawatt systems with high-voltage generators, they overcome the problem of the high input voltage applied to the converter. In case of dc generation, such as in PV or FC systems, they may overcome the need of a dc/dc converter, often in charge of MPPT and voltage boost. Figure 10

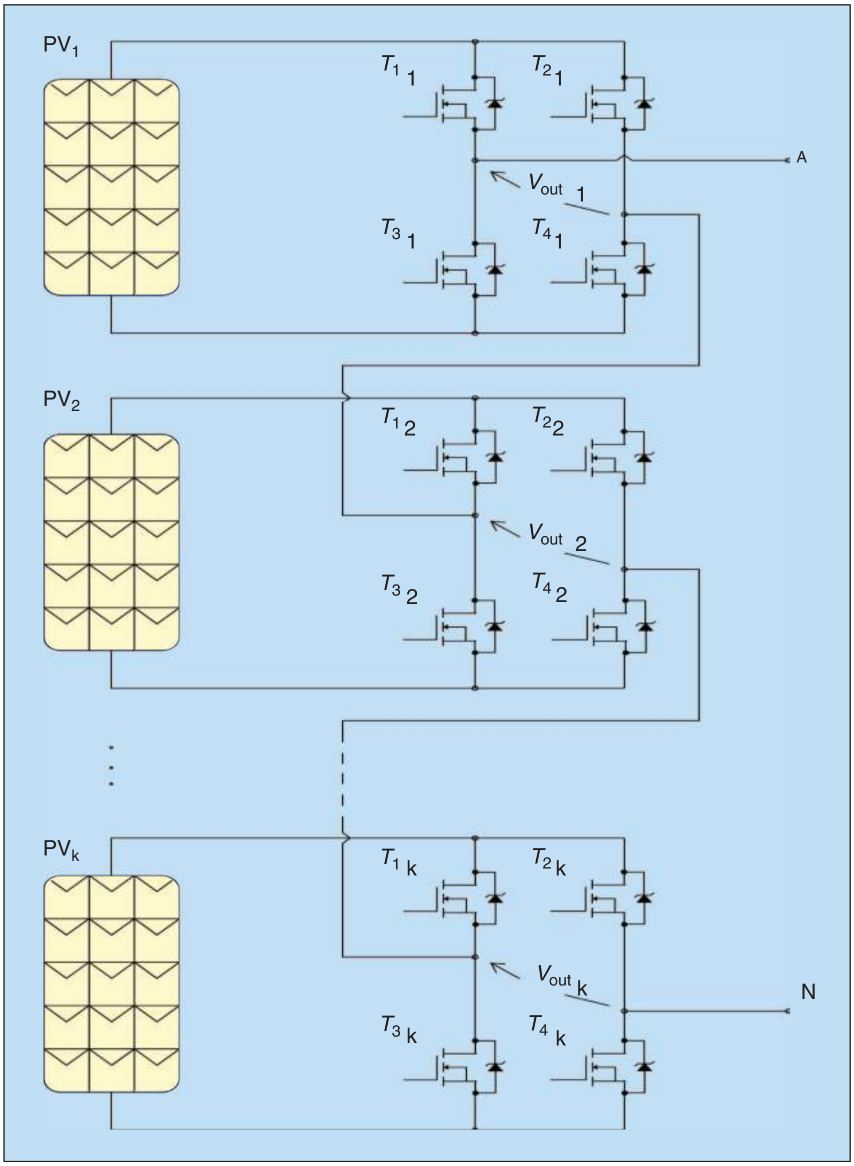


FIGURE 10 – A PV system with multilevel inverter.

shows a schematic diagram of an *n*-level inverter for solar systems.

The main drawbacks of multilevel converters are the higher number of power devices introducing potential power losses problems and the complexity of the pulse generation that requires the design of ad hoc pattern generators. Current electronic technology overcomes both of them: in fact, power devices (MOSFETs and IGBTs) operating at low-voltage levels have better characteristics than those operating at low voltage, thus reducing or eliminating this gap; moreover, the availability of field-programmable gate arrays (FPGAs) solves the second problem, allowing the implementation on a single chip of both control and modulation algorithm at moderate cost.

Wave Dragon MW Offshore Wave Energy Converter

Oceans cover approximately 75% of our planet's surface, and renewable energy comes from the planet in different forms: waves, currents, thermal gradients, salinity gradients, and tides [21]. Until now, more than 1,000 patents have been dedicated to wave energy converters aimed at exploiting this energy. Wave Dragon (Figure 11) is an overtopping device consisting of two wave reflectors, a main platform—body, hydroturbines (low-head type), electrical generators, and finally, power electronic converters (ac–dc–ac). The Wave Dragon offshore wave energy converter is a slack-moored, floating overtopping device [22]. The design of such a system has attracted many researchers who are active in different research fields to solve problems related to body and wave reflectors construction, hydroturbines, power electronics, electrical machines, and control.

Erik Friis-Madsen, the inventor of the Wave Dragon wave energy converter, and his team are responsible for the development of the body and wave reflectors. He designed the Wave Dragon prototype in the 1:4.5 scale (33-m long and 58-m wide).

This Wave Dragon prototype has operated since 2003 in Nissum Bredning, northwest Denmark. The device is automatically controlled and grid connected as a small power plant. The prototype, shown in Figure 11, is built with steel (total mass including water ballast is equal to 237 tons) [22]. Power produced by RESs should be delivered to the grid. At the point of common coupling, this energy has to meet more and more restrictions defined by the local grid code. Renewable power plants should be robust and efficient. However, at the present stage, this is not an easy task. There are still problems with energy storage, robustness, and power quality that need to be solved. To assure the best immunity and efficiency, the topology presented in Figure 12 is considered optimal. The difficulty of handling large components offshore dictates a limited turbine size and high number of individual turbines. Dedicated to each turbine, full-scale ac–dc–ac converters assure very

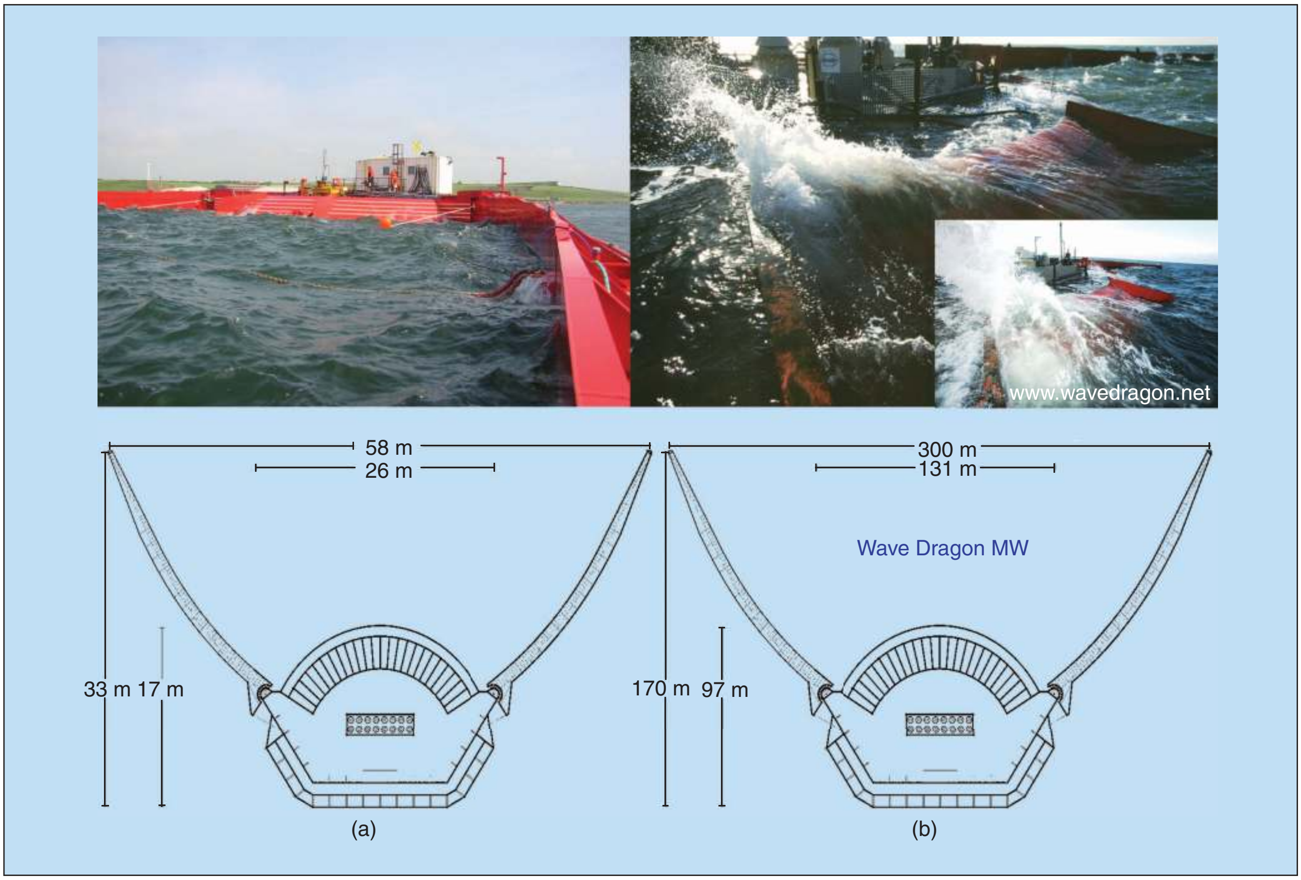


FIGURE 11 – Wave Dragon: (a) small-scale demonstrator; (b) MW full-scale demonstrator (www.wavedragon.net).

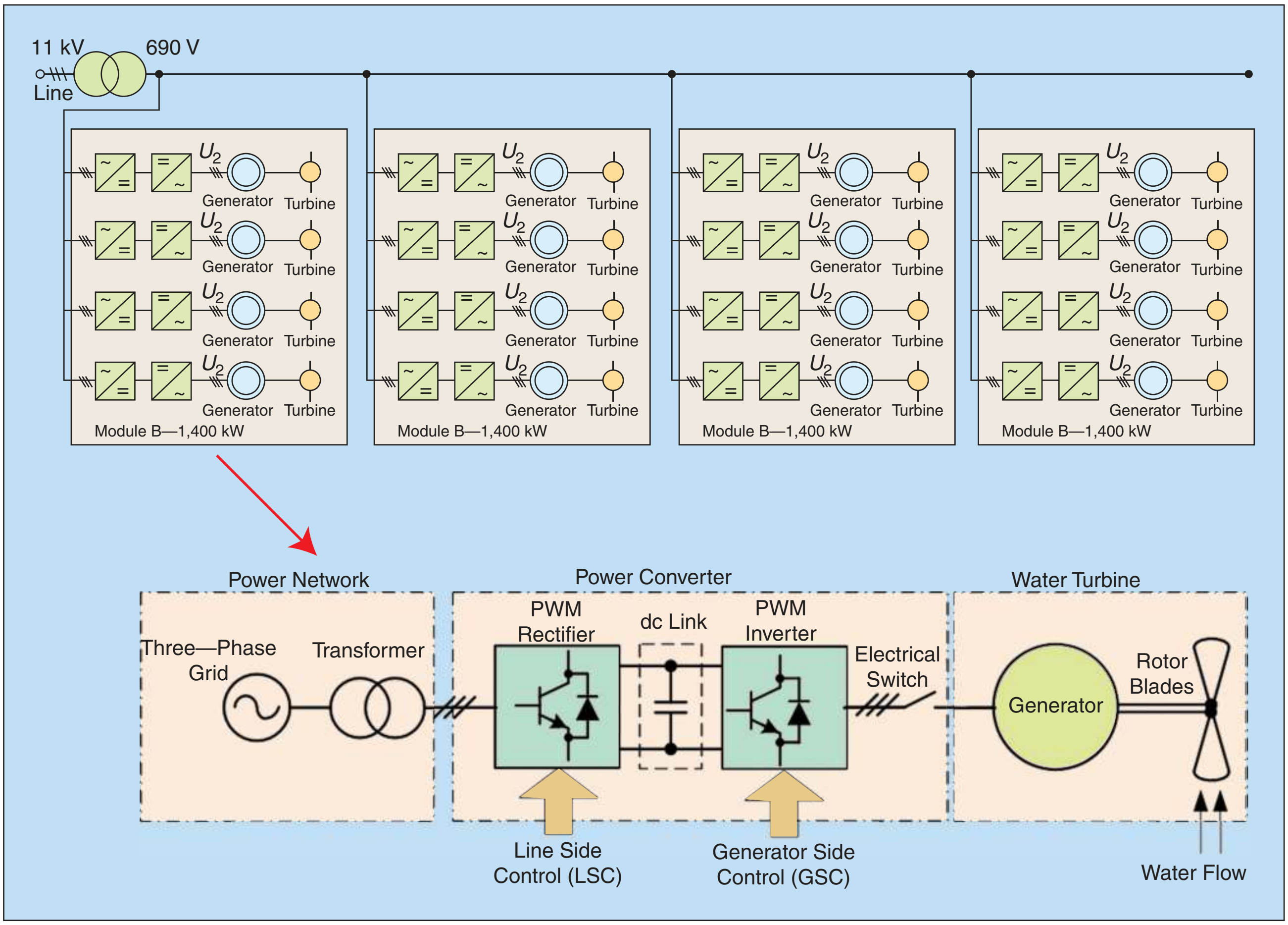


FIGURE 12 – The ac–dc–ac converters as a power electronics interface for wave energy converter.

flexible power conditioning and turbine/generator set speed control. The structure of the proposed ac–dc–ac consists of two similar ac–dc and dc–ac converters (back-to-back converter). Therefore, it is a well-known, proven technology implemented in many applications (e.g., variable speed drives), which results in favorable costs and the possibility for a relatively easy update. Based on the experience with the scaled prototype shown in Figure 11(a), it is obvious that control of the ac–dc–ac/generators set should be optimized. Control methods for both converters [line side converter (LSC) and machine side converter (MSC)] should be closed-loop-based. Therefore, vector control methods are the only alternative. Chosen control methods can be classical voltage and flux-oriented control (or direct power and torque control) for the LSC and MSC converters under the condition that control methods take into account and solve the following problems (see Figure 13): harmonics and voltage dips compensation, islanding mode detection and operation, turbine model, and operation point optimization.

On the machine side, there is the possibility to use a low-speed squirrel cage induction machine (SCIM) or a low-speed permanent magnet

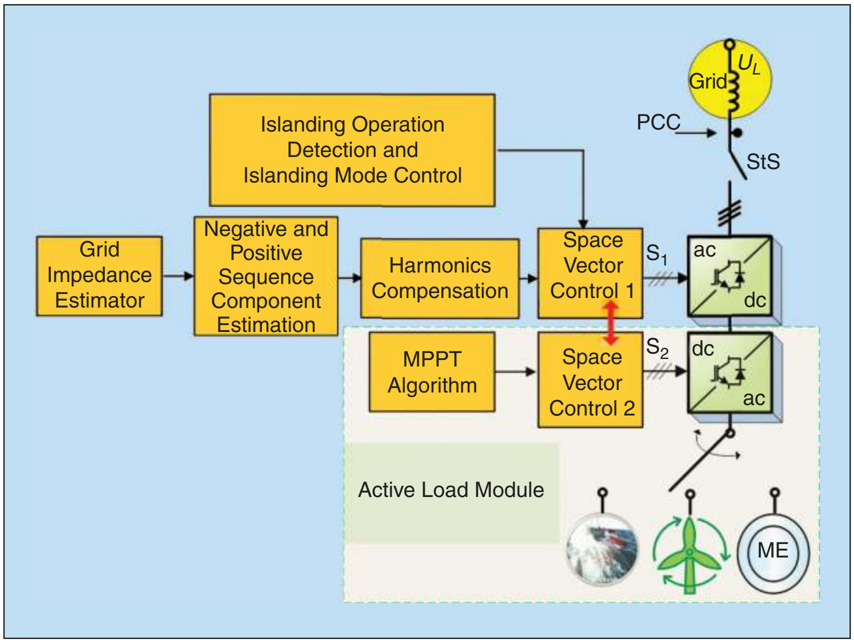


FIGURE 13 – Control accuracy impact on power quality produced by renewable energy.

synchronous machine (PMSM). In the latter case, the MSC can be constructed as a three-phase diode bridge with step-up chopper. This solution has some advantages; however, control quality is less. A comparison of the different machine types is shown in Table 1.

At the present stage, it can be concluded that a direct-driven SCIM with dedicated ac–dc–ac converter is the best solution. However, it would be advantageous to include one or two permanent magnet generators, as this type of machine does not need external excitation. This would facilitate a black start in case of grid loss, which is a desirable feature in an offshore application. This is because in offshore application a transformer between the grid and RESs should be designed as a set of smaller transformers connected in parallel.

The task is rather demanding, because the full-scale Wave Dragon energy converter will be 170-m long and 300-m wide (total design weight is 33,000 tons) [23]. Wave Dragon will collect overtopped water in a reservoir. Low-head Kaplan hydroturbines in the bottom will be the first link in the energy conversion chain. These turbines are developed by a team at Technische Universität München (TUM), which is lead by Wilfried Knapp, who is also the team leader of the Power Take Off (PTO) group in the project [21]. The turbines convert the hydraulic head in the reservoir into mechanical power. This power (mechanical torque and angular speed) is delivered to the shaft of the electrical machine. At this point, electrical power appears. The electrical machine operates as a generator. However, the produced electrical energy fluctuates as the wave energy fluctuates. In this stage, some effort for energy tuning is needed. This role is given to the ac–dc–ac power electronics converters; these devices convert wild electrical energy to controlled and standardized energy. International teams from the United Kingdom (Petar Igic and Zhongfu Zhou with team) and Poland (Marian P. Kazmierkowski, Mariusz Malinowski, and Marek Jasinski along with their team) are working in this field.

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The Grid Converter As a Universal Interface for Integrating Renewable Energy in the New Power System

Smart grids represent the most useful and efficient way of integrating renewable energy generation in the main grid. Power converters are the technology that enables efficient and flexible interconnection of different players (producers, energy storage, flexible transmission, and loads) to the electric power system (Figure 14).

TABLE 1–ELECTRICAL MACHINE TYPES COMPARISON.

LP	FEATURE	PMSM	SCIM/ GEARBOX	SCIM DIRECT DRIVEN
	Costs			
1	Investment	−1	1	1
2	O&M	nd	nd	nd
	Performances			
3	Efficiency	1	−1	1
4	Lifetime	1	−1	1
	Technical risk			
5	Direct drive (no gearbox)	1	−1	1
6	No overvoltage with runway speed	−1	1	1
7	Do not need magnetizing current	1	−1	−1
8	Lower height of system T/G/G	1	−1	1
9	Lower total weight	−1	1	−1
	Environmental considerations			
10	Oil or other critical liquids	1	−1	1
11	Noise	1	−1	1
12	Complete offer from one manufacturer (whole PTO system)	0	0	1
13	Ability to control more than one generator by one ac/dc converter	−1	1	1
14	Additional protection requirements	−1	0	1
	Summary:	2	−3	9

−1: not good; 0: neutral; 1: good; nd: no data.

Power electronics is needed not only to connect RESs, distributed power generation system (DPGS), and storage systems to the power system but also for loads, with regulation capability, and transmissions systems [high-voltage dc transmission (HVDC) and flexible ac transmission (HVAC)].

An in-depth analysis of the disturbances appearing in grid-connected systems helps in improving the MPPT efficiency.

In fact, power consumers may accept regulating the consumed power to contribute to the stability of the grid or to provide an indirect storage [e.g., charging systems for the batteries of hybrid electric vehicles (HEVs)]. Consumers may adapt their power even to accept operation in stand-alone mode when it is not possible to operate a controlled island, and emergency (e.g., in case of hospital) requires an uninterruptible power system (UPS) functionality.

Finally, since it is possible to foresee the operation of different grids at different power levels and based on different technologies such as dc or ac, single-phase or multiphase, the interconnection of these systems through flexible transmission systems such as HVDC and FACTS will allow the transfer of more power, preserving dynamic stability and with minor right of way (ROW) restriction with respect to traditional transmission systems. The possibility of these transmission systems to manage a bidirectional and controlled power flow and full control of reactive power relies on the use of bidirectional energy conversion structures adopting PWM technology and a proper control [24].

Hence, it is possible to foresee that how the synchronous machine that had a central role in the centralized power system (the grid converter also denoted as synchronous converter) will be a major player in the future power system based on smart-grid technologies. While the electromagnetic field has a major role in the synchronous machine, the grid converter is mainly based on semiconductor technology and signal processing, but its connection filter, where the inductor is dominant, still has a crucial role in shaping its frequency behavior. The PWM grid converter is equivalent to multiple synchronous machines; in fact, the grid converter can control the active and reactive power flow in a wide frequency range [25].

Particularly, if attention is paid to the power converter, the increase in power leads to the use of more voltage levels, leading to more complex structures based on single-cell converter (like NPC multilevel converters) or multicell converter (like CHB or interleaved converters) [26]. In the design and control of the grid converter, the challenges and opportunities are not only related to the need of using lower switching frequency to manage higher power level but also to the availability of more powerful computational device and more distributed intelligence (e.g., in the sensors and PWM drivers) [14], [27]. Some possible solutions to these challenges are in the use of nonlinear analysis and optimization with deterministic and stochastic techniques [28]. These can be applied both at device level to optimize the synchronization with the grid, the harmonic control and stability, and at the system level to detect and manage islanding conditions for low-power DPGS (Figure 15), ridethrough grid faults for high-power DPGS (Figure 16), which in turn contribute to the grid stability and power quality [29]–[32].

FC Systems

Among the five existing FC technologies, each type can be configured in a system focusing on the market segments that match its characteristics most favorably. Because of their quick start-up potential, low-temperature FCs [alkaline FCs and polymer electrolyte FCs (PEFCs)] are being considered

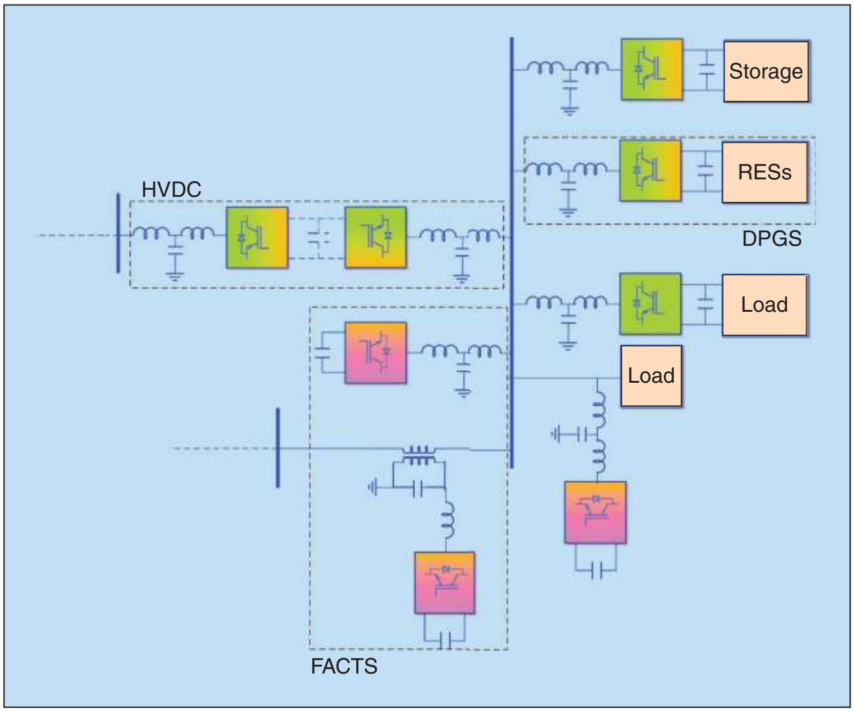

FIGURE 14 – Different roles of the grid converter used to interface: RESs, loads, storage systems, flexible ac transmission system devices (FACTS), high-voltage dc transmission (HVDC), and active filters. The green color denotes the exchange of active power, orange the exchange of reactive power, and violet the exchange of harmonics.

for portable, residential power and transportation applications. Higher temperature FCs [phosphoric acid FCs, molten carbonate FCs, and solid oxide FCs (SOFCs)] are often considered for stationary power generation. Nevertheless, because of their solid electrolyte, SOFCs are also considered for transportation applications by some car manufacturers or car suppliers.

If FC stacks are intrinsically able to respond quickly to the load changes, their balance of plant subsystems (hydrogen supply, air compressor, gas humidification, and coolant circuit) respond in times that are several orders of magnitude higher. This apparent contradiction diminishes the reliability and performance of the whole FC system. Figure 17 presents a general scheme of an FC system. As it can be seen, an FC stack needs a lot of ancillaries to operate. The fuel must first be produced or stored. Then, it is finally processed (mostly, in terms of pressure, hydration, and flow regulation) before entering the FC stack. The oxidant must also be processed in the same way. For both fuel and oxidant gases, the water produced by the FC stack can be removed from the exhaust gases to be reused in the hydration of incoming gases. Then, as the electrochemical reaction is exothermal and as the FC stack must be operated in a dedicated temperature range, thermal management is essential. Moreover, the gas supplying and the stack thermal management are strongly coupled with the gas hydration level control. Finally, electrical power conditioning (in association or not with an energy-storage device) and overall control of the whole system are other important subsystems [33].

Of course, considering the whole FC system, the gains in terms of both energy savings and pollutant emissions depend greatly on whether this whole FC system is well designed or not and on whether global optimization has been performed on this system or not. Accordingly, a great number of technological challenges has to be solved before efficient, competitive, reliable FC power generators can be actually seen on the market. Among them, electrical

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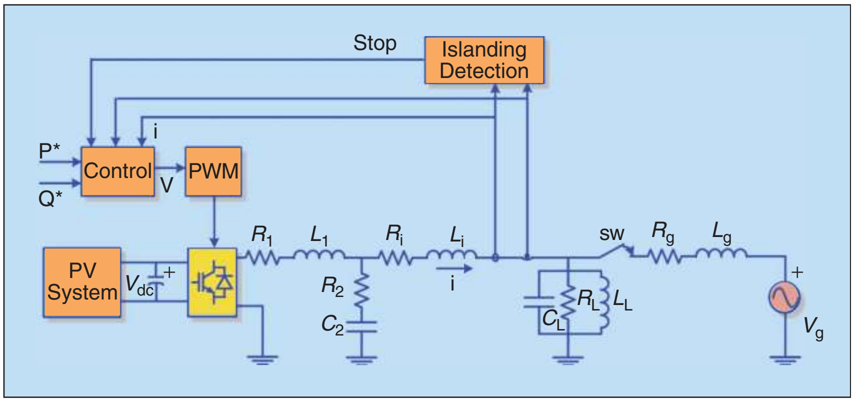

FIGURE 15 – Low-power DPGS antiislanding protection.

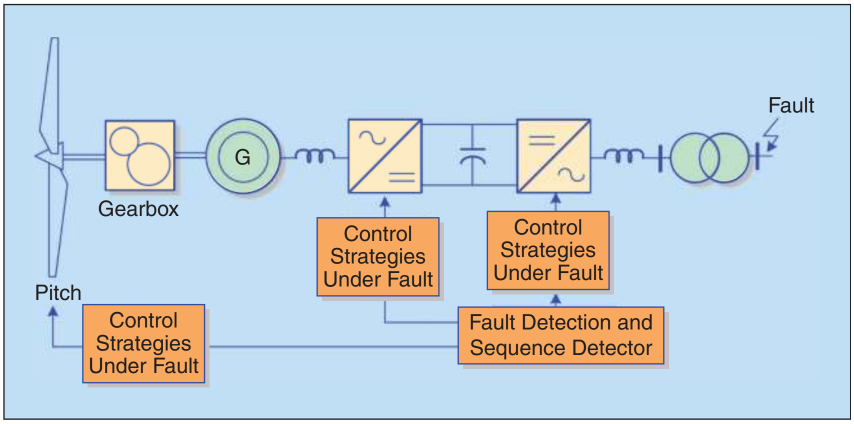

FIGURE 16 – High-power DPGS grid fault ride through.

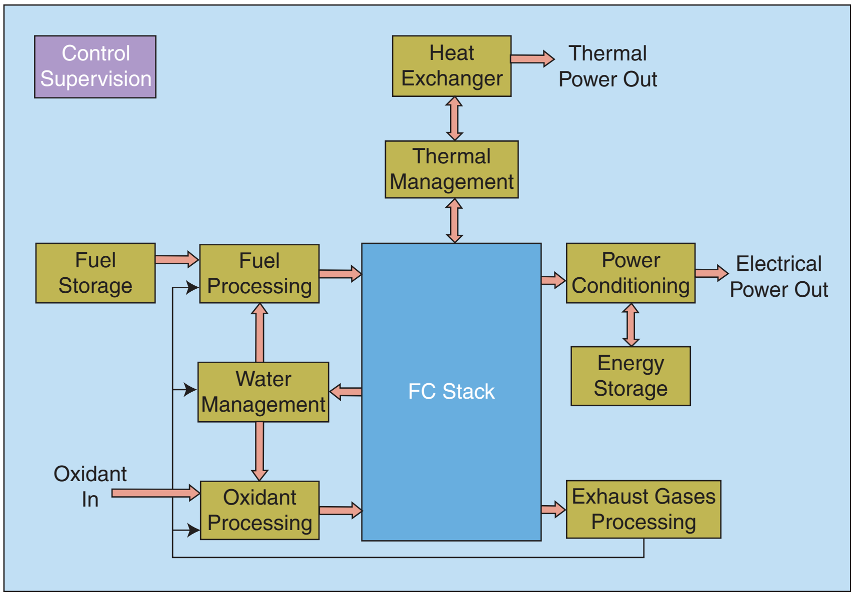

FIGURE 17 – An FC system scheme.

engineering relating technological challenges are of greatest importance.

- Modeling challenges have to be overcome. The difficulty is here to propose an efficient, easy-to-tune, real-time suitable model of the whole FC system. Many solutions have already been proposed: analytical models, gray and black-box models [34].
- New power conversion solutions have to be proposed for those high-current, low-voltage power devices. The coupling (and the relating optimization) of the FC stack with electrical energy-storage devices (e.g., supercapacitors and batteries of flywheels) has to be investigated to propose new high-efficient hybridized power architectures.

The durability must be increased, and new online diagnostic tools can be proposed (Figure 18), based directly on the power converter [35]. Those tools are used to modify (in real time) the control laws on an FC system to improve the lifetime of an FC stack.

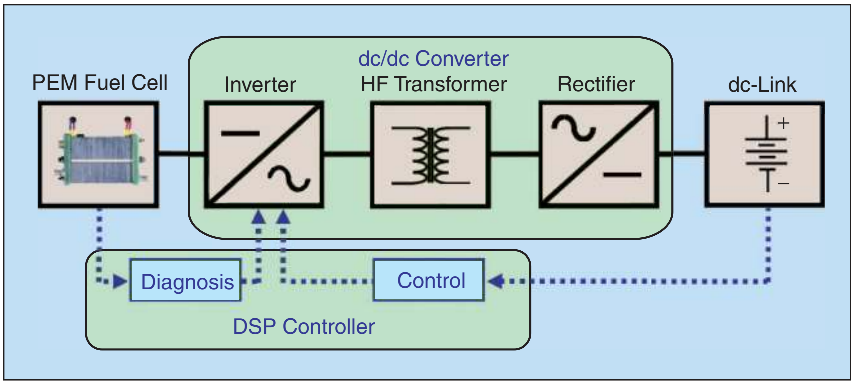

FIGURE 18 – Online diagnosis of the FC stack based on the electrical power converter.

Conclusions

In this article, a short summary of some speeches given during SERENE has been given. The contributions have been mainly focused on power electronics for PV and sea wave energies, pointing out some aspects related to efficiency, reliability, and grid integration. Finally, main issues concerning FC systems as generators based on hydrogen as a low environmental impact energy vector have been discussed.

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