# Wide-Scale Adoption of Photovoltaic Energy

*Grid Code Modifications Are Explored in the Distribution Grid*

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# Suggested Grid Code Modifications to Ensure Wide-Scale Adoption of Photovoltaic Energy in Distributed Power Generation Systems

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***Abstract*— Current grid standards seem to largely require low power (e.g. several kilowatts) single-phase photovoltaic (PV) systems to operate at unity power factor with maximum power point tracking, and disconnect from the grid under grid faults by means of islanding detection. However, in case of a wide-scale penetration of single-phase PV systems in the distributed grid, the disconnection under grid faults can contribute to: a) voltage flickers, b) power outages, and c) system instability. In this paper, grid code modifications are explored for wide-scale adoption of PV systems in the distribution grid. More recently, Italy and Japan, have undertaken a major review of standards for PV power conversion systems connected to low voltage networks. In view of this, the importance of low voltage ride-through for single-phase PV power systems under grid faults along with reactive power injection is studied in this paper. Three reactive power injection strategies are discussed in detail. Simulations are presented for a PV power system with low voltage ride-through capability and ancillary services. An example of a full-bridge single-phase grid-connected system is tested experimentally to demonstrate the potential benefits. Moreover, a summary of the grid codes for advanced PV systems with the discussed features is presented.**

***Index Terms*—Grid requirements; photovoltaic systems; low voltage ride through; ancillary services; grid support; reliability**

## I. Introduction

Due to the declining photovoltaic (PV) module price and the strong feed-in tariff policies for grid-connected PV power systems in different countries, the global cumulative PV capacity hit a new record by the end of 2012, now being more than 100 GW, which is shown in Fig. 1 [1]-[6]. This strong market is mainly shared by the European countries, such as Germany, Spain and Italy, in contrast to other countries like China, Japan and the United States. However, recent reports show that those countries have set ambitious goals for the next few decades to accept high penetrated PV systems as a part of the renewable energy systems [2]. Even Denmark, which has limited sunshine in the winter, is accelerating the pace of PV installations and reshaping the future renewable energy structure. Moreover, Japan has set a national goal of 60 GW of PV capacity by 2030, and the total installed PV capacity in U.S. reached 3.3 GW in 2012 with California being the leading state in PV development and installation [4]-[6]. Thus, there are increasing worldwide expectations for energy production by means of renewable energy resources, such as solar (PV) energy and wind power systems. However, the high penetration level of PV systems also imposes new challenges for the Distributed System Operators (DSO) and the end-consumers, leading to the discussion of appropriate adoption of PV power systems and modifications of current active grid standards.

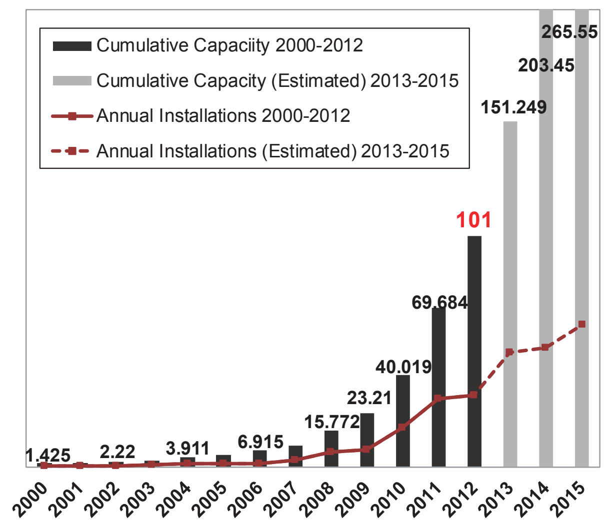

Fig. 1. Evolution of global accumulative photovoltaic capacity (GW) from 2000 to 2015 (data source: www.epia.org).

Currently published PV grid requirements are designed to guide the PV integration with distributed grids based on a low penetration level of PV systems. In fact, the PV market has been dominated by residential applications with low rated power [7], [8]. For example, in Germany, nearly 70% of all PV installations are connected to the low voltage grid [9]. In this case, those guidelines defined in the grid codes are valid for such applications and include some basic demands for PV systems [10], [11]. For instance, in the IEEE Std 929-2000, the Total Harmonic Distortion (THD) for the injected grid current

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should be lower than 5% in normal operation mode to avoid adverse effects on other equipment connected to the grid [10]. Moreover, the boundaries of the grid voltage and frequency are also specified. In response to the abnormal grid conditions, the PV systems are currently in those grid requirements required to disconnect from the distributed grid for safety concern [12]-[27], which is also known as the islanding protection.

However, the impacts of the disconnection from the distributed grid recently gained increased attention from the DSOs and the PV inverter manufacturers, especially when a very high penetration of PV power conversion systems is coming into reality. In light of this thriving situation, a typical anti-islanding disconnection may impose severe challenges for the whole power system, especially for the end-consumers' equipment. For instance, an anti-islanding operation that results in the disconnection of PV systems may cause voltage flickers, low voltage and power quality problems for the customers, leading to the loss of customers' money and the necessity to limit the PV integration for DSOs [12], [27], [31].

Thus, it is necessary to rethink the appropriation of the current active grid codes in respect to the operation modes under grid faults. Further, if the PV power conversion systems can provide ancillary services, such as reactive power support and Low Voltage Ride-Through (LVRT) capability, it can contribute to increased system stability [12], [13], [27], [30]-[50]. The resulting system can be devoid of voltage flickers and power quality issues. In the presence of many "actively" controlled multi-functional PV power conversion systems, there is no need for a DSO to limit the PV integration into the grid. Furthermore, by a thermally optimized operation, improvements of the overall system reliability can be achieved, as reported in recent studies [12], [51]-[60]. Therefore, the next generation PV systems are expected to be multi-functional with LVRT capability and the provision of reactive power in different operation modes.

In view of the above, it is inevitable for the international standard committees or national organizations to explore new grid codes or to modify the present active grid standards. Based on this discussion, the aim of this paper is to provide an overview of the current grid requirements, especially for low voltage PV applications in § II, followed by focuses on the grid code modification recommendations for the next generation multi-functional PV systems. A summary of the grid codes for advanced PV systems including the modification and implementation considerations is given after the discussion. Further, in § IV, operational examples are presented to demonstrate the potential benefits of PV power conversion systems with LVRT and reactive power injection capability. Simulations are presented for a PV power conversion system with LVRT capability and ancillary services. An example of a full-bridge single-phase grid-connected system is tested experimentally to demonstrate the potential benefits.

## II. Evolution of PV Grid Codes

The grid-integration requirements are the essential guidelines for the design, control and operation of grid-connected renewable energy systems, including single-phase PV systems. Based on a low penetration level of PV systems, the grid standards initially addressed elementary demands for

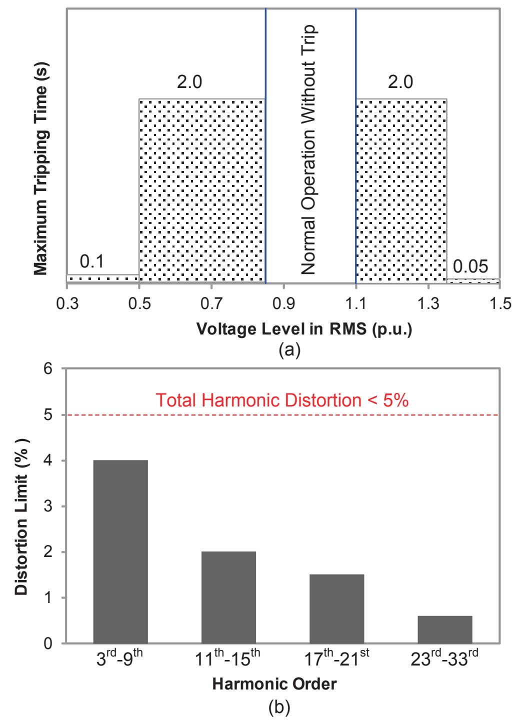



Fig. 2. Basic grid requirements: (a) response to abnormal grid voltage conditions and (b) current harmonics requirements defined in IEC 61727 for PV power systems with rated power lower than 10 kW considering low penetration level [11].

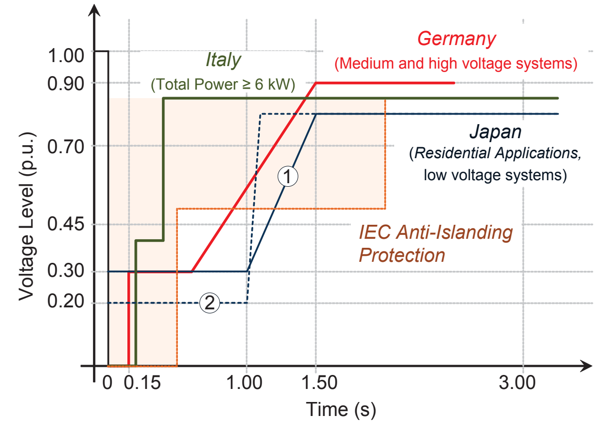
such systems. For example, most of the grid-connected PV systems should cease to energize the local loads in the case of grid transient disturbances, e.g. voltage sags [9]-[11]. In normal operation, the PV systems are required to produce as much energy as possible with satisfactory injected grid currents, which is shown in Fig. 2 - an example of IEC 61727. Those grid requirements, including anti-islanding protection, are introduced to ensure the safety of utility maintenance personnel, to protect the equipment, and also to guarantee the utility stability [27].

As previously illustrated, PV systems are dominantly connected to low-voltage and/or medium-voltage networks [7], [8], which is different from conventional power plants or large wind power farms. In the low penetration level scenario, the current active grid requirements could be valid. The influence of electricity generation from PV systems on the electrical systems has been proven negligible.

Nevertheless, in a high penetration level scenario, grid-connected PV systems will impose new challenges to the distributed electrical network. The impact lies in two aspects: one is due to the intermittent nature of PV sources [31] and the other is due to the disconnection of PV systems from the distributed grid in response to abnormal grid conditions. Therefore, it may induce the instability of the entire electrical network, leading to a blackout and a power grid failure, and thus could cause severe consequences in the customer loads. To overcome the above issues, the present grid requirements are expected to be upgraded with combined standardized features and custom demands. Several previous studies have demonstrated the potential of PV systems to play an active role in the regulation of distributed grids as what conventional power plants do today [12], [17]-[27], [30]-[32]. Moreover, PV systems can provide ancillary services to effectively mitigate the challenges related to intermittency [31].

Today, several countries have already modified their grid codes for medium- or high-voltage renewable energy systems, and a few countries have also published similar requirements for low-voltage applications. For instance, the German grid code requires that the systems connected to the medium- or high-voltage networks should be capable of riding through voltage sag and at the same time to provide reactive current to the faulted grid [28]. In the new Italian grid code, it is required that the generation units serving low-voltage grid with the nominal power exceeding 6 kW should have the ability to ride through grid voltage faults, regardless of single-phase configuration or multi-phase systems [29]. Recently, a study done in Japan presented the LVRT requirements on PV systems connected to single-phase low-voltage grids [30], [33]-[35]. Obviously, the challenges from high penetration PV systems are being forecasted. Thus, the DSOs have given priority to finding a solution in order to guarantee reliable and stable operation of distributed power systems. Hence, current active grid requirements need to be modified.

One major modification of grid standards is to allow the PV power conversion systems to inject reactive power. This is similar to the current active grid codes for wind turbine power generation systems connected to the medium- and high-voltage levels. In the modified grid codes, the single-phase multi-functional PV systems serving low-voltage networks (feeders) in the future should make a contribution to the network by means of riding through grid faults and injecting reactive power under voltage sags. The LVRT and grid support requirements for future multi-functional PV systems can be summarized as shown in Fig. 3 and Fig. 4. When the grid voltage level is higher than the specified ones defined in Fig. 3, the PV systems should maintain connected to the distributed grid and inject reactive power to support the grid during LVRT. Additionally, some of the basic requirements (e.g. power quality) are likely to be more stringent in the future, since the multi-functional PV systems are able to provide ancillary services – voltage flickers mitigation, harmonics suppression and reactive power compensation.




Notes:
1. The German low voltage ride through requirement is defined for medium- and/or high-voltage applications [28];
2. The PV systems with total power exceeding 6 kW should have low voltage ride through capability in Italy [29];
3. The Japanese low voltage ride-through requirements are proposed in [30]: ① before 2016 and ② after 2016;
4. The PV systems must trip in the shaded area to avoid islanding mode according to IEC standard [11].

Fig. 3. Low voltage ride-through requirements in different counties and the anti-islanding requirement for small PV units defined by IEC.

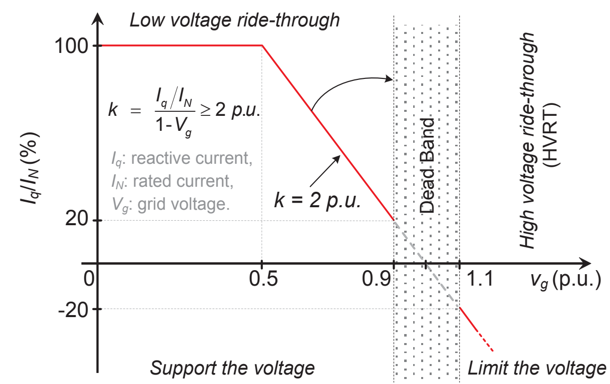



Fig. 4. Reactive current injection requirements for medium- and/or high-voltage systems defined in E.ON grid code [28].

## III. Suggestions on PV Grid Codes Modifications

The tendency for the next generation multi-functional PV systems discussed in § I and § II features with LVRT capability, grid support functionality and intelligent ancillary services. In order to fulfill those advanced features for future high penetration scenario, the existing active PV grid standards need to be reexamined and updated accordingly based on the following main considerations [12], [14]:

- Reactive power control (voltage support);
- Frequency control through active power control;
- Dynamic grid support capability; and
- High efficiency and high reliability.

### A. Reactive Power Control (Voltage Support)

Voltage rise on distributed feeders has been observed as one of the major issues brought with highly PV-penetrated systems due to the reverse power flow towards upstream voltage levels [4], [4], [9], [17]-[20], and the power difference between PV systems and load demands. One possibility to solve this is to directly reduce the PV output power when the distributed grid line voltage hits the upper limitation, e.g. 1.06 p.u. (107 V) in Japan and 1.03 p.u. in Germany [14]. It implies that the PV systems should be capable to operate with a controllable active power generation, and thus may including a remote control function in the future grid codes. This further requires enhanced monitoring and communication.

Another solution is to allow the PV system to inject reactive power into the distributed grid. Since PV systems are usually designed with reasonable margins and are operated under partial loading conditions, there is a room for reactive power injection to keep the voltage at a desirable level. However, the amount of the reactive power that a PV inverter can deliver to the grid depends on the inverter apparent power (rated current value, $I_{rated}$), which is illustrated in Fig. 5. In normal operation mode with Maximum Power Point Tracking (MPPT), the maximum output reactive power of a single-phase PV inverter is calculated as:

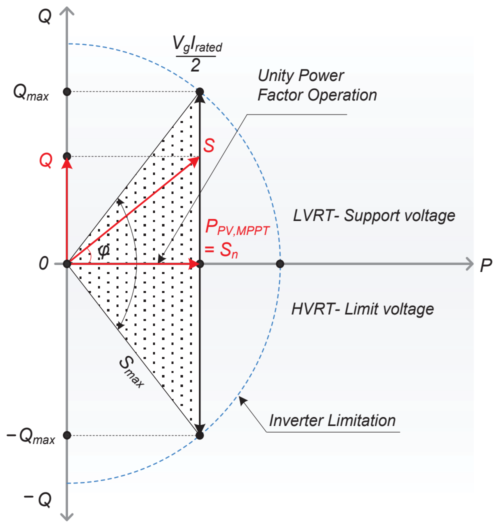



Fig. 5. *PQ*-diagram for a single-phase PV inverter.

$$Q_{\max} = \sqrt{S_{\max}^2 - P_{PV,MPPT}^2}\,. \tag{1}$$

in which $Q_{\max}$ is the maximum output reactive power, $S_{\max}$ is the maximum apparent power for the inverter and $P_{PV,MPPT}$ is the maximum active power with MPPT control.

It should be noted that the injection of reactive power to the grid induces a redistribution of the power losses, thus, the thermal stresses, among components in a PV inverter. Therefore, the impact of the injected reactive power on reliability performance of the PV inverter should also be taken into account, allowing an optimal selection of the reactive power level [58].

As a matter of fact, there have been some grid requirements for a very high penetration level of PV systems to activate reactive power control in order to support the grid [9], [14], [17]-[21]. For example, all PV systems in Germany connected to either low- or medium-voltage grids are required to be able to provide reactive power [14], but at the same time, the minimum power factor should be satisfied. With this power factor constraint, several reactive power control approaches are available for highly integrated PV systems, such as fixed *cosφ*, fixed *Q* and *Q* (*U*) droop function methods [14], [19], [62]. In the future, similar requirements are expected to be enhanced and imposed on low voltage PV systems in order to host more PV capacity, since they are able to participate in the reactive power management [63], [64]. As for single-phase low power PV systems, being the typical configurations, the voltage support by controlling reactive power can be achieved at the substation side or integrated in advanced PV inverters. Those possibilities require more investigations from an operational and economical point of view. Thus, more intelligent and advanced control strategies have to be developed and implemented, and then integrated in the grid codes.

## B. Frequency Control through Active Power Control

Recent studies show that the disconnection due to unintentional islanding protection might introduce instability problems, e.g. power outage, when the penetration level is very

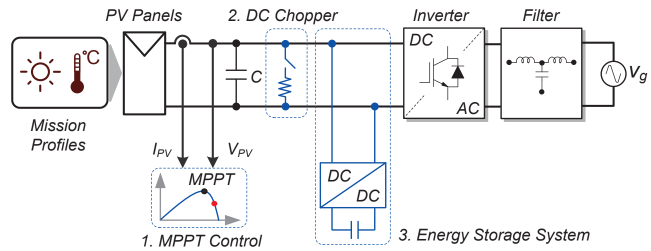



Fig. 6. Possible hardware solutions for single-phase grid-connected PV systems with low voltage ride-through capability: 1. modify MPPT, 2. use DC chopper, and 3. use energy storage systems.

high [9], [17], [21]-[26]. Hence, the suggested modifications of PV grid standards should require next-generation PV systems to provide frequency control functionality in order to ensure the grid stability. The frequency control can be realized by reducing the active power output as it has already been defined in the German grid codes. It is stated that the reduction of active power has to be activated with a gradient of 40 % generated active power *P* per Hz, when the grid frequency is within a range (50.2 Hz to 51.5 Hz) [17], [21].

Meanwhile, due to the intermittent nature of PV sources, the output power of a PV system is significantly dependent on the environmental conditions, and will fluctuate when it is fed into the grid. Consequently, a large amount of fluctuated power will contribute to frequency variations or even instability of the power grid. As the capacity of a single PV system is continuously growing, and thus the penetration level, the frequency fluctuation owing to intermittency will become even serious. Therefore, it calls for enhanced frequency control requirement integrated in the modified grid codes for future PV system in order to enable a more wide-scale adoption of PV power.

## C. Dynamic Grid Support

The dynamic grid support capability for the next generation PV systems is mainly focused on LVRT and reactive current injection under voltage faults [13], [27]-[30], according to the requirements in Fig. 3 and Fig. 4. The objectives of dynamic grid support are: a) to prevent the inverter from over-current shutdown and b) to support the grid voltage during recovery. Unlike three-phase wind turbine systems, the low voltage PV systems serving single-phase lines have much lower physical inertia as the energy storage is currently limited. However, without dispatching the active power (to reduce active power generation), the power devices might be overheated due to increased currents when the system goes into LVRT operation. To avoid this, the power should be dispatched by: a) modifying the MPPT control, b) activating the DC chopper to absorb power and c) managing power exchange between PV systems and the energy storage systems, which are illustrated in Fig. 6.

The transient performance of single-phase PV systems during LVRT is affected by the grid fault detection (i.e. the monitoring system), the synchronization and the control system. A fast fault detection can improve the LVRT performance. By modifying the MPPT, the PV output power can be reduced; while by adding a DC chopper at the DC-side, during the voltage sag, the additional active power is dispatched on the resistor, which allows injecting the required reactive power without tripping the inverter over-current protection. Both methods lead to the loss of energy production. Actually, the lost energy can be absorbed by an energy storage system, but it increases the control complexity with additional devices, and thus the cost. Nevertheless, three alternatives can be adopted to enhance the LVRT capability for single-phase PV systems seen from a hardware point of view.

In respect to reactive power injection during LVRT, there are four major control solutions available for three-phase systems: a) unity power factor control, b) positive sequence control strategy, c) constant active power control strategy and d) constant reactive power control strategy [15], [16]. For single-phase PV systems, the possible strategies for reactive power injection are as follows [42]:

1) *Constant I (Peak Current) Strategy*

For this control strategy, the injected grid current level ($I_{gmax}$) is kept constant (e.g., $I_{gmax}=I_N$, rated current) under grid faults. The injected reactive current is calculated according to Fig. 4. This control method can prevent the inverter from over-current shutdown.

2) *Constant Active Current Strategy*

Another control possibility during LVRT is to keep the active current constant (e.g. $I_d=I_N$). The injected reactive current ($I_q$) is proportional to the voltage sag depth as it is shown in Fig. 4. Thus, the amplitude of the injected current may exceed the inverter limitation ($I_{max}$) under this control strategy. In order to avoid inverter shutdown due to over-current, the following condition should be fulfilled,

$$I_d^2 + I_q^2 \leq I_{\max}^2 . \quad (2)$$

For example, when $I_d = I_N$, $k = 2$ p.u., the maximum inverter current $I_{max} \geq 1.41\ I_N$. Considering a large $I_{max}$, the overload capability and the cost of the PV inverter will increase.

3) *Constant Active Power Strategy*

In order to deliver the maximum active power to the grid during voltage faults, the active power can be kept constant but also at the risk of over-current protection. The inverter current limitation should be considered during the design of the PV inverters.

The injected grid current under grid faults using the above control strategies can be plotted as shown in Fig. 7. As a result, by using one of the reactive power injection strategies, the PV systems can fulfill the requirements, which should be modified based on the above concerns.

On the other hand, integrating the LVRT function into the next-generation PV inverters covering a wide application range is a key way to further increase the PV hosting capacity [13], [14], [46], [49]. Hence, it is recommended that the grid codes should focus more on the LVRT capability for PV systems in order to enhance the system stability during grid faults. Such requirements have been in effectiveness in some countries, e.g. Italy. It is going to be further extended to other PV systems, even PV modules as it has been discussed in [13]. However, the implementation of LVRT is against anti-islanding requirements, e.g. IEEE Std 1547. Hence, it is suggested that the anti-islanding requirement should be extended in order to incorporate the fault ride-through capability, as it is demonstrated in Fig. 8.

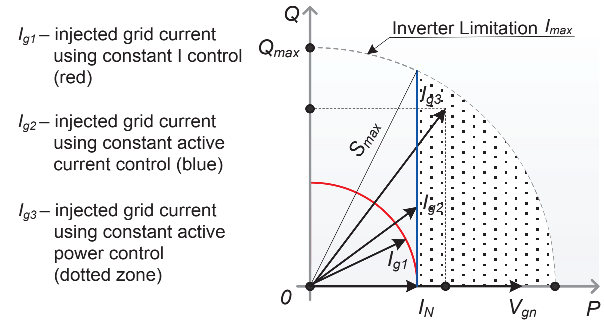


Fig. 7. Representations of the injected grid current using different control strategies considering the inverter current limitation.

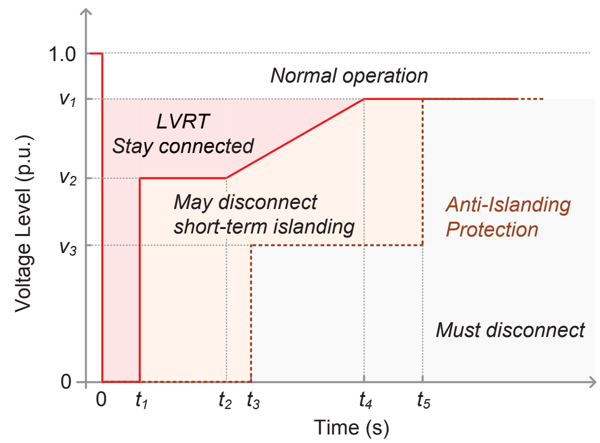


Fig. 8. Compatible implementation of low voltage (and zero voltage) ride-through and anti-islanding requirements for PV systems.

## D. *High Efficiency and High Reliability*

Achieving high efficiency and high reliability is always of intense interest in order to reduce the cost of energy and extend service time. The transformerless PV inverters with high efficiency have gained much popularity in Europe. However, the removal of the transformer also introduces side effects, such as lack of galvanic isolation and the abilities of fault ride-through and reactive power injection [42].

By adding extra power devices either at the DC side (PV panel side) or at the AC side, the isolation problems can be solved. However, this may impose new challenges for the reliability of the whole PV system in different operation modes. Possible solutions to increase the reliability can be done by means of proper component selection (considering rated power, advanced packaging technologies, the most stressed situations, the severe users), effective thermal management, robustness design and validation [51], [55]-[59], [61]. Moreover, a better knowledge of the operating conditions, e.g. temperature, irradiance, and humidity, can contribute to better design and operation of the entire PV system. Thus, these

Table I

SUMMARY OF GRID CODES FOR ADVANCED PV SYSTEMS CONNECTED TO LOW VOLTAGE GRID AT A HIGH PENETRATION LEVEL.
LEGEND: × -- NO SUCH ABILITY/REQUIREMENT, ✓ -- WITH THE ABILITY, MORE MEANS HIGHER REQUIREMENT.

| Grid-Integration Features | Conventional PV Systems (medium- / low- voltage) | Next-Gen. PV Systems at a High Penetration Level | Remarks (grid code revision considerations) |
|---|---|---|---|
| **Active Power Control (Power regulation, set-point by DSOs)** | ✓✓ / ✓ | ✓✓ | Remote set-point for power regulation should be extended to low voltage systems. Even more stringent, e.g. constant power production (e.g. 80% of rated power) and power ramp limit. |
| **Reactive Power Control (Volt-VAR control, Power Factor- PF adjustment)** | ✓✓ / ✓ | ✓✓ | Settings by DSOs are dependent on the power capacity of the PV systems. More reactive power provision strategies, e.g., constant PF. |
| **Frequency Control (Freq.-Watt control)** | ✓✓ / ✓ | ✓✓ | Frequency support through active power droop control (e.g. 40% power reduction) is active in some countries. Focuses should be paid to solve intermittency issue. |
| **Dynamic Grid Support (Fault ride-through functionality)** | ✓✓ / × | ✓✓ | PV systems have the ability to support the grid dynamically associated with reactive power injection. This should be enhanced for a wide application range to secure power supply. Zero-voltage ride-through and recurring fault ride-through capabilities are also emerging features for PV systems. |
| **Anti-Islanding Protection** | ✓✓ | ✓ | Should be compatible with fault ride-through. |
| **Energy Storage Enhancement** | ✓ / × | ✓ | More decentralized grid requires an enhancement of energy reserve, which can be performed by PV systems. It is also a way to produce power more locally. |
| **Monitoring and Communication** | ✓ | ✓✓✓ | Have to be even strengthened in order to realize the above features. |
| **Efficiency and Reliability** | ✓ | ✓✓ | Adoption of advanced power devices. Reliability should also be improved to reduce the downtime and thus cost of energy. Fault-tolerant capability is suggested. |

aspects should be taken into consideration in the design process and also during the field operation phase.

Besides, next-generation PV systems should be flexibly and appropriately integrated with other systems, e.g. electrical vehicle systems, energy storage systems, smart grids and micro-grid systems. Proper deployment of those systems into PV systems has brought significant benefits to the grid [18], [22]-[25], [65], [66]. They also have to be able to switch into short-term islanding operation mode smoothly in order to secure power supply, as it is shown in Fig. 8, and reconnect after fault clearance, which means that the compatibility of islanding detection and LVRT is also important for such systems. By doing so, the future PV systems can provide reactive power compensation and harmonic suppression through intelligent power electronics systems and also more advanced control methods [67]-[75]. Thus, the current active PV grid standards are suggested to be modified according to the above features, which are summarized in Table I.

## IV. OPERATION EXAMPLES IN COMPLIANCE WITH MODIFIED GRID REQUIREMENTS

In this section, a single-phase grid-connected PV system with LVRT capability is examined in compliance with the suggested modifications of grid standards for the next generation PV systems at a high penetration level. Fig. 9 shows the topology and control structure of the single-phase PV system. A voltage sag could be simulated by using a sag generator formed by the switching resistors, $R_S$ and $R_L$. In order to test the effect of operation modes on the reliability of the PV system, the power losses and the thermal cycling on the power devices of a 3 kW single-phase system are investigated firstly. The ambient temperature is set as 50 °C and the reactive power injection is based on single-phase $PQ$ theory [27], [58]. The proportional integrator current controller with harmonic compensators is used to guarantee a good power quality of the injected current according to the grid requirements defined in [10] and [11]. The results are shown in Fig. 10 and Fig. 11.

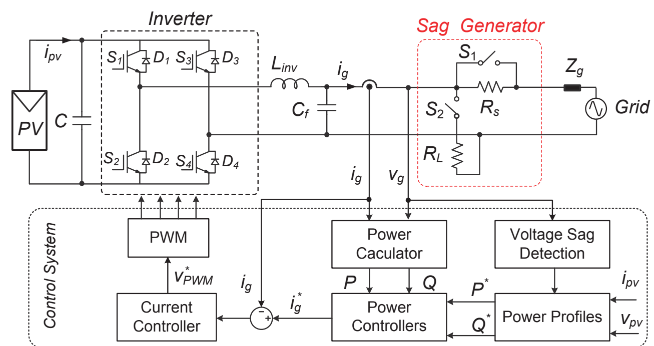


Fig. 9. Hardware schematic and control diagram of a single-phase full-bridge PV system with low voltage ride through capability.

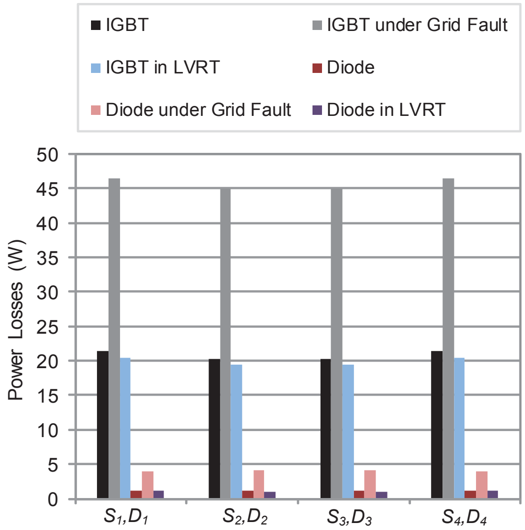


Fig. 10. Power loss distribution of the 3 kW single-phase full-bridge PV inverter shown in **Error! Reference source not found.** in different operational modes: *S* - IGBT, *D* - Diode, 0.45 p.u. voltage sag.

As shown in Fig. 10, the power losses on the switching devices of a single-phase PV system are significantly reduced in LVRT operation mode, which results in a lower mean junction temperature as proved in Fig. 11. Moreover, the temperature cycling amplitude is also reduced to 10 °C from 24 °C by means of thermally optimized operation (LVRT operation with reactive current injection). Thus, with thermally optimized control (LVRT control), the overall reliability of the PV system is improved.

To demonstrate the ability of reactive power injection under grid faults for the next generation PV systems, a 1 kW grid-connected system has been examined in the laboratory based on single-phase *PQ* theory [27], [41], [58]. The proportional and integrator controller with harmonic compensators is adopted to achieve high power quality of the injected current. The test results are shown in Fig. 12.

During the LVRT operation, the single-phase system is injecting reactive power into the distributed grid according to requirements defined in Fig. 4. At the same time, the active power is limited below the current limitation of the PV inverter, which is shown in Fig. 12, in order to prevent inverter shutdown from over-current (over-heat) protection. When the voltage fault is cleared (the voltage amplitude goes to 90% of the nominal value), the system returns to its normal operation mode and it is injecting satisfactory current at unity power factor. The experiments demonstrate the flexibility of a single-phase system to provide multi-functions in the future. The single-phase *PQ* power control method in the test is effective in terms of a fast dynamic response.

## V. Conclusions

In this paper, several suggested grid code modifications to ensure a more wide-scale adoption of photovoltaic energy in distributed power generation systems have been presented. The modifications should be carried out in the future with the following considerations in order to increase PV hosting capacity and also to reduce the cost of energy:

(1) Future PV grid standards should allow low-voltage PV systems to be equipped with LVRT capability and reactive power injection under grid faults.
(2) Suggested PV grid codes should enable the reactive power control (to support voltage) and frequency control of next-generation multi-functional PV power systems connected to low voltage grids.
(3) Both LVRT and reactive power injection modifications should be done with the purpose of keeping high system efficiency and reliability.
(4) Modifications of both LVRT requirement and the islanding protection should be carried out to make them compatible with each other for the next generation PV systems.
(5) Requirements on monitoring, communication and energy storage systems should also be strengthened in order to achieve advanced functions.

With reference to LVRT control under grid faults, three control strategies for reactive power injection have been proposed and discussed: a) constant *I* strategy, b) constant active current strategy, and c) constant active power control strategy. Design concerns of the next generation PV inverters have been explored as well. Regarding reactive power control to support the grid voltage, it can be implemented either at the distribution transformer side by changing the tap setting or integrated in the PV inverters with advanced control strategies. Those should be further investigated from an economical point of view, and then appropriate solutions can be included in future grid standards.

In summary, it has been shown that the next generation PV systems should incorporate advanced functionalities to achieve high penetration in distribution grids. To achieve this goal, the current active grid standards have to be modified.

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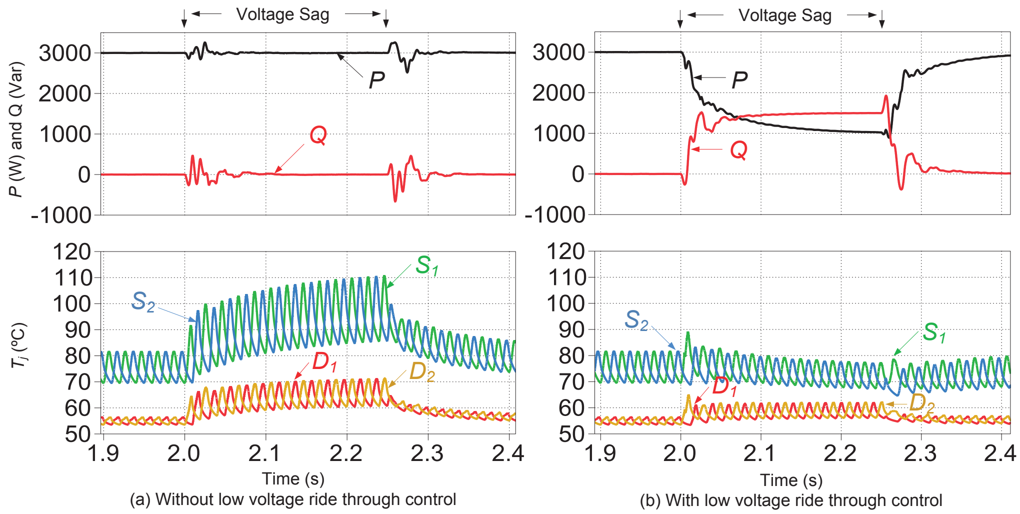


Fig. 11. Simulation results of a 3 kW single-phase full-bridge PV inverter with/without low voltage ride through control (constant *I* control strategy): *P*: injected active power to the grid, *Q*: injected reactive power to the grid, $T_j$: junction temperature, *S* - IGBT, *D* - diode, voltage sag depth: 0.45 p.u..

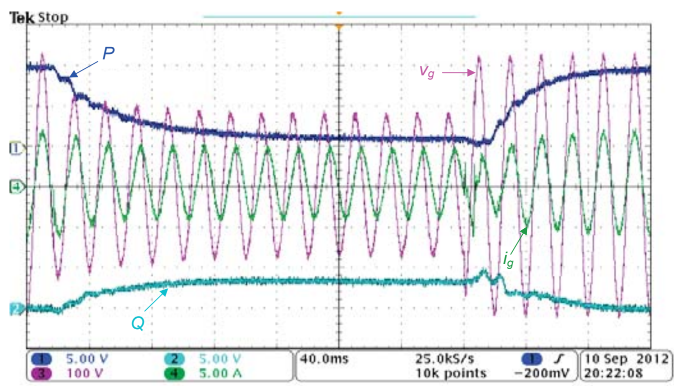


Fig. 12. Experimental results of a 1 kW single-phase grid-connected system in low voltage ride through operation modes: grid voltage $v_g$ [100 V/div]; grid current $i_g$ [5 A/div]; active power *P* [500 W/div]; reactive power *Q* [500 Var/div]; time [40 ms/div].


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