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Current grid standards largely require that low-power (e.g., several kilowatts) single-phase photovoltaic (PV) systems operate at unity power factor (PF) with maximum power point tracking (MPPT), and disconnect from the grid under grid faults by means of islanding detection. However, in the case of wide-scale penetration of single-phase PV systems

WIDE-SCALE ADOPTION OF PHOTOVOLTAIC ENERGY

Grid code modifications are explored in the distribution grid

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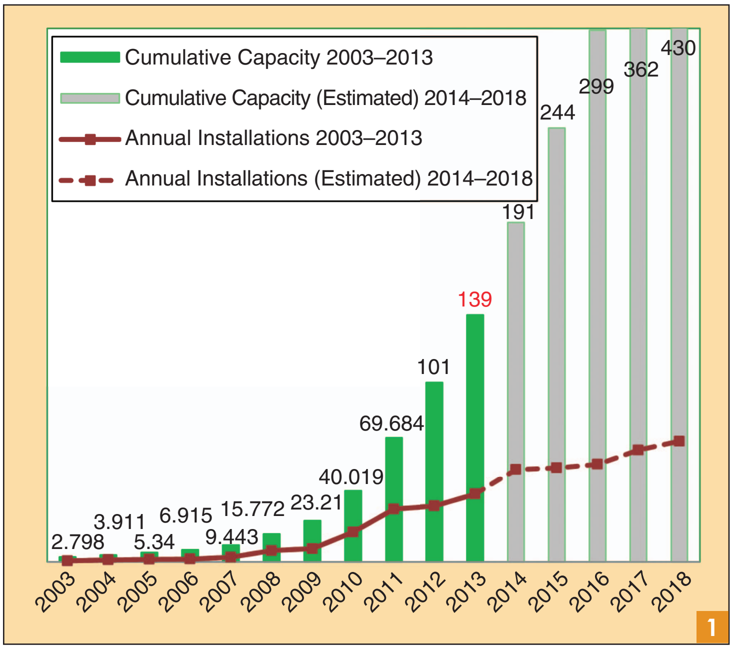
in the distributed grid, disconnection under grid faults can contribute to 1) voltage flickers, 2) power outages, and 3) system instability. This article explores grid code modifications for a wide-scale adoption of PV systems in the distribution grid. In addition, based on the fact that Italy and Japan have recently undertaken a major review of standards for PV power conversion systems connected to low-voltage networks, the importance of low voltage ride-through (LVRT) for single-phase PV power systems under grid faults is considered, along with three reactive power injection strategies. Simulations are presented for a PV power system with a LVRT capability and ancillary services. An example of a full-bridge single-phase grid-connected system is tested experimentally to demonstrate the potential benefits. Additionally, grid codes for advanced PV systems with the discussed features are summarized.

Growing Market for PV Power

Due to declining PV module prices and strong feed-in tariff policies for grid-connected PV power systems in many countries, global cumulative PV capacity hit a new record at the end of 2012 and is now more than 100 GW, as shown in Figure 1 [1]–[6]. This strong market is mainly seen in European countries, such as Germany, Spain, and Italy, and less so in Asian nations like China and Japan and in the United States. However, recent reports show that countries are increasingly setting ambitious goals for the next few decades to accept high-penetrated PV systems as a part of renewable energy systems [2]. Japan has set a national goal of 60 GW of PV capacity by 2030, and the total installed PV capacity in the United States reached 3.3 GW in 2012 with California being the leading state in PV development and installation [4]–[6]. Even Denmark, which has limited sunshine in the winter, is accelerating the pace of PV installations and reshaping future renewable energy structures.



An evolution of global accumulative PV capacity (in gigawatts) from 2003 to 2018 (data source: www.epia.org).

Worldwide expectations for energy production by means of renewable energy resources, such as solar PV energy and wind power systems, are increasing. However, the high penetration level of PV systems poses new challenges for distributed system operators (DSOs) and consumers and will require consideration of how best to adopt PV power systems and modify current active grid standards.

Current Grid Requirements

Current PV grid requirements are designed to guide PV integration with distributed grids based on a low penetration of PV systems. And it is true that, up until recently, 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 a low-voltage grid [9]. In such cases, guidelines defined in existing grid codes are valid for such applications and include some basic demands for PV systems [10], [11]. For instance, in IEEE Standard 929-2000, the total harmonic distortion for the injected grid current should be lower than 5% in a normal operation mode to avoid adverse effects on other equipment connected to the grid [10]. In addition, the boundaries of the grid voltage and frequency are specified. In response to abnormal grid conditions, PV systems are currently required to disconnect from the distributed grid in those systems due to safety concerns [12]–[27], which is known as islanding protection.

However, the impact of disconnection from the distributed grid is increasingly important to DSOs and PV inverter manufacturers as high penetration of PV power conversion systems becomes a reality. In light of this new reality, a typical anti-islanding disconnection may impose severe challenges for the whole power system, especially for end consumers: an anti-islanding operation that results in the disconnection of PV systems may cause voltage flickers, low voltage, and power-quality problems for customers, causing them to lose money and requiring necessary limits on the PV integration for DSOs [12], [27], [31].

Rethinking Grid Codes for PV Penetration

Thus, it is necessary to rethink the appropriateness of current active grid codes with respect to the operation modes under grid faults. If the PV power conversion systems can provide ancillary services, such as reactive power support and LVRT capabilities, they can contribute to increased system stability [12], [13], [27], [30]–[50]. The resulting system would avoid voltage flickers and power quality issues. In the presence of many actively controlled, multifunctional PV power conversion systems, there is no need for a DSO to limit the PV integration into the grid. Furthermore, by using a thermally optimized operation, improvements of overall system reliability can be achieved, as reported in [12] and [51]–[60]. Therefore, the next-generation PV systems are expected to be multifunctional with LVRT capabilities and the ability to provide reactive power in different operation modes.

It is inevitable, then, that the international standard committees and national organizations must explore new grid codes or modify present grid standards. The aim of this article is to provide an overview of current grid requirements, especially for low-voltage PV applications, and recommend grid code modifications for the next generation of multifunctional PV systems.

Evolution of PV Grid Codes

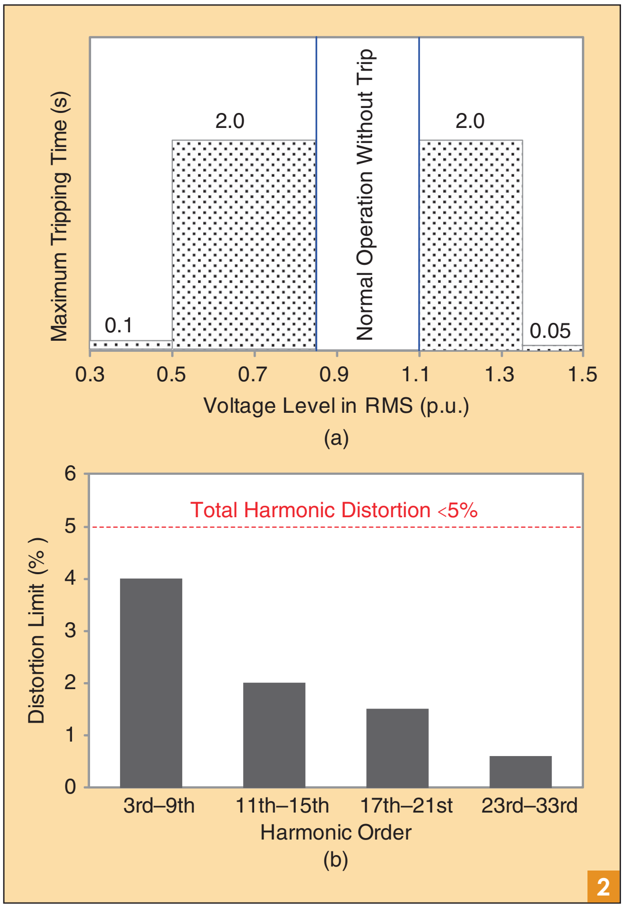
Grid-integration requirements are the essential guidelines for the design, control, and operation of grid-connected renewable energy systems, including single-phase PV systems. Based on current low penetration levels of the PV systems, grid standards up until now have addressed only elementary demands for such systems. For example, most grid-connected PV systems cease to energize the local loads in the case of grid transient disturbances, e.g., voltage sags [9]–[11]. In normal operation, PV systems are required to produce as much energy as possible with satisfactory injected grid currents, as shown in Figure 2—an example of IEC 61727. Those grid requirements, including anti-islanding protection, were introduced to ensure the safety of utility maintenance personnel, to protect equipment, and also to guarantee utility stability [27].

PV systems are predominantly connected to low-voltage and/or medium-voltage networks [7], [8], which is different from the conventional power plants or large-wind power farms. In low penetration scenarios, the current active grid requirements could be valid. Electricity generation from PV systems has so far been fairly negligible.

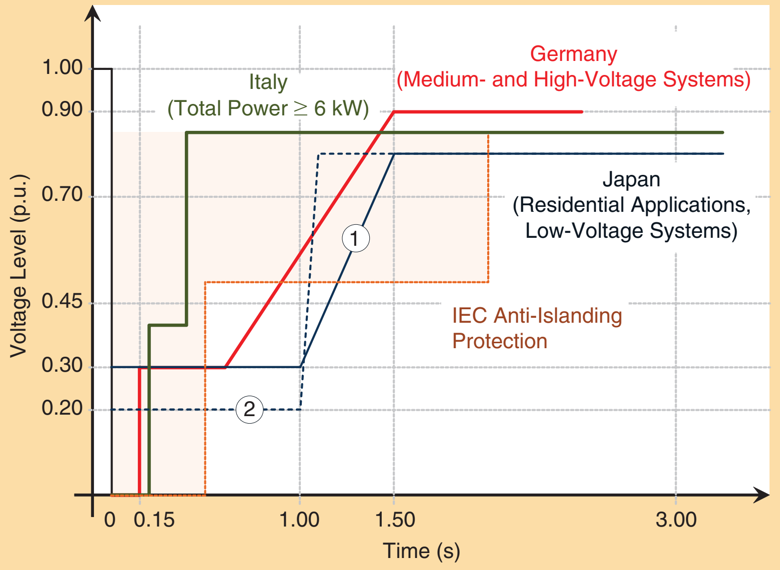
In high-penetration scenarios, however, grid-connected PV systems will impose new challenges to the distributed electrical network. These challenges will primarily be due to 1) the intermittent nature of PV sources [31] and 2) the disconnection of PV systems from the distributed grid in response to abnormal grid conditions. The instability of the entire electrical network may be induced, leading to a blackout and power grid failure, and causing severe consequences in the customer loads. To overcome these challenges, present grid requirements are expected to be upgraded with combined standardized features and custom demands. Several studies have demonstrated the potential of PV systems to play an active role in the regulation of distributed grids similar to what the 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 medium- or high-voltage networks should be capable of riding through voltage sag while providing reactive current to the faulted grid [28]. Italy's new grid code requires that the generation units serving low-voltage grids with nominal power exceeding 6 kW have the ability to ride through grid voltage faults, regardless of single-phase configuration or multiphase systems [29]. Recently, a study in Japan presented the LVRT requirements on PV systems connected to single-phase low-voltage grids [30], [33]–[35] and forecast the challenges from high-penetration PV systems. Thus, DSOs have given priority to finding a solution to guarantee a reliable and a stable operation of distributed power systems, and current grid requirements need to be modified.

One such important modification of grid standards is to allow PV power conversion systems to inject reactive power. This is similar to the current grid codes for wind turbine power-generation systems connected to the medium- and high-voltage levels. Under a modified grid code, the single-phase multifunctional 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 multifunctional PV systems can be summarized, as shown in Figures 3 and 4. When the grid voltage level is higher than the specified ones defined in Figure 3, the PV systems should remain connected to the distributed grid and inject reactive power to support the grid during LVRT. Some of the basic requirements (e.g., power quality) are likely to be more stringent in the future since multifunctional PV systems are able to provide ancillary services, such as voltage flicker mitigation, harmonics suppression, and reactive power compensation.



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



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

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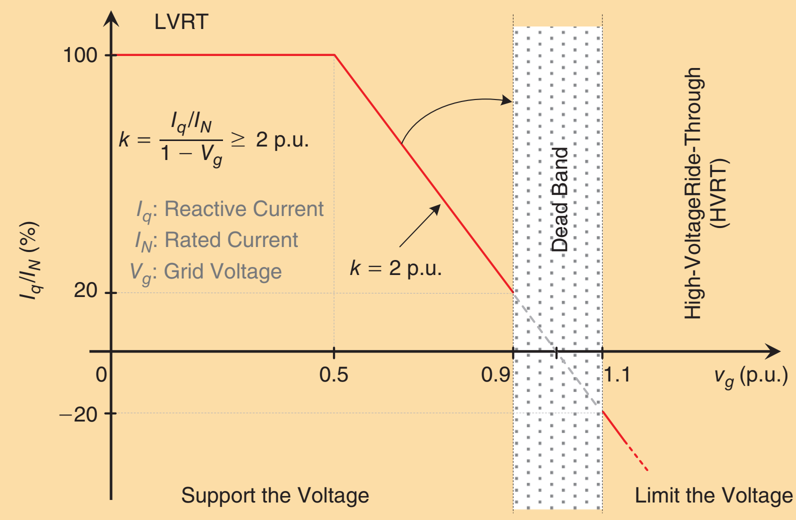
The LVRT requirements in different countries and the anti-islanding requirement for small PV units defined by IEC.



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

PV Grid Code Modifications

The tendency for the next generation of multifunctional PV systems will be to feature LVRT capabilities, grid support functionality, and intelligent ancillary services. To fulfill these advanced features for future high-penetration scenarios, existing PV grid standards need to be reexamined and updated based on the following considerations [12], [14]:

1) reactive power control (voltage support)
2) frequency control through active power control
3) dynamic grid support capability
4) high efficiency and high reliability.

Reactive Power Control (Voltage Support)

Voltage rise on distributed feeders has been observed as one of the major issues in high-penetration PV systems due to the reverse power flow toward upstream voltage levels [4], [9], [17]–[20], and the power difference between PV systems and load demands. One way to solve this is to directly reduce the PV output power when the distributed grid-line voltage hits the upper limitation [for example, 1.06 p.u. (107 V) in Japan and 1.03 p.u. in Germany] [14]. This implies that the PV systems should be able to operate with controllable active power generation, which may include a remote control function in the future grid codes, and will require enhanced monitoring and communication.

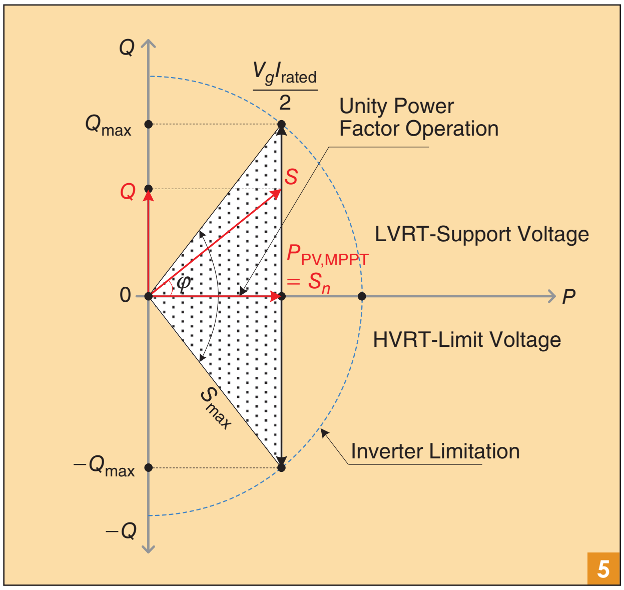
Another solution is to allow the PV system to inject reactive power into the distributed grid. Since PV systems are usually designed with reasonable margins and are operated under partial loading conditions, there is room for reactive power injections to keep the voltage at a desirable level. However, 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 shown in Figure 5. During normal operation with MPPT, the maximum output reactive power of a single-phase PV inverter is calculated as

$$Q_{\max} = \sqrt{S_{\max}^2 - P_{\text{PV, MPPT}}^2} \qquad (1)$$

in which $Q_{\max}$ is the maximum output reactive power, $S_{\max}$ is the maximum apparent power for the inverter, and $P_{\text{PV, MPPT}}$ 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 (and, consequently, of 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 considered, allowing an optimal selection of the reactive power level [58].

There have been some grid requirements for high penetration levels of PV systems to activate reactive power control 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 PF should be satisfied. With this PF constraint, several reactive power control approaches are available for highly integrated PV systems, such as fixed $\cos\varphi$, fixed Q, and $Q(U)$ droop function methods [14], [19], [62]. In the future, similar requirements are expected to grow and be imposed on low-voltage PV systems 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, in typical configurations 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, implemented, and integrated in the grid codes.



The power quality diagram for a single-phase PV inverter.

Frequency Control Through Active Power Control

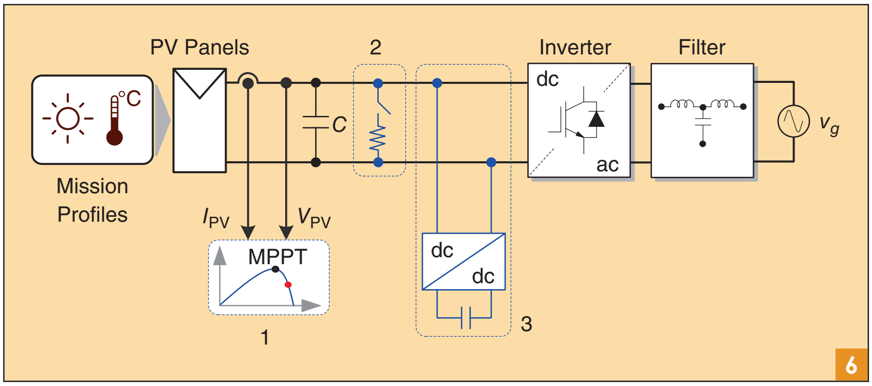
Recent studies show that disconnection due to unintentional islanding protection might introduce instability problems, e.g., a power outage, when the penetration level is high [9], [17], [21]–[26]. Hence, the suggested modifications of PV grid standards should require next-generation PV systems to provide frequency control functionality to ensure grid stability. The frequency control can be realized by reducing the active power output, as it has already been defined in the German grid code, which requires that the reduction of active power has to be activated with a gradient of 40% generated active power P/Hz, when the grid frequency is within a range of 50.2–51.5 Hz [17], [21].

Due to the intermittent nature of PV sources, the output power of a PV system is significantly dependent on 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 grows, with its penetration level growing as well, the frequency fluctuation caused by intermittency will become more serious. The solution to this problem is an enhanced frequency control requirement integrated into the modified grid codes for future PV systems to enable a more widescale adoption of PV power.

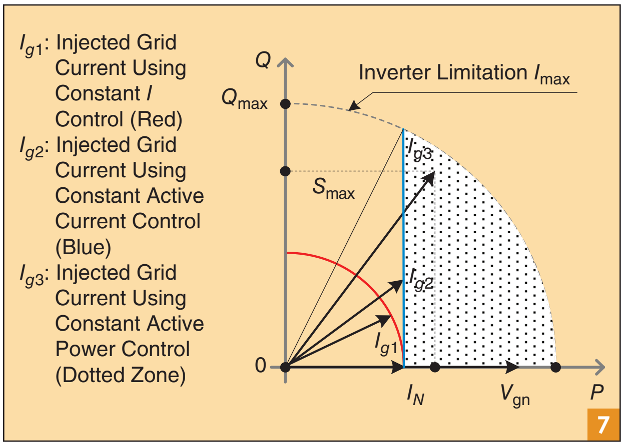
Dynamic Grid Support

The dynamic grid support capability for the next generation of PV systems is mainly focused on LVRT and reactive current injection under voltage faults [13], [27]–[30], according to the requirements in Figures 3 and 4. The objectives of dynamic grid support are 1) to prevent the inverter from overcurrent shutdown and 2) to support grid voltage during recovery. Unlike three-phase wind turbine systems, low-voltage PV systems serving single-phase lines have a 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 the LVRT operation. To avoid this, the power should be dispatched by 1) modifying the MPPT control, 2) activating the dc chopper to absorb power, and 3) managing power exchange between the PV systems and the energy storage systems, which are shown in Figure 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 LVRT performance. By modifying the MPPT, the PV output power can be reduced; by adding a dc chopper at the dc side, during the voltage sag the additional active power



The possible hardware solutions for single-phase grid-connected PV systems with LVRT capability. 1: modified MPPT. 2: A dc chopper. 3: Energy storage systems.



The representations of the injected grid current using different control strategies considering the inverter current limitation.

is dispatched on the resistor, allowing the injection of the required reactive power without tripping the inverter overcurrent protection fast fault detection. Both methods lead to the loss of energy production. The lost energy can be absorbed by an energy storage system, but this increases control complexity with additional devices, and thus increases cost. Nevertheless, three alternatives can be adopted to enhance LVRT capability for single-phase PV systems as seen from a hardware point of view.

With respect to reactive power injection during LVRT, there are four major control solutions available for three-phase systems:

- unity PF control
- positive sequence control strategy
- constant active power control strategy
- constant reactive power control strategy [15], [16].

For single-phase PV systems, there are three possible strategies for reactive power injection [42].

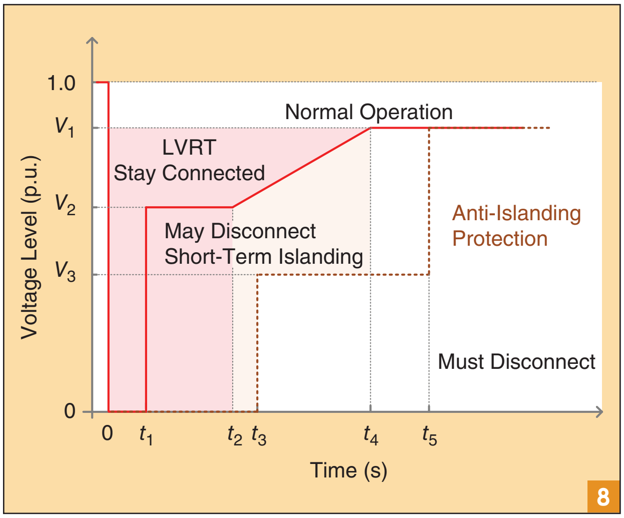
- *Constant I (Peak Current) Strategy*
  For this control strategy, the injected grid current level $(I_{g\max})$ is kept constant (e.g., $I_{g\max} = I_N$, rated current) under grid faults. The injected reactive current is calculated according to Figure 4. This control method can prevent the inverter from overcurrent shutdown.
- *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 shown in Figure 4. Thus, the amplitude of the injected current may exceed the inverter limitation $(I_{\max})$ under this control strategy. To avoid inverter shutdown due to overcurrent, the following condition should be fulfilled:

$$I_d^2 + I_q^2 \leq I_{\max}^2. \tag{2}$$

  For example, when $I_d = I_N$, $k = 2$ p.u., the maximum inverter current is $I_{\max} \geq 1.41\, I_N$. Considering a large $I_{\max}$, the overload capability and the cost of the PV inverter will increase.
- *Constant Active Power Strategy*
  To deliver the maximum active power to the grid during voltage faults, the active power can be kept constant, but this poses 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 these control strategies can be plotted, as shown in Figure 7. 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.

Integrating 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]. It is recommended that grid codes focus more on LVRT capability for PV systems to enhance system stability during grid faults. These requirements have been in effect in some countries, e.g., Italy, and are going to be further extended to other PV systems, and even PV modules, as has been discussed in [13]. However, implementation of LVRT goes against anti-islanding requirements, e.g., IEEE Standard 1547. It is suggested that the anti-islanding requirement should be extended to incorporate fault ride-through capability, as shown in Figure 8.



A compatible implementation of LVRT (and zero voltage) and anti-islanding requirements for PV systems.

High Efficiency and High Reliability

Achieving high efficiency and high reliability is always important so that the cost of energy is reduced and service time is extended. Transformerless PV inverters with high efficiency have gained much popularity in Europe. However, the removal of the transformer also introduces side effects, such as the lack of galvanic isolation and fault ride-through and reactive power injection abilities [42].

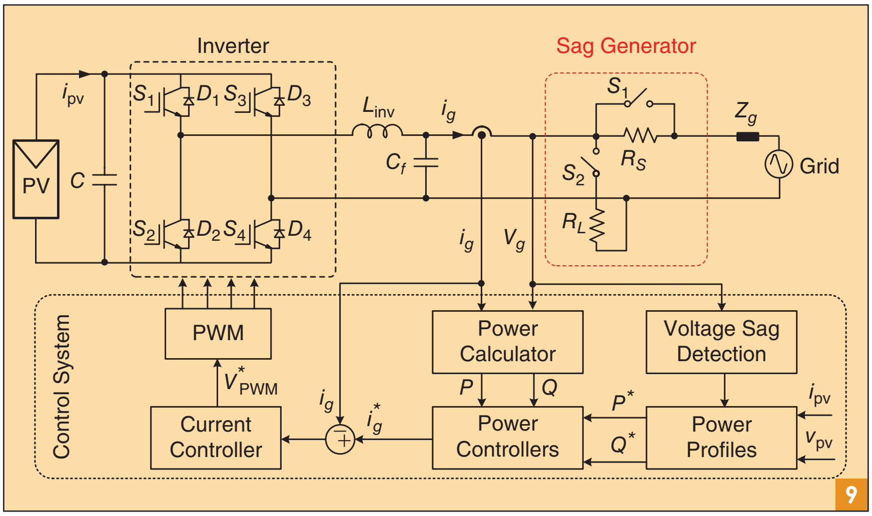
By adding extra power devices either at the dc side (PV panel side) or at the ac side, isolation problems can be solved. However, this may impose new challenges for the reliability of the whole PV system in different operation modes. Increased reliability can potentially be achieved through proper component selection (considering rated power, advanced packaging technologies, the most stressed situations, and severe users), effective thermal management, robustness of design, and validation [51], [55]–[59], [61]. 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 aspects should be taken into consideration in the design process and also during the field operation phase.

The next generation of PV systems should be flexible and appropriately integrated with other systems, e.g., electrical vehicle systems, energy storage systems, smart grids, and microgrid systems. Proper deployment of those systems into the PV systems has brought significant benefits to the grid [18], [22]–[25], [65], [66]. PV systems also have to be able to switch into a short-term islanding operation mode smoothly to secure power supply, as shown in Figure 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, 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, modifications of the current active PV grid standards are suggested according to various features, as summarized in Table 1.

TABLE 1. SUMMARY OF GRID CODES FOR ADVANCED PV SYSTEMS CONNECTED TO A LOW-VOLTAGE GRID AT A HIGH PENETRATION LEVEL.

Grid-Integration Features	Conventional PV Systems (Medium/Low Voltage)	Next-Generation PV Systems at a High Penetration Level	Remarks (Grid Code Revision Considerations)
Active power control (power regulation, setpoint by DSOs)	✓✓/✓	✓✓	Remote setpoint for power regulation should be extended to low-voltage systems. Constant power production (80% of rated power) and the power ramp limit is even more stringent.
Reactive power control (voltage-Var control, power factor-PF adjustment)	✓✓/✓	✓✓	Settings by DSOs are dependent on the power capacity of the PV systems, such as more reactive power provision strategies, e.g., constant PF.
Frequency control (frequency-watt control)	✓✓/✓	✓✓	Frequency support through active power droop control (e.g., 40% power reduction) is active in some countries. More research is needed to solve the 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	✓✓	✓	Anti-islanding protection should be compatible with fault ride-through.
Energy storage enhancement	✓/×	✓	A more decentralized grid requires an enhancement of energy reserve, which can be performed by PV systems. It is also a way to produce power locally.
Monitoring and communication	✓	✓✓✓	Monitoring and communication have to be evenly strengthened to realize the above features.
Efficiency and reliability	✓	✓✓	Advanced power devices must be adopted. Reliability should also be improved to reduce the downtime, and thus the cost of energy. Fault-tolerant capability is suggested.

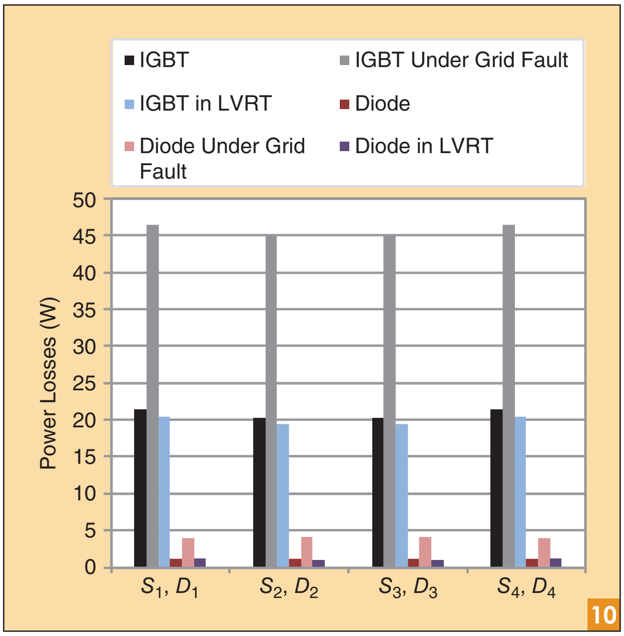
LEGEND: ×— NO SUCH ABILITY/REQUIREMENT. ✓—WITH THE ABILITY and MORE ✓s MEAN a HIGHER REQUIREMENT.



The hardware schematic and control diagram of a single-phase full-bridge PV system with LVRT capability.

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 of PV systems at a high penetration level. Figure 9 shows the topology and the control structure of the single-phase PV system. Voltage sag could be simulated using a sag generator formed by the switching resistors, R_S and R_L. 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. The ambient temperature is set as 50 °C, and the reactive power injection is based on a single-phase PQ theory [27], [58]. The proportional resonant 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 Figures 10 and 11.



The power loss distribution of the 3-kW single-phase full-bridge PV inverter shown in different operational modes. *S*: IGBT. *D*: Diode. Voltage sag: 0.45 p.u.

As shown in Figure 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 (shown in Figure 11). The temperature cycling amplitude is also reduced from 24 °C to 10 °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.

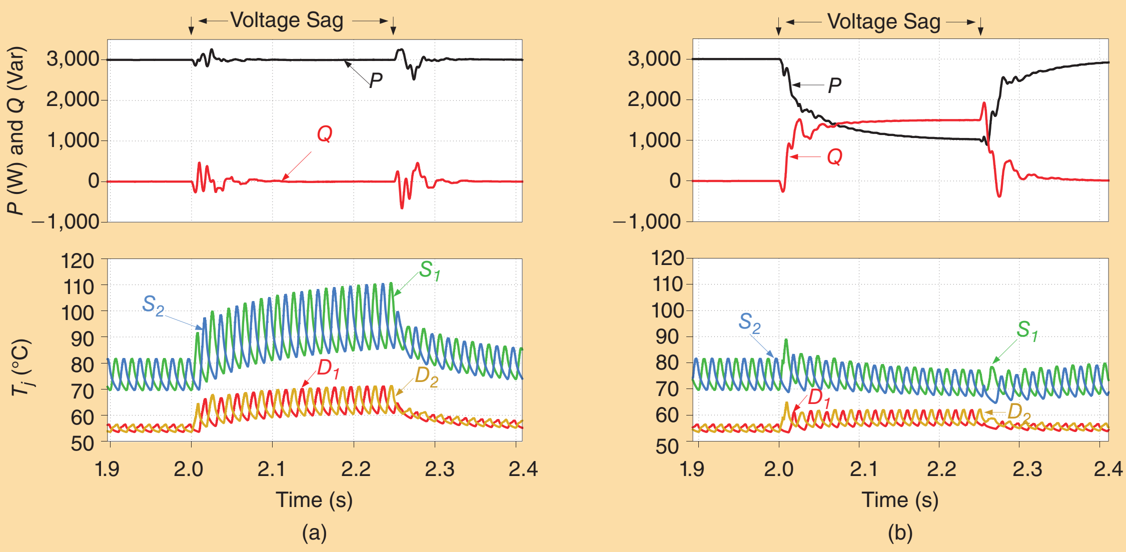
To demonstrate the ability of reactive power injection under grid faults for the next generation of PV systems, a 1-kW grid-connected system has been examined in the laboratory based on single-phase PQ theory [27], [41], [58]. The proportional resonant controller with harmonic compensators was adopted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

During LVRT operation, the single-phase system is injecting reactive power into the distributed grid according to requirements defined in Figure 4. At the same time, the active power is limited below the current limitation of the PV inverter, which is shown in Figure 12, to prevent the inverter from shutting down due to overcurrent (overheating). 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 PF. The experiments demonstrate the flexibility of a single-phase system to provide multifunctions in the future. The single-phase PQ power control method in the test is effective in terms of providing a fast dynamic response.

Conclusions

In this article, several suggested grid-code modifications to ensure a more wide-scale adoption of PV energy in the distributed power generation systems have been presented. The modifications should be carried out in the future with the following considerations 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 capabilities and reactive power injection under grid faults.
2) Suggested PV grid codes should enable reactive power control (to support voltage) and frequency control of the next generation multifunctional PV power systems connected to low-voltage grids.



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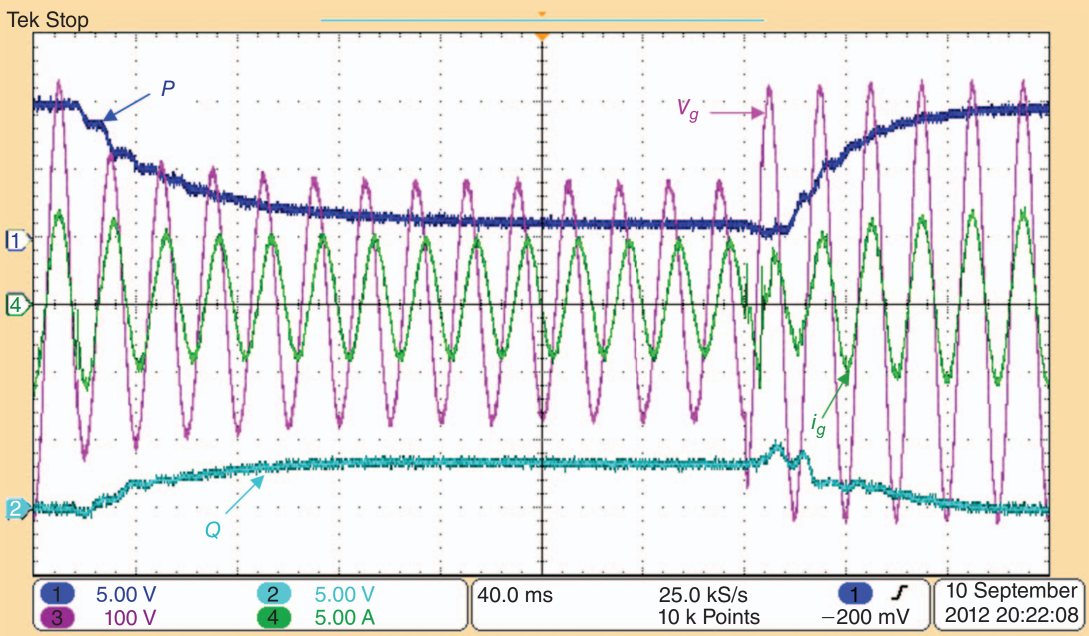
The simulation results of a 3-kW single-phase, full-bridge PV inverter (a) with LVRT control and (b) without LVRT control (constant *I* control strategy). *P*: injected active power to the grid. *Q*: injected reactive power to the grid. T_j: junction temperature. *S*: IGBT. *D*: diode. Voltage sag depth: 0.45 p.u.



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The experimental results of a 1-kW single-phase, grid-connected system in LVRT 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], and time [40 ms/div].

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 the LVRT requirement and the islanding protection should be carried out to make them compatible with each other for the next generation of PV systems.
5) Requirements on monitoring, communication, and energy storage systems should also be strengthened to achieve advanced functions.

With reference to LVRT control under grid faults, three control strategies for reactive power injection have been proposed and discussed: 1) constant *I* strategy, 2) constant active current strategy, and 3) 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 methods should be investigated from an economic point of view, and then appropriate solutions can be included in future grid standards.

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

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