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Power Control Flexibilities for Grid-Connected Multi-Functional Photovoltaic Inverters

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Abstract— **This paper explores the next-generation Photo-Voltaic (PV) system integration issues at a high penetration level, where the grid is becoming more decentralized and vulnerable. Therefore, the PV systems are expected to be more controllable with higher efficiency and higher reliability. Provision of ancillary and intelligent services, like Low Voltage Ride-Through (LVRT), reactive power compensation, and reliability-oriented thermal management/control by PV systems is a key to attain higher utilization of solar energy. Those essential functionalities for the future PV inverters can contribute to reduced cost of energy. To implement the advanced features, a flexible power controller is developed in this paper, which can be configured in the PV inverter and flexibly be changed from one to another. This power control strategy is based on the single-phase *PQ* theory, and it offers the possibilities to generate appropriate references for the inner current control loop. The references depend on the system conditions and also specific demands from both system operators and customers. Besides, this power control strategy can be implemented in a commercial PV inverter as standardized functions, and also it can be achieved online in a predesigned PV inverter. Case studies with simulations and experiments are provided to verify the effectiveness and flexibilities of the power control strategy.**

I. INTRODUCTION

Another spectacular growth of grid-connected photovoltaic (PV) systems has been witnessed in the year of 2013 [1]. The penetration level of PV systems will be further increased in the future [2], since it is an effective solution to carbon-dioxide reduction and also an essential part of "smart" grid. However, the increase installations of PV systems into the grid also bring side effects on the entire distributed network due to the intermittent nature of solar PV energy (e.g. solar irradiance variations and temperature fluctuations), which will as a consequence affect the availability, the reliability, and the quality of the distributed grid. Even for residential PV systems of a few kWs, the impact can not be ignored today [3]. Possibly, the controllability of the whole power system will be weakened, especially when a very high penetration level is reached. In order to facilitate a reliable and efficient power generation from solar PV energy, grid integration guidance associated with critical customer demands is continuously being updated [3], [4], which imposes more challenges for the interfaced PV inverters. As a result, it calls for advanced and intelligent control strategies for the next-generation multi-functional PV inverters to be of much flexibility in order to achieve those goals.

Hence, it is expected for the future PV systems to be of much controllability by providing ancillary and intelligent services, e.g. Low Voltage Ride-Through (LVRT) [5]–[9], reactive power compensation (Var Comp.) [10]–[12], power quality enhancement [13]–[16], frequency control through active power curtailment (Freq.-Watt function) [7], [17]–[19], and reliability-oriented thermal management/control [20]–[23]. Together with higher efficiency and higher reliability demands, those functionalities for the future PV inverters are the key to reduce the total cost of PV energy. To implement those advanced features, a flexible power controller thus is developed in this paper, which can be configured in the PV inverter to fulfill the above services and flexibly be changed from one to another according to the grid requirements and/or the end-customer demands. This power control strategy is based on the single-phase *PQ* theory [24], and it offers the possibilities to generate appropriate power references, which are dependent on the system conditions and also specific demands from both system operators and customers. Besides, this power control strategy can be implemented in a commercial PV inverter as standardized functions, and also it can be achieved online in a predesigned PV inverter in accordance to the PV system operation conditions.

This paper serves to explore the next-generation PV system integration features, develop a power control solution to achieve those advanced features, and initiate further research perspectives. In § II, a summary of key features for next-generation PV systems is given by reviewing the currently active grid standards/codes, followed by the power control strategy for multi-functional PV inverters. Case studies on the LVRT, reactive power injection, and temperature management using the power control strategy are conducted on a single-phase PV system. The results presented in § IV have demonstrated the power control flexibilities for grid-connected PV inverters of multiple functionalities. It can enable a more controllable and more manageable integration of PV systems.

II. ADVANCED PV INVERTER FEATURES

Seen from the thriving trend of PV systems, it can be predicted that the grid, where more PV systems are going to be connected to, will become even decentralized and vulnerable. This will result in complicated control systems but reduced carbon-dioxide emission. However, it should be noted that PV

TABLE I

MULTIPLE FUNCTIONS FOR FUTURE PV INVERTERS.

Features	Remarks
Volt.-Var control	Reactive power control to maintain the grid voltage level [27], [28].
Freq.-Watt control	Based on the droop characteristic between grid frequency and active power production to achieve a constant grid frequency [17], [18], [29], [30].
P constraints	Active power constraints [23], [25], e.g. delta power production, power ramp control, and peak power limiting control.
Dynamic grid support	In response to voltage faults, PV systems should stay connected to the grid with reactive power injection, especially at a high PV penetration level [5]–[7].
Lower downtime & higher efficiency	To further reduce the cost of energy [31], [32].
Harmonic comp.	Take an active role in power quality control, e.g. as an active power filter [33], [34].
Smart operation	Var injection/compensation at nights, when there is no solar irradiance.

systems are not just about decarbonisation, and they can be beneficial in different ways to both grid operators and the customers beyond the basic electricity generation [25].

In order to reach a goal of wider scale adoption of PV systems and also to expand the benefits, a smoother transition has to be initiated by the grid system operators and the PV generators by means of revising the integration regulations and developing advanced control strategies, respectively. Nonetheless, most of the currently active grid standards/codes seem largely to require the grid-connected PV inverters to cease energizing once a grid disturbance is confirmed [25], [26], which is against the transition. To make the most of solar PV energy in a cost-effective way, a common control strategy has to be developed, and it should be simple but flexible for future advanced PV inverters with the features listed in Table I.

Notably, the “Volt.-Var control” and “Freq.-Watt control” are based on the droop relationship between grid voltage and reactive power injection, and the relationship between grid frequency and active power production , respectively [35], [36]. Due to the very low X/R ratio of single-phase feeders, grid voltage and frequency control through reactive power and active power control is not very effective in a single-phase PV system. While this could be an option for the PV systems at a high penetration level by appropriately managing the active power production and properly using the reactive power. In this paper, a part of the advanced features shown in Table I for grid-friendly PV systems have been demonstrated. Additionally, to implement these functions, forecasting, monitoring, and communication technologies have to be advanced.

III. FLEXIBLE POWER CONTROL STRATEGY

A. System Description

Fig. 1 exemplifies a grid-connected single-phase PV system, which is a commonly used configuration for residential applications of lower power ratings (e.g. up to 5 kW). As achieving high efficiency is always of interest for the inverter manufacturers and also the PV users, normally, the isolation transformer is removed, being the popular transformerless PV inverters. To flexibly maximize the output PV energy with extended operational hours, a DC-DC converter can be adopted between the PV panels and the PV inverter, where the Maximum Power Point Tracking (MPPT) is implemented [23]. In that case, the DC-link control is aimed at power injection by controlling the PV inverter. A current controller with harmonic compensation is normally implemented in the inverter control unit as shown in Fig. 1, since the current controller is responsible for the power quality of injected current, being synchronized with the grid voltage usually by means of a Phase Locked Loop (PLL) in the normal operation mode [37], [38]. Table II shows the system specifications.

TABLE II

SPECIFICATIONS OF THE SINGLE-PHASE PV SYSTEM.

Parameter	Symbol	Value
PV nominal maximum power	P_{MPP}	1∼3 kW
PV nominal voltage	v_{MPP}	400 V
Grid voltage (RMS)	V_g	230 V
Grid frequency	ω_0	$2\pi\times50$ rad/s
DC-link capacitor	C_{dc}	2200 μF
LCL filter	L_1	3.6 mH
	C_f	2.35 μF
	L_2	708 μH
Sampling and switching freq.	f_s, f_{sw}	10 kHz

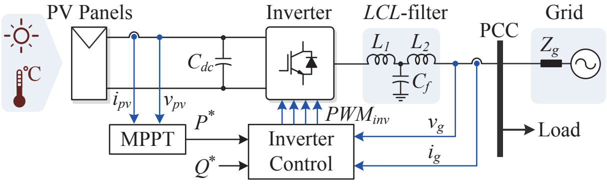

Fig. 1. A typical single-stage single-phase grid-connected PV system (transformerless) with an *LCL* filter.

B. Flexible Power Control Strategy

With the help of Clarke transformation ($abc \rightarrow \alpha\beta$), the instantaneous power theory proposed by Akagi has been widely used in the three-phase systems [39]. Although this theory is not appropriately applicable to single-phase systems due to a limited number of control variables (i.e. the grid voltage v_g and the grid current i_g), its attractiveness of direct and intuitive active power and reactive power control remains in single-phase systems. Therefore, efforts have been devoted to create an imaginary system [24], [37] in order to adopt the instantaneous power theory as it is shown in Fig. 2, being the single-phase *PQ* theory.

According to the single-phase *PQ* theory [24], the active power and the reactive power in the $\alpha\beta$ stationary reference frame can be expressed as,

$$\begin{cases} P = \frac{1}{2}(v_\alpha i_\alpha + v_\beta i_\beta) \\ Q = \frac{1}{2}(v_\beta i_\alpha - v_\alpha i_\beta) \end{cases} \tag{1}$$

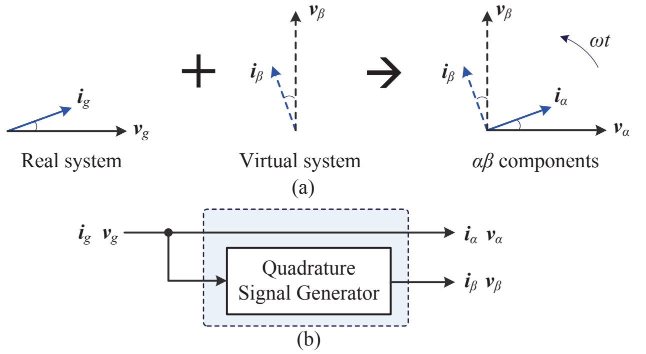

Fig. 2. (a) graphic representations of the single-phase *PQ* theory and (b) in-quadrature system generation.

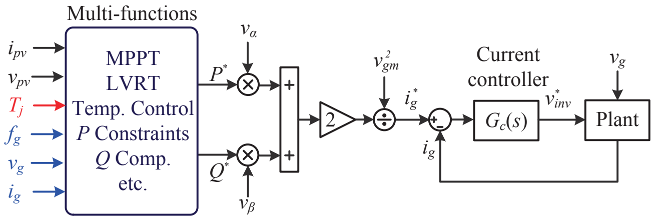

Fig. 3. Closed-loop control block diagram of the single-phase PV system based on the single-phase *PQ* theory.

with $v_{\alpha\beta}$, $i_{\alpha\beta}$ being the grid voltage and grid current in the $\alpha\beta$ reference frame, and P, Q being the active power and the reactive power, respectively. Referring to Fig. 2, the grid current can be derived from (1) and it can be given by,

$$i_g^* = i_\alpha^* = \frac{2}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \end{bmatrix} \begin{bmatrix} P^* \\ Q^* \end{bmatrix} \tag{2}$$

with

$$v_{gm} = \sqrt{v_\alpha^2 + v_\beta^2} \tag{3}$$

where "*" denotes the reference signals and v_{gm} is the grid voltage amplitude. Subsequently, the entire flexible power control diagram based on the single-phase *PQ* theory can be illustrated in Fig. 3. The single-phase *PQ* theory also enables the use of popular Proportional Integrator (PI) controllers in the dq rotating reference frame for the grid current control where a Park transformation is required. Moreover, it is also possible to use PI controllers to control the active power and the reactive power injected to the grid [5].

It can be observed in Fig. 3 and (2), the power control solution does not require a PLL system to synchronize the grid current with the grid voltage. Instead, the dynamics of the power control system are highly dependent on the performance of the built-up $\alpha\beta$ system, i.e. v_α and v_β, where the synchronization actually is also achieved. Consequently, as it is shown in Fig. 2, the implementation of the power control strategy is shifted to create a quadrature signal generator based on like Hilbert transformation, inverse Park transformation, and the Second Order Generalized Integrator (SOGI) [24], [37], [40]. Due to its good harmonic rejection ability, the SOGI based in-quadrature signal generation system has been adopted in this power control strategy.

It should be pointed out that, in such a power control system, all the current controllers in the $\alpha\beta$ stationary reference frame like the Proportional Resonant (PR) and the repetitive controller can directly be adopted to regulate the injected grid current. In contrast to the PI-controlled system, there is no need for Park and inverse Park transformations ($\alpha\beta \to dq$) for the current controllers acting in dq reference frame. The "Multi-Functions" unit (i.e. power reference unit) is an objective-determined reference generator for the power control strategy. As a consequence, the power control of multi-functional PV inverters can be achieved by flexibly setting appropriate power references, in spite of its performance-dependency on the in-quadrature system, as it is shown in Fig. 3. In addition, in the flexible power control strategy, only current controllers have to be designed (i.e. control parameter tuning in the current controllers).

IV. APPLICATION EXAMPLES

A. *Low Voltage Ride Through*

LVRT requirements were firstly introduced to the renewable systems of high power ratings (e.g. several megawatts) connected to medium- or high-voltage grids, e.g. wind turbine systems and utility-scale PV power plants. As the PV penetration level is continuously growing at a rapid rate and also the power rating of an individual PV system is going higher, similar requirements have been extended to and imposed on other PV systems. A shift of those requirements towards next-generation PV systems, covering a wide range of applications from single-phase PV systems of lower power ratings to three-phase higher power PV plants, has been initiated in some countries [3], [6], [8], [9], e.g. Italy, Germany, and Japan, where PV systems have a large share of the electricity generation.

Associated with the fault ride-through, which is defined as the stay-connected time for the system in response to voltage faults as shown in Fig. 4(a), the reactive current injection has also to be enabled to support the voltage recovery. Fig. 4(b) shows an example of the minimum reactive current for medium- and high-voltage systems in response to a voltage fault [3], [7]. Consequently, the PV system has to meet two requirements in the case of voltage faults: (a) remain connected to the grid during the transient and (b) provide reactive current to support the voltage recovery. Both can be implemented in the flexible power control strategy shown in Fig. 3. Notably, the power injection is limited by the PV inverter rating, as it can be given by

$$\sqrt{P^2 + Q^2} \le S_{max} \tag{4}$$

in which P, Q are the injected active power and reactive power according to the voltage level, and S_{max} is the inverter maximum apparent power.

Considering the above operation constraints under grid faults, a 1 kW single-phase grid-connected system has been tested in LVRT operation mode referring to Fig. 3. Other parameters of the system has been given in Table II. A PR current

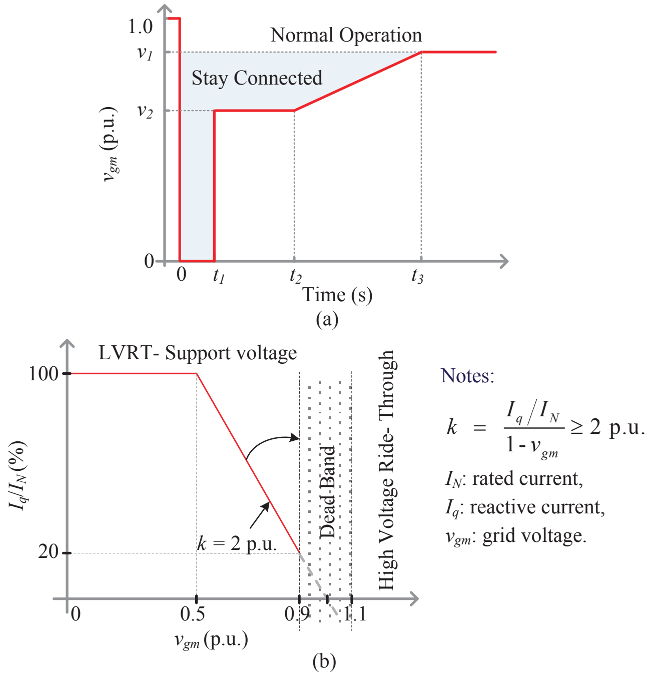

Fig. 4. Fault ride-through requirement: (a) stay-connected time under grid faults and (b) reactive current profile in response to voltage faults [7].

controller with paralleled resonant Harmonic Compensators (HC) has been adopted for the grid current control [38]. The current controller $G_c(s)$ is given as (5) where only the 3rd, 5th, and 7th order harmonics are compensated.

$$G_c(s) = \overbrace{k_p + \frac{k_r s}{s^2 + \omega_0^2}}^{PR} + \overbrace{\sum_{h=3,5,7} \frac{k_{ih} s}{s^2 + (h\omega_0)^2}}^{HC} \tag{5}$$

in which k_p = 20, k_r = 2000, and k_{ih} = 5000 are the control gains of the current controller.

Fig. 5 shows the performance of the single-phase system under grid faults with the flexible power control strategy. As it can be observed in Fig. 5, once a voltage fault is confirmed, the system with the power control is able to inject appropriate reactive power, which is dependent on the grid voltage level. In the consideration of the inverter rating, the injection current amplitude is maintained constant during this short-term event. Besides, when the grid fault is cleared, the power control solution can quickly change back to unity power factor operation mode with the maximum active power injection. The test results have demonstrated that the single-phase PV inverter is capable of riding through voltage faults enabled by the flexible power control strategy.

B. VAR Operation at Nights

Although double-stage PV inverters can extend the operating hours during a day, there is still a gap at nights where the solar irradiance level is almost 0 kW/m^2. Consequently, no active power is available in that period, while the reactive power is not like that case. The PV systems can provide

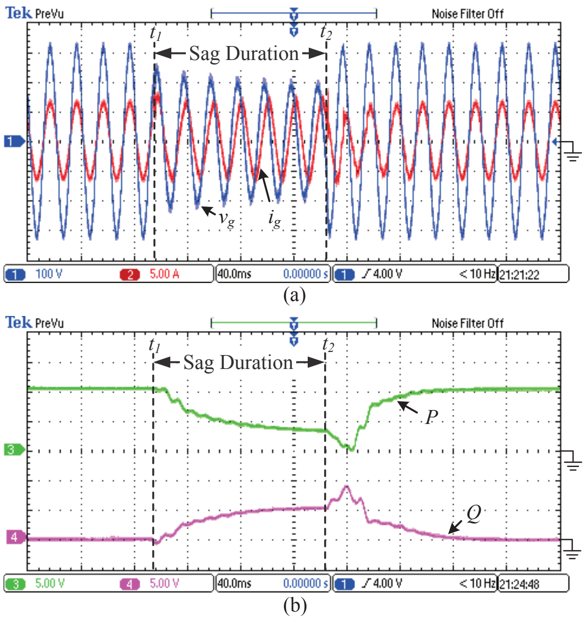

Fig. 5. Low voltage ride-through operation of a single-phase PV system (0.43 p.u. voltage sag): (a) grid voltage v_g [100 V/div] and grid current i_g [5 A/div] and (b) active power P [500 W/div] and reactive power Q [500 var/div], time [40 ms/div].

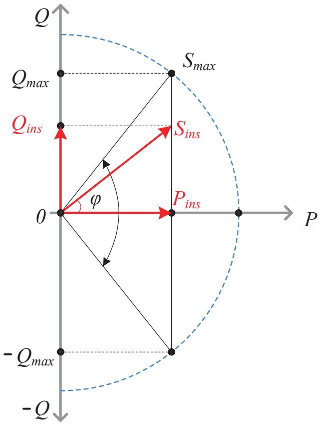

Fig. 6. Reactive power capability of a PV inverter.

reactive power which can be used to secure the entire grid since it affects the grid voltage throughout the system. In addition to reactive power operation at nights, there is a room for most PV inverters to provide reactive power compensation even in day-time operations [41]–[43], as it is shown in Fig. 6. Thus, according to (4) and Fig. 6, the maximum available reactive power $|Q_{max}|$ can be determined by

$$|Q_{max}| = \sqrt{S_{max}^2 - P_{ins}^2} \tag{6}$$

where P_{ins} is the instantaneous active power and S_{max} has been defined previously.

Considering the reactive power constraint shown in (6), the flexible power control strategy can enable the VAR operation mode of PV system at nights. However, the key to implemen-

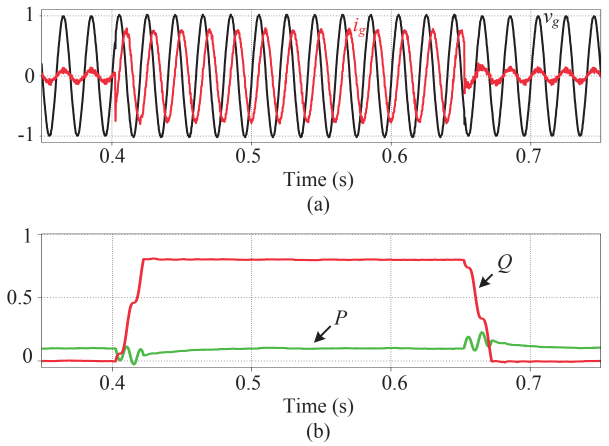

Fig. 7. VAR operation of a single-phase PV system (very low solar irradiance): (a) grid voltage v_g [p.u.] and grid current i_g [p.u.] and (b) active power P [p.u.] and reactive power Q [p.u.].

tation of this function is to monitor the available active power, and thus to determine the start of VAR operation. This requires advanced monitoring and forecasting technologies.

Fig. 7 shows the performance of the flexible power control strategy for a single-phase PV system in the VAR injection mode, where the solar irradiance is very weak. It can be seen that, the power control strategy can effectively enable the PV system to inject reactive power when the solar irradiance level is very low (and thus the active power is also low). However, when the PV inverter is operating in the VAR injection mode at nights, an additional power loss and thus thermal stress will appear in the PV inverter [21], [44]. The increased thermal loading can accelerate the device degradation, and thus increase maintenance cost. When compared to the costs for compensation plants, the investment costs brought by PV systems in the VAR injection at nights are significantly lower [44]. Therefore, a research perspective regarding VAR operation at nights for PV systems can be directed to the thermal loading analysis under different VAR injection levels, so that a tradeoff between the PV inverter reliability and the savings for reactive power compensations. Besides, further in-depth investigations of the reactive power compensation effect on the distributed grid should be conducted considering the interactions between paralleled PV inverters.

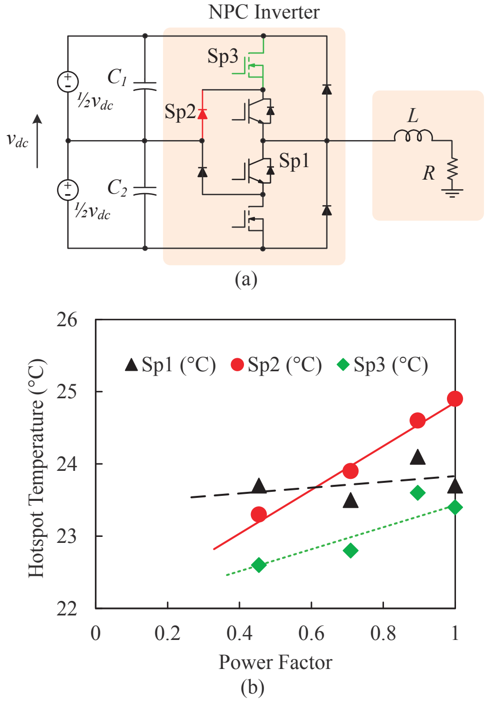

Fig. 8. Experiments of a single-phase three level NPC PV inverter under different power factors: (a) experimental setup and (b) test results.

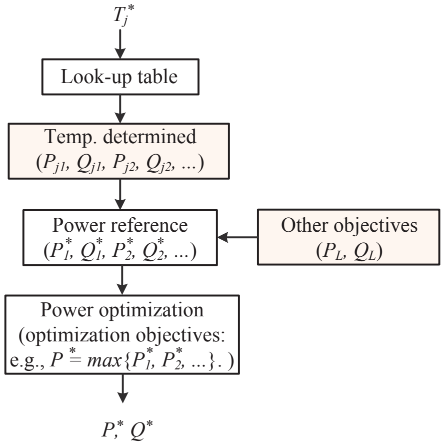

Fig. 9. Flowchart of the junction temperature control to generate references the power control strategy shown in Fig. 3.

C. Power Control to Enhance Reliability

Since the thermal stress on the power switching devices will induce additional power losses and may cause the device fail to operate, reliability-oriented design and control of power electronics converters (e.g. PV inverters) have become of high interest [20], [23], [45]. It is also observed in the power electronics applications that temperature peaks and variations on the power electronics devices are more challenging to the reliability [20], [46]. Hence, a stable junction temperature with small variations is desirable from the reliability point of view. Due to the coupled relationship between power losses and junction temperatures, it is possible to control or manage the device temperature by appropriately allocating the active power and reactive power distributions. The feasibility of this temperature control strategy is demonstrated by the test results of a three level Neutral Point Clamped (NPC) PV inverter shown in Fig. 8. It is therefore possible to control the junction temperature of the power electronics devices through appropriate power control and the control can be implemented in the flexible power control strategy shown in Fig. 3. As a consequence, the flexible power control strategy offers a possibility to enhance the reliability of the power electronics devices, and thus to reduce the cost of PV energy.

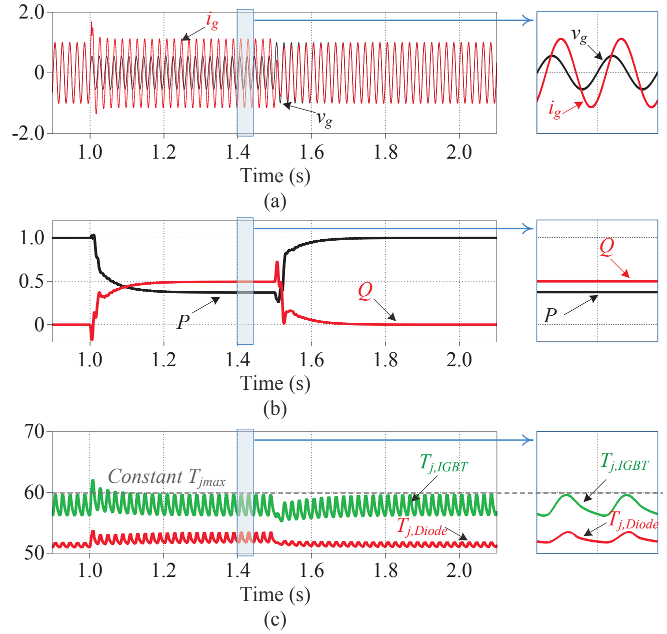

Fig. 10. Simulation results of a 1 kW single-phase grid-connected PV system under a grid fault (0.45 p.u.): (a) grid current i_g [p.u.] and grid voltage v_g [p.u.], (b) active power P [p.u.] and reactive power Q [p.u.], and (c) junction temperature of the power devices T_j [°C].

The flowchart of the junction temperature control through power control is further illustrated in Fig. 9, which shows the possibility to achieve multi-objective at the same time (e.g. a desirable junction temperature and the fault ride-through operation). In that case, the power references for different control objectives (e.g. P^*_{j1}, Q^*_{j1}, P^*_{j2}, Q^*_{j2}, ..., and P^*_L, Q^*_L) have to be optimized.

To demonstrate the flexibility of the power control method in terms of temperature management, a single-phase PV system has been simulated under grid faults, where a constant junction temperature is desired through the operation. The control system is shown in Fig. 3. The results which are given in Fig. 10 have confirmed that, with the flexible power control, the junction temperature of the IGBT power devices is maintained constant during fault ride through, and sufficient reactive power is injected to support the voltage recovery as required, as long as the power references are generated appropriately. Nonetheless, multiple functions of PV inverters have been achieved by the flexible power control strategy.

V. CONCLUSIONS AND DISCUSSIONS

Integration issues of next generation PV systems have been presented in this paper firstly. In order to achieve a smooth and grid-friendly integration of PV systems, the power control flexibilities based on single-phase *PQ* theory have been focused on and explored in this paper. The introduced control strategy can be an enhancement of future PV inverters, and it offers a flexible power controllability to enable intelligent services from multi-functional PV systems. Selected cases for single-phase PV systems have demonstrated the effectiveness and flexibility of the power control strategy.

As it can be seen in this paper, the implementation of the flexible power control strategy is strongly dependent on the performance of the built-up in-quadrature system. The virtual system will thus introduce delays and may also trigger the system stability. An alternative to flexible power control especially for single-phase PV systems based on the Conservative Power Theory (CPT) is ascertained in recent studies [47]–[49]. This could be an attractive solution for grid-friendly PV inverters, as the CPT offers more terms to flexibly control, e.g. harmonic compensation, reactive power compensation, and active power injection.

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