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Constant Power Generation of Photovoltaic Systems Considering the Distributed Grid Capacity

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Abstract— With an imperative demand of clean and reliable electricity generation in some countries, the increasing adoption of new photovoltaic (PV) systems pushes the Distribution System Operators (DSOs) to expand the transmission/distributed lines. However, the potential cost brought by such extensions and increased maintenances introduce new obstacles. In view of this concern, the DSOs starts to reduce PV installations in order to avoid an extension of the power infrastructure. Besides, another alternative solution is to limit the maximum feed-in power of the existing PV systems to a certain level. It can contribute to a weakened requirement of grid expansion and at the same time an increased penetration level. Therefore, to meet the need of this emerging ancillary service provided by future PV systems, a Constant Power Generation (CPG) control concept of PV inverters is proposed in this paper. Accordingly, it is worth investigating into two main issues: a) analyzing the reduction of the energy yield due to CPG control to study its feasibility from an economic point of view and b) developing robust CPG control methods, otherwise, it may introduce instabilities. Thereby, the implementation possibilities for PV systems in CPG operation mode are also discussed in this paper. Additionally, the loss of energy is calculated to reveal the viability of the proposed CPG control method. Operation examples of a PV system are presented to show the effectiveness of the CPG control method to unload the distributed grid.

I. INTRODUCTION

Traditionally, the electricity generated from fossil-source-based power plants is transferred to the customers through long transmission lines. Today, more Renewable Energy Sources (RESs), e.g. PhotoVoltaic (PV) systems and wind turbine systems, have been connected to the grid, which is mainly pushed by advanced power electronics technologies [1]–[4]. The power of RESs is dependent on environmental conditions (e.g. wind speed, solar irradiance and ambient temperature), and thus aging transmission lines and local substations have to cope with an increasing amount of fluctuated power. Moreover, the imperative demand of clean, environmental-friendly, and reliable electricity generation has been another principal driver for a wide-scale adoption of RESs to reduce carbon-dioxide emissions from conventional power plants. This also makes the power system highly decentralized and vulnerable.

Consequently, the aging grids will experience severe overloading issues [5], [6], introducing further stability problems and follow-up maintenance tasks, if the distributed grid remains at its current capacity. This situation tends to be even worse in those countries, where ambitious goals have been set for RESs. For example, in Germany, electricity generation from RESs is expected to be over 80% by 2050 [7]. Thus, it calls for grid reinforcement measures, and it is of importance and necessity for those countries to realize high RES acceptance plans. Alternatively, the Distributed System Operators (DSOs) have to reduce the RES installations. However, with power infrastructure expansion, the existing systems have to be retrofitted and thus the total cost increases. Hence, the line extension approach is not the optimal solution to increase renewable energy utilizations, including PV power, when it is seen from a total cost perspective.

Among variable renewables, wind turbine power systems have been witnessed as one of the most successful technologies in some countries, e.g. Denmark [8]. As a result, many grid codes have been developed to flexibly regulate the connection situations, such as output power control and voltage support capability [9]–[12]. Regarding PV systems, they still account for a minor share of the overall electricity production in most countries. Therefore, it is required PV systems to operate with Maximum Power Point Tracking (MPPT) control, and they are not allowed to participate in the grid voltage regulation [6], [13]–[15]. As aforementioned, the increasing adoption of PV systems poses more challenges for the distributed grid, which requires infrastructure upgrades. Thus, some of the grid codes are undergoing a major revision to enable the grid support capability for PV systems at a high penetration level [15]–[22]. In that case, similar to wind power systems, the PV systems should be able to flexibly control the active power, e.g. curtailment control and power ramp limitation, in order to maintain the grid stability.

Solutions to realize these advanced features include integrating energy storage systems and expanding the grid capacity [7], [15], [22]. However, the increased cost, which may severely exceed the initial project outlay, hinders the development of both technologies. According to a study of a grid-connected PV system based on a yearly mission profile (ambient temperature and solar irradiance level), limiting the maximum feed-in power can contribute to the unloading of the distributed grid. Consequently, achievement of an even wide-scale adoption of PV systems is quite feasible. Reducing the maximum feed-in power will violate the MPPT function for PV systems with current control methodologies. Thus, it is necessary to develop more robust control solutions.
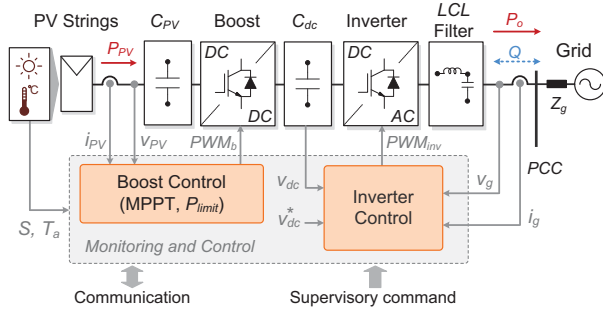
Fig. 1. A two-stage single-phase grid-connected PV system with MPPT control: S - Solar irradiance and T_a - Ambient temperature.

Fig. 2. Active power control functions for wind turbine power systems defined in the Danish grid code [10].

In view of the above issues, a Constant Power Generation (CPG) control concept of PV inverters is proposed in this paper. Since the total energy loss in CPG operation mode is limited, its feasibility is discussed in §II. The detailed implementation of this control method is presented in §III, followed by operation examples to show the potential contributions to the reduction of grid expansion requirements, and thus pave the way for the next generation PV systems to take a major part in electricity generation. Finally, §V concludes this work.

II. VIABILITY OF LIMITING FEED-IN POWER OF PHOTOVOLTAIC SYSTEMS

A typical single-phase grid-connected PV power generation system is shown in Fig. 1. Maximizing the feed-in power from such systems, also known as MPPT control, is required in current grid integration policies. This objective can be achieved with a dedicated MPPT system as it is shown in Fig. 1, and normally a DC-DC boost stage is adopted. The resultant two-stage system offers a flexible controllability of the input PV power, and an extension of operational hours when the solar insolation reduces. Moreover, the PV systems have to disconnect from the grid in the case of disturbances, e.g. voltage variations and frequency deviations. Those requirements were introduced initially based on a low penetration level of PV systems, where adverse impacts were negligible. However, catering for a vast amount of PV hosting capacity magnifies the influences from PV systems on the grid, and thus those policies are going to change [1], [9], [15]

A. Active Power Control Functions

The rapid installation of PV systems can cause voltage rise, which could damage household appliances in worst case scenarios. In order to solve the problem of voltage rise on the distributed feeders, the PV inverters have to either enable reactive power control or to limit the active power generation [12], [15], [23]–[25]. Due to the high R/X ratio of low-voltage grids, reduction of active power shows more effectiveness in voltage regulation than reactive power control. Curtailing active power output is similar to constant power production when the voltage amplitude reaches the upper level. Moreover, frequency control through active power has been introduced for PV systems as well to stabilize the grid frequency [8],
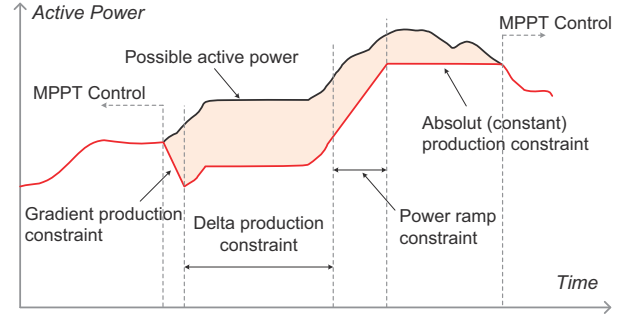
[12], [15], [25]–[27]. It can be achieved by the droop function of the grid frequency and the active power.

Besides, when a high penetration degree of PV systems is achieved, imbalances in or overloading of the grid will appear due to intermittency and/or reconnection from fault situations. Hence, similar to the requirements for wind power systems in Denmark [10], [28], it is better for PV systems to be equipped with active power control functions, such as active power production constraint, delta production constraint, and power ramp constraint. Those active power control functions are indicated in Fig. 2. In that case, the PV systems have to provide a wide range of active power controllability, including constant power generation, the feasibility of which will be detailed in the following.

B. Constant Power Generation Viability

Integrating energy storage systems into PV systems seems to be a good solution to desirably control the active power, as it has been presented in [7], [16], [18] and [19]. However, it will introduce additional cost and additional lifetime-limited energy storage components, making it not an optimal approach [27]. Considering the expenses, energy storage systems are mostly installed at the substation side instead of integrated in the PV inverters in order to achieve constant power production.

The constant (absolute) power production control can also be attained at the PV inverter level. A representative study of a 3 kW single-phase PV system in a certain place with a yearly mission profile has revealed its feasibility. The yearly mission profile shown in Fig. 3 includes recorded ambient temperature and solar irradiance level, and hence the annual energy production of the same place has little variation in different years. As it is shown in the results (Fig. 4), a 20% reduction of the maximum feed-in power from PV systems only leads to a 6.23% reduction of yearly total energy yield. Thus, it is viable and reasonable to increase PV penetration degree without violating the grid capacity by limiting the maximum feed-in power from current existing PV systems. At the same time, frequency stability can potentially be improved by enabling absolute power control [27]. Such issues are already being discussed in some countries [1], [6], [7], where the PV systems share a considerable proportion of electricity generation, e.g. Germany.
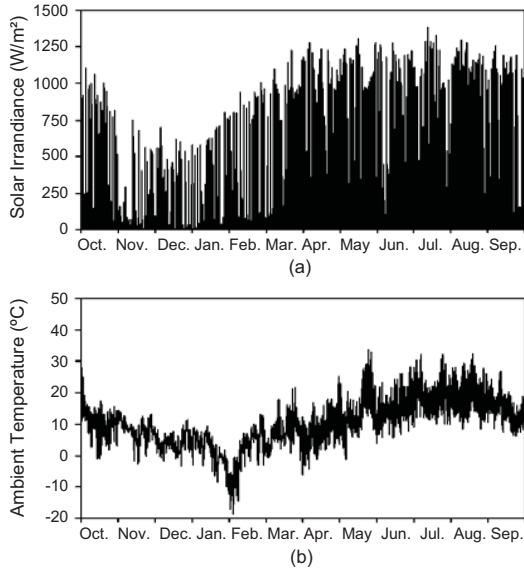
Fig. 3. A yearly mission profile from October 2011 to September 2012 for a 3 kW single-phase grid-connected PV system in a certain place: (a) solar irradiance and (b) ambient temperature.
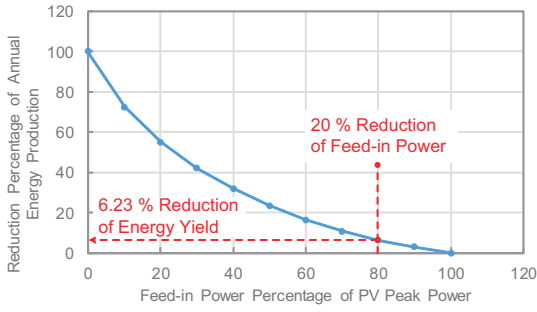

Fig. 4. Energy reduction due to the limitation of maximum feed-in power from a 3 kW grid-connected single-phase PV system.

As it has been illustrated, reducing the maximum feed-in power from the PV systems can contribute to decreased burden of the distributed grid with a high penetration level. This means that a certain percentage of the energy from the current PV systems is cut off arbitrarily in a long-term operation, which is shown in Fig. 4, and thus in a short-term operation, the PV systems should be able to operate in CPG mode when the output power reaches a certain level (e.g. 80% of the nominal maximum power). The following section presents the implementation of the CPG approach.

III. IMPLEMENTATION OF CONSTANT POWER GENERATION CONTROL

The objectives of active power control functions include: 1) further increasing the penetration degree of PV systems without the necessity of grid expansion and 2) participating in frequency regulations to ensure grid stability. Hence, the PV system should be able to enter into a CPG mode when the output reaches a certain level (e.g. 80% of the peak power).
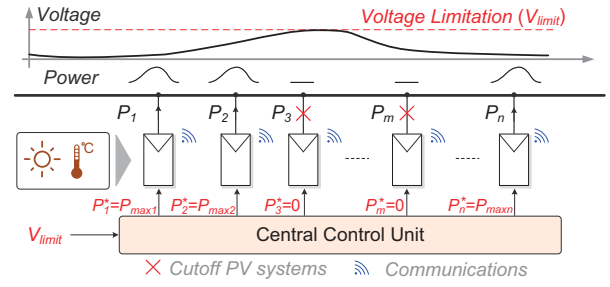

Fig. 5. Voltage reduction by cutting off PV systems during peak production period in a highly PV-penetrated system.

This control strategy can be implemented by means of: a) enabling the energy storage systems, b) managing the total power of an aggregated PV system, and c) modifying the MPPT control of the PV inverters.

A. Integrating Energy Storage Systems

Although integration of energy storage systems into highly PV-penetrated grids will increase the total expenses, significant improvements of active power control functions can be achieved [7], [16], [19]. Mostly, energy storage systems are installed at the medium-voltage side (substations), and thus for large PV power plant applications. This technology has several advantages and gives flexibility to the active power control by providing an energy "reservoir", and thus smoothing the active power [16], [19]. One important feature with energy storage system is that the PV output power can be free of fluctuations and higher than its nominal value by continuously discharging the energy storage systems. The penalty is additional cost and the introduction of lifetime-limited energy storage components into the system. Nevertheless, due to the significance in the increase of self-consumption abilities and the reduction of energy bills, many efforts have been made into the integration of PV systems with batteries or mobility energy storage systems (e.g. electric vehicles) [21], [29], [30].

B. Power Management Control

Inspired by the concept to alleviate voltage rise through active power curtailment, appropriately managing the power at the secondary control level in an aggregated PV system can contribute to a constant power production. As it is shown in Fig. 5, when the distributed grid voltage exceeds the limitation due to strong solar insolation in a highly PV-penetrated system, several PV systems have to be cut-off in order to bring the voltage back [25]. Similarly, the total output power can be maintained constant by properly managing the power of each PV unit, as it is shown in Fig. 6, where the entire system is controlled centrally. The power reference command for each PV system is sent out from a central control system. The total output power can be expressed as,

$$P_{total} = \begin{cases} \sum_{i=1}^{n} P_i, & \text{when } \sum_{i=1}^{n} P_{maxi} < P_{limit} \\ P_{limit}, & \text{when } \sum_{i=1}^{n} P_{maxi} \geq P_{limit} \end{cases} \quad (1)$$
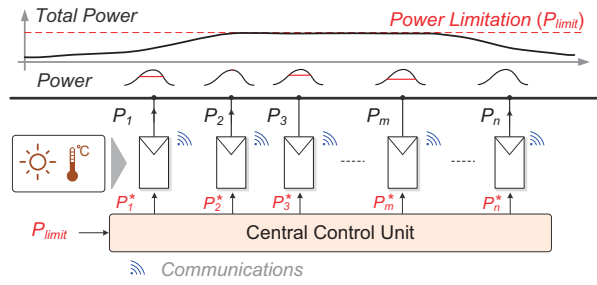
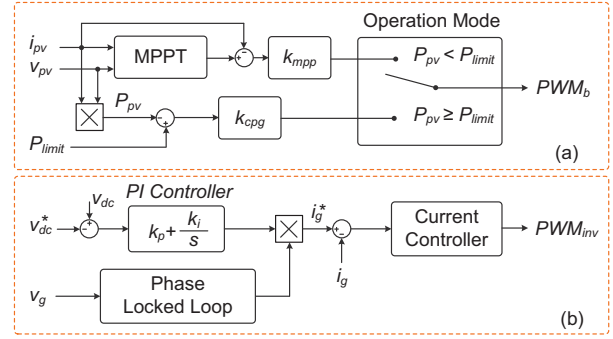Fig. 6. Power management control to achieve a total constant power production in an aggregated PV system.

Fig. 7. Control diagram of a two-stage single-phase PV system with constant power generation ability by modifying MPPT control: (a) boost control diagram and (b) PV inverter control system.
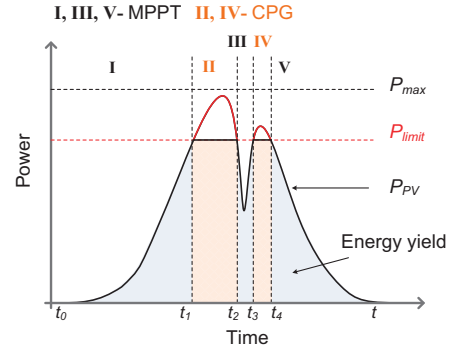

Fig. 8. Operation regions for a single-phase PV system during a day.

where P_{maxi} is the maximum power of each PV system achieved by MPPT control and P_{limit} is the total power limitation of the distributed grid.

As it is illustrated in Fig. 6, in this control strategy, some PV units operate in MPPT mode, while some in CPG mode. This means that an individual PV inverter should be able to adjust its output power (e.g. constant power) according to the power set-points from the central control unit. Moreover, this system can also operate in delta power production mode or in a controlled power ramp-rate mode, only when the power reference for each PV unit is allocated appropriately. Notably, the implementation of this control strategy requires the knowledge of the forecasted mission profiles (a better monitoring system and forecast algorithms) and an enhanced communication system.

C. Modifying MPPT Control

For an individual PV inverter, the controllability of active power can be achieved by modifying the MPPT algorithm [6]. In contrast to constant power production with energy storage systems, with modified MPPT control in the CPG operation mode, there is no need to install extra devices and thus there are no additional expenses in order to increase the penetration degree of PV systems.

In regard to Fig. 1, the control structure of a two-stage single-phase PV system with CPG control by modifying the MPPT control algorithm can be represented as shown in Fig. 7. As it is shown in Fig. 7(a), the CPG control is implemented in the control of the DC-DC stage, and hence the whole system can be divided into two operation modes based on the output power of the PV panels - the MPPT control mode and the constant power production mode. Hence, the actual power production can be expressed as,

$$P_o = \begin{cases} P_{PV}(t), & \text{when } P_{PV}(t) < P_{limit} \\ P_{limit}, & \text{when } P_{PV}(t) \geq P_{limit} \end{cases} \quad (2)$$

in which P_o is the output power, $P_{PV}(t)$ is the instantaneous power of the PV system, and P_{limit} is the power limitation.

During a day, the output power of PV strings is changing with the environmental conditions, which means that the operation modes will also alter with solar insolation and/or ambient temperature, especially in a cloudy day. Fig. 8 shows an example of different operation regions for a single-phase

PV system during a day. Then, the energy production in different operation modes can be calculated as ,

$$\begin{cases} E_{mpp} = \int_{t_0}^{t} P_{PV}(t)dt \\ E_{cpg} = \int_{t_1}^{t_2} P_{limit}dt + \int_{t_3}^{t_4} P_{limit}dt \end{cases} \quad (3)$$

where E_{mpp} is the available energy during a day with MPPT control, and E_{cpg} is the energy production in CPG operation mode in regions of II and IV in Fig. 8. Subsequently, the cut-off energy can be expressed as $E_{ess} = E_{mpp} - E_{cpg}$, which could be used to size, e.g. an energy storage system.

According to Fig. 7, Fig. 8, and (3), the operation principle of CPG control for a PV inverter can be described as follows. When $P_{pv} \geq P_{limit}$, the system enters into CPG operation mode and the MPPT control is deactivated. The PV output power is regulated by a proportional controller (k_{cpg}). The proportional controller is able to maintain the output power constant during the operation. When $P_{pv} < P_{limit}$, the system should deliver as much energy as possible to the grid with an advanced MPPT control algorithm, and thus the CPG control is disabled. In both operation modes, the DC-link voltage (v_{dc}) is regulated via a Proportional Integrator (PI) controller to be constant to ensure the power injection. Current controllers should be selected in terms of good harmonics rejection.

Fig. 9. Solar irradiance level profile under a constant ambient temperature.

The constant power production control discussed in this paper is achieved by changing the operation modes. An alternative way to attain constant power production is to directly modify the MPPT algorithm, as it is presented in [6]. Both solutions require a better knowledge of MPPT control algorithms. Typically, the Perturb-and-Observe (P&O) and incremental-conductance MPPT methods can be adopted in a PV system. However, a sudden change of the operation condition (e.g. from MPPT operation to CPG operation mode) may introduce instability [31], being a challenge for those MPPT control systems, which needs in-depth investigations.

IV. OPERATION EXAMPLES OF CONSTANT POWER GENERATION CONTROL

In order to verify the effectiveness of the proposed CPG control concept, simulations of a two-stage single-phase PV system are carried out in MATLAB/Simulink referring to Figs. 1 and 7. The model of BP 365 PV panel [32] is adopted in the verifications. Parameters of the PV panel are given in Table I. Three PV strings are connected in parallel to the DC-DC converter, and each consists of 15 PV panels in series. Thus, the rated maximum power is $P_{max} = 2925$ W. Other specifications of the system are listed in Table II.

Control systems are implemented according to Fig. 7. The P&O MPPT control method is adopted in the MPPT operation mode [33]. In the CPG operation mode, the control unit receives the power set-point command, and the PV output power is regulated using a simple proportional controller. As for the control of PV inverter, the first objective is to maintain the DC-link voltage, i.e. $v_{dc}^* = 400$ V. The second objective is to ensure the quality of grid current, and thus a Proportional Resonant (PR) controller shown in (4) is adopted in the current control loop, since it can track a sinusoidal reference quickly and accurately [14], [34]. In some cases of high power quality demands, harmonic compensations are necessary. Regarding the grid synchronization, a second-order generalized integrator [34] based phase locked loop is adopted in this system. Parameters of the control system are shown in Table III.

$$G_{PR}(s) = k_{rp} + \frac{k_{ri}s}{s^2 + \omega_0^2} \qquad (4)$$

where ω_0 is the grid nominal frequency, and k_{rp}, k_{ri} are the control parameters.

Firstly, the single-phase PV system with CPG control by modifying MPPT algorithm is tested under a constant ambient temperature, but the solar irradiance level has experienced ramp-changes, as it is shown in Fig. 9. The results of the PV system under this mission profile are presented in Figs. 10 and 11. It has been shown in those test results that, when the maximum power exceeds the limitation (80% of nominal power set by the central control system), the CPG control has been activated and thus constant output power of PV strings is achieved effectively. Once the output power goes below the limitation due to low solar insolation or high ambient temperature, the system returns to the MPPT operation with ensured stability, as it is shown in Figs. 10 and 11. Then, the maximum power from the PV strings are fed into the grid.

Fig. 12 demonstrates the performance of the PV system with CPG control under two daily profiles according to Fig. 3. The energy production is also calculated based on equation (3). The effectiveness of the proposed method by modifying
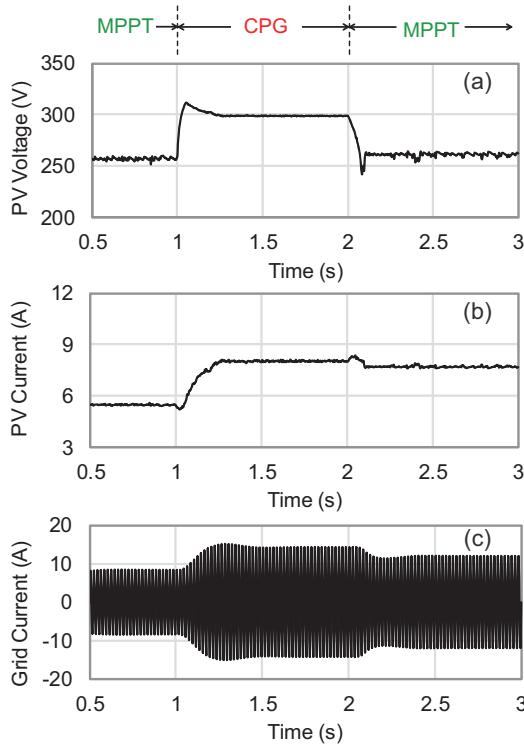
Fig. 10. Performance of the single-phase PV system with constant power generation control: (a) PV voltage, (b) PV current and (c) grid current.
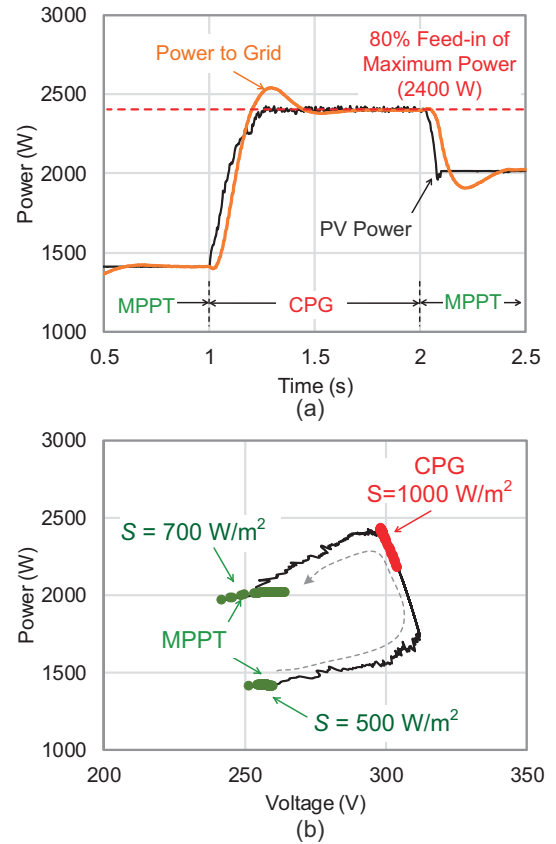

Fig. 11. Simulation results of a single-phase PV system with constant power generation control by limiting the maximum feed-in power: (a) output power and (b) PV power v.s. PV voltage.

MPPT control to limit maximum feed-in power has been demonstrated in the results. However, the injected power to the grid presents large overshoot as shown in Fig. 12(c) due to rapid solar insolation changes of a cloudy day. This means that the robustness of the control system has to be enhanced by optimizing the control parameters. Nonetheless, the proposed concept is able to control the PV systems with a constant power output and limited loss of energy, and thus more PV systems can be installed without upgrading the grid capacity.

V. CONCLUSION

In this paper, a Constant Power Generation (CPG) control concept of PV systems considering the distributed grid capacity has been explored. Since a certain limitation (e.g. 80%) of PV maximum feed-in power has an insignificant impact on the annual total energy production (e.g. 6.23% energy reduction), the CPG control concept has been proposed, which can help the DSOs to avoid grid expansion and thus save money, but at the same time increase the PV hosting capacity. Moreover, this concept can alleviate overloading issues for PV systems operating during peak production. The implementations of CPG control could achieved by power management control, integration of energy storage systems and modification of the MPPT control. The results verified the effectiveness of the CPG control by modifying MPPT algorithm. While the PV systems with integrated energy storage systems can contribute to not only the avoidance of grid expansion but also smoothing of PV feed-in power fluctuations, and thus

the system reliability is possible to be enhanced. However, installations of energy storage systems increase the total cost. Based on the discussions in the paper, further research can be put on: stability analysis of MPPT methods and the entire control system, detailed calculation of energy losses, controller parameter design, experimental verifications, and application of the CPG concept in advanced power control strategies.

REFERENCES

[1] D. Rosenwirth and K. Strubbe, "Integrating variable renewables as Germany expands its grid," [Online]. Available: http://www. renwableenergyworld.com/, Mar. 2013.

[2] K.O. Kovanen, "Photovoltaics and power distribution," *Renewable Energy Focus*, vol. 14, no. 3, pp. 20–21, May/Jun. 2013.

[3] REN 21, "Renewables 2013: Global Status Report (GSR)," [Online]. Available: http://www.ren21.net/, Jun. 2013.

[4] C. Winneker, "Worlds solar photovoltaic capacity passes 100-Gigawatt landmark after strong year," [Online]. Available: http://www.epia.org/ news/, Feb. 2013.

[5] D. Maxwell, "Parts of Northern Ireland's electricity grid overloaded," *BBC News*, [Online]. Available: http://www.bbc.co.uk/, 13 Nov. 2013.

[6] A. Ahmed, L. Ran, S. Moon, and J.-H. Park, "A fast PV power tracking control algorithm with reduced power mode," *IEEE Trans. Energy Conversion*, vol. 28, no. 3, pp. 565–575, 2013.

[7] T. Thien, R. Alvarez, Z. Cai, P. Awater, M. Leuthold, A. Moser, and D.U. Souer, "Storage- and grid expansion needs in a European electricity-supply-system with a high share of renewable energy," in *Proc. of IRES'12*, pp. 656-663, Nov. 2012.
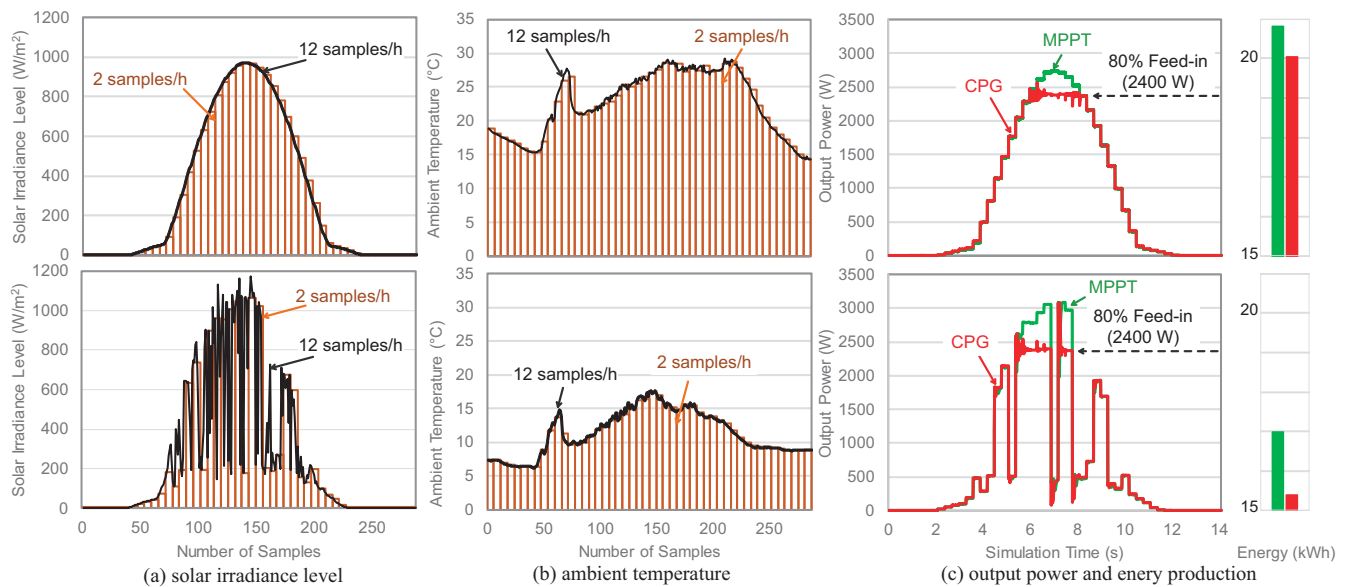
Fig. 12. Results of a 3 kW single-phase PV system with constant power generation control using recorded daily data (up: a clear day, down: a cloudy day).

[8] F. Blaabjerg and K. Ma, "Future on power electronics for wind turbine systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 139–152, 2013.

[9] Y. Bae, T.-K. Vu, and R.-Y. Kim, "Implemental control strategy for grid stabilization of grid-connected PV system based on German grid code in symmetrical low-to-medium voltage network," *IEEE Trans. Energy Conversion*, vol. 28, no. 3, pp. 619–631, Sept. 2013.

[10] ENERGINET.DK, "Wind power plants with a power output greater than 11 kW," *Technical Regulation 3.2.5*, Sept. 2010.

[11] E.ON GmbH, "Grid Code-high and extra high voltage," 2006.

[12] VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V., "Power generation systems connected to the low-voltage distribution network - Technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks," *VDE-AR-N 4105:2011-08*, Aug. 2011.

[13] S.B. Kjaer, J.K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1292–1306, Sept./Oct. 2005.

[14] F. Blaabjerg, R. Teodorescu, M. Liserre, and A.V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[15] Y. Yang, P. Enjeti, F. Blaabjerg, and H. Wang, "Suggested grid code modifications to ensure wide-scale adoption of photovoltaic energy in distributed power generation systems," in *Proc. of IEEE-IAS Annual Meeting*, pp. 1-8, 6-11 Oct. 2013.

[16] H. Gaztanaga, J. Landaluze, I. Etxeberria-Otadui, A. Padros, I. Berazaluce, and D. Cuesta, "Enhanced experimental PV plant grid-integration with a MW Lithium-Ion energy storage system," in *Proc. of ECCE*, pp. 1324-1329, 15-19 Sept. 2013.

[17] T. Stetz, F. Marten, and M. Braun, "Improved low voltage grid-integration of photovoltaic systems in Germany," *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 534–542, 2013.

[18] H. Beltran, E. Perez, N. Aparicio, and P. Rodriguez, "Daily solar energy estimation for minimizing energy storage requirements in PV power plants," *IEEE Trans. Sustain. Energy,*, vol. 4, no. 2, pp. 474–481, 2013.

[19] H. Beltran, E. Bilbao, E. Belenguer, I. Etxeberria-Otadui, and P. Rodriguez, "Evaluation of storage energy requirements for constant production in PV power plants," *IEEE Trans. Ind. Electron.*, vol. 60, no. 3, pp. 1225–1234, 2013.

[20] W. Deis and C. Kolligs, "Yet another storage project? Going beyond just storing photovoltaic energy," in *Proc. of IRES'12*, pp. 1029-1047, Nov. 2012.

[21] G. Hoffmann, "Intelligent PV- Technologies, costs and potential," in *Proc. of IRES'12*, pp. 976-1009, Nov. 2012.

[22] M. Vandenbergh, D. Craciun, V. Helmbrecht, R. Hermes, R. Lama, P.M. Sonvilla, M. Rekinger, G. Concas, H. Loew, C. Mateo, P. Frias, E. Collado, Z. Musilova, and D. Busek, "Prioritization of technical solutions available for the integration of PV into the distribution grid published," PV GRID Project, Tech. Rep.

[23] G. Mokhtari, A. Ghosh, G. Nourbakhsh, and G. Ledwich, "Smart robust resources control in LV network to deal with voltage rise issue," *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 1043–1050, 2013.

[24] R. Caldon, M. Coppo, and R. Turri, "Distributed voltage control strategy for LV networks with inverter-interfaced generators," *Electric Power Systems Research*, vol. 107, pp. 85–92, 2014.

[25] Y. Miyamoto, "Technology for high penetration residential PV systems on a distribution line in Japan," in *Proc. of the fifth Int'l Conf. on Integration of Renewable and Distibuted Energy Resources*, 4-6 Dec. 2012.

[26] G. Kaestle and T.K. Vrana, "Improved requirements for the connection to the low voltage grid," in *Proc. of CIRED*, pp. 1-5, 6-9 Jun. 2011.

[27] A. Hoke and D. Maksimovic, "Active power control of photovoltaic power systems," in *Proc. of SusTech'13*, pp. 70-77, 2013.

[28] J. Cochran, L. Bird, J. Heeter, and D.J. Arent, "Integrating variable renewable energy in electric power markets: Best practices from international experience," National Renewable Energy Laboratory (NREL), Golden, CO, USA, Tech. Rep., Apr. 2012.

[29] R. Doelling, "Greater economic viability with smaller storage capacities?" [Online]. Available: http://www.solarenergystorage.org/en/, 2013.

[30] J. Traube, F. Lu, D. Maksimovic, J. Mossoba, M. Kromer, P. Faill, S. Katz, B. Borowy, S. Nichols, and L. Casey, "Mitigation of solar irradiance intermittency in photovoltaic power systems with integrated electric-vehicle charging functionality," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 3058–3067, 2013.

[31] L. Nousiainen, J. Puukko, A. Maki, T. Messo, J. Huusari, J. Jokipii, J. Viinamaki, D.T. Lobera, S. Valkealahti, and T. Suntio, "Photovoltaic generator as an input source for power electronic converters," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 3028–3038, 2013.

[32] Plexim GmbH, "PLECS User Manual Version 3.4," [Online]. Available: http://www.plexim.com/, 14 Jun. 2013.

[33] D. Sera, L. Mathe, T. Kerekes, S.V. Spataru, and R. Teodorescu, "On the perturb-and-observe and incremental conductance MPPT methods for PV systems," *IEEE Journal of Photovoltaics*, vol. 3, no. 3, pp. 1070–1078, 2013.

[34] M. Ciobotaru, R. Teodorescu, and F. Blaabjerg, "Control of single-stage single-phase PV inverter," in *Proc. of EPE'05*, pp. P.1-P.10, 2005.