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Mitigation of Voltage Variation by REMS for Distribution Feeders

C. C. Yeh, C. S. Chen, T. T. Ku, C. H. Lin, C. T. Hsu, H.J. Chuang and H.Y. Yu

***Abstract*-- This study develops a renewable energy management system (REMS) for the control of photovoltaic (PV) smart inverters to mitigate the voltage violation of distribution systems with high penetration of PV installation. The impact analysis of distribution feeders with PV system integration for decision making of smart inverter control has been embedded in REMS to solve the voltage violation problem. To verify the effectiveness of the proposed REMS to enhance the system voltage quality, a PV system installed in a distribution feeder of Taiwan Power Company (Taipower) has been selected for field testing. The real power, reactive power and voltage of the study PV system have been collected. The impact analysis of PV integration is performed to solve the mitigation of voltage variation by the control of reactive power compensation of smart inverters. It is found that the voltage at the test PV system is very consistent to the field test results. The computer simulation of a distribution feeder with a large PV farm has been executed to illustrate that the control of smart inverters can enhance the utilization of solar energy by reducing the curtailment of renewable power generation dramatically for a distribution system with high penetration of PV systems.**

***Index Terms*—renewable energy management system, photovoltaic, distribution mapping management system, smart inverter**

I. Introduction

THE development of various types of renewable energy resources such as wind, solar, etc., is essential for achieving a sustainable environment. Although most renewable energy is less stable than conventional bulk power generation, renewable energy resources have an important role in national energy plans to reduce the greenhouse gas emissions in many areas, including Taiwan. With the decreasing price of photovoltaic (PV) panels and the financial incentive schemes for renewable energy initiatives, the installation of PV systems has been increasing rapidly. It is expected that more and more renewable programs will be introduced worldwide in the next few decades [1]. Globally, there was a total photovoltaic capacity increase of 40.1 GW in 2014 and the total cumulative capacity of PV systems reached 178 GW by the end of 2014 [2]. With Taiwan's abundant solar energy, the average daily energy that can be harnessed by PV systems is 3.6 kWh for each kWp panel capacity. The cumulative photovoltaic capacity was 847 MWp by the end of 2015 [3]. To further achieve the usage of solar energy, Taiwan government has established a set the roadmap for PV development as shown in Fig.1. To achieve the goal of 8700 MW of PV capacity by 2030, the selling price of power generated by PV has been set to 16 cents/kWh for a ground-mounted PV system and 22 cents/kWh for a rooftop PV system to promote the development of PV projects by the private sector [4].

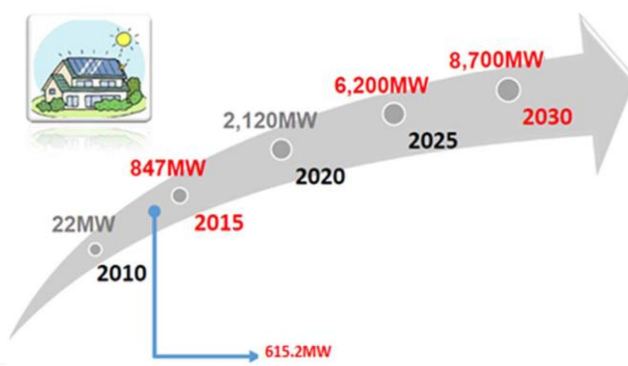

Fig. 1. Development of PV Program in Taiwan.

Although the renewable energy of PV systems provides good potential for green energy, the increased PV penetration in distribution feeders may have severe impacts on the operation of distribution systems, such as reverse power flow, voltage rise and fluctuation. It may also jeopardize the voltage regulation for conventional on-load tap changers of substation transformers, etc. [5]-[10].

To the present, considerable efforts have been devoted to mitigate the overvoltage problem introduced by the injection of intermittent renewable power generation. Reactive compensation facilities such as STATCOM have been used at

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the connection point of large renewable power generation to reduce the problem of voltage flicker [11]. Active power curtailment techniques have been proposed to reduce the real power injection in case of peak solar irradiation when high penetration PV systems have been installed in the distribution feeders [12]-[13]. For conventional PV inverters, the power factor is fixed at 1.0 so that only the real power is generated. When the output terminal voltage of PV systems violates the overvoltage constraint, the output active power of the PV inverter must be reduced by changing its operation mode from the maximum power point towards the open circuit voltage of PV panel. The operation mode of minimum power output will be adopted if the overvoltage problem at point of common coupling (PCC) cannot be completely solved by reducing PV power generation [14]-[15]. Stetz et al. [16] propose autonomous control of inverters for voltage improvement using the reactive power consumption and curtailment of the feed-in active power. A two-stage voltage control architecture for PV generation is proposed in [17]. The optimal control of the reactive power output by PV inverters to reduce voltage violation with respect to a control reference is proposed in [18]. In [19], the authors present an optimization strategy applied to a new algorithm for decentralized voltage control based on sensitivity analysis [20]. Reference [21] analyzes impacts of the cloud effect on voltage stability to find that reactive power support provided by PV inverters can solve the instability problem [22].

To enhance the service reliability of distribution systems, the Distribution Automation System (DAS) has been implemented in Taipower since 1996 to support service restoration when a system fault contingency occurs. In this case, load transfer among distribution feeders is executed to restore the power service of unfaulted but out of service line sections. The connected PV systems as well as the loading of unfaulted sections of the faulted feeder will be transferred to another neighboring feeder by closing the tie switch between two feeders after the faulted section is isolated. It is found, however, that very severe overvoltage problems will be introduced after the execution of load transfer when distribution feeders with high PV penetration are involved. To solve this overvoltage problem, the DAS will inform the REMS of the load transfer operation with the line switches to be operated. The topology process is executed to update the network configuration of the supporting feeder. The PV systems to be transferred from the faulted feeder are also identified. The impact analysis of PV integration for the supporting feeder is then applied to solve the voltage magnitude of all PV systems. The control command is issued by REMS to adjust the power factor setting and even the real power reduction of PV systems. After completing the control of PV smart inverters, the REMS will inform the DAS to perform the load transfer of service restoration [23].

This paper makes the following contributions.

1) Estimate the PV power generation according to the PV panel temperature and the hourly solar irradiation provided by the weather bureau for the area of the distribution feeder.
2) Automatically generate the network configuration of study feeders by retrieving the attributes of distribution components from Taipower's facility database to support the impact analysis of PV integration.
3) Develop REMS to support the decision making for the control of PV smart inverters to adjust its power factor and even real power reduction to maintain good service voltage quality for both steady state and fault emergency operation of distribution systems.

This paper is organized as follows. Section II briefly describes the renewable energy management system. In Section III, the proposed approach for active power dependent power factor control by PV inverters is presented. In Section IV, the assessment approach is then applied on an actual Taipower distribution feeder for field testing of smart inverters. The testing results are then applied to verify the accuracy of impact analysis of PV integration. The effectiveness of smart inverters to mitigate the problem of voltage variation due to PV power generation has been demonstrated. In Section V, a case study of a practical Taipower distribution feeder with a large PV farm is conducted to illustrate the reduction of real power curtailment of PV system with smart inverters. Finally, conclusions are presented in Section VI.

II. Renewable Energy Management System

To provide more effective control of PV renewable power generation that can help solve the overvoltage problem due to high PV penetration in a distribution system, this study develops a renewable energy management system (REMS) to control PV smart inverters and thereby enhance system voltage quality [24]. The hourly PV power generation of field PV systems is predicted according to day-ahead weather forecasting data. The three phase load flow analysis is then executed to solve the possible voltage rise at the PCC of all PV systems. The control algorithm is then applied in the REMS master station to derive the proper power factor setting and even the real power curtailment for each PV system. The public 4G communication system is used to transmit the control command to the gateway of PV smart inverters. The voltage, real power and reactive power generation of the PV system after executing the control command are then reported to the master station. To support the impact analysis of PV integration in distribution system, system data of the distribution feeder must be determined using the interface programming to retrieve the attributes of the line segment and integrated PV systems from the database of a digital mapping system. A topology process is executed to find the network configuration of the study distribution feeder based on the connectivity attributes of line segments. Based on the simulation results, the decision making process is then derived for the control of PV smart inverters to adjust the power factor and the real power output of PV system when a voltage violation occurs due to excessive PV power generation during peak solar energy periods.

The REMS performs the control of PV smart inverters for regulation of reactive power compensation and real power output reduction when an overvoltage problem occurs due to excessive PV power generation during peak solar energy periods [25]. It also derives the decision making process and performs real time control of a smart inverter before the load transfer is executed for service restoration after fault contingency. Three-phase load flow analysis is applied to solve the system power flows and node voltages according to the expected power generation of PV systems. A sorting analysis of hourly weather data retrieved from the Central Weather Bureau of Taiwan is performed to derive the solar irradiation profiles for the next following day, and this is used to estimate the hourly power generation of each PV system connected in the study distribution feeder.

The attributes of line segments such as conductor size and length, the attributes of distribution transformers such as capacity and impedance are retrieved from the facility database of the Distribution Mapping Management System (DMMS) in Taipower. The network configuration of a distribution feeder is then identified after performing the topology process according to the connectivity attributes of distribution line segments. The impedance matrix of study distribution feeder is then built and applied for the load flow analysis to solve the system voltage by considering the power generation of all PV systems and the load demand of all load buses.

The network configuration of a distribution system often varies with the operation of line switches for executing the load transfer between two neighboring feeders to achieve service restoration after a fault contingency and to support scheduled maintenance. With high penetration of PV integration in distribution feeders, it is expected that system overvoltage problems will be introduced due to excess PV power generation after load transfer. Therefore, the line switches to be operated for load transfer and the corresponding feeder network reconfiguration must both be transmitted from DAS to REMS. The impact analysis of PV generation is then executed to solve the new bus voltage according to the revised feeder topology and PV systems. If the solved bus voltage violates the operation constraint of 1.05 pu, the power factor of each PV inverter is then adjusted adaptively to mitigate the voltage violation due to the increase of both PV power generation and the length of supporting feeder after load transfer.

The power factor setting for each PV system derived by impact analysis is downloaded to the gateway of each smart inverter to perform proper control of reactive power compensation. If the bus voltage violation still exists after power factor control, the real power output of the PV system must be reduced until it reaches the lowest limit of 10% of smart inverter rating capacity. After completing the decision making for control of power factor and real power generation curtailment, the control command is transmitted by the REMS master station to the gateway of each PV system by using the public G4 communication network. Figure 2 shows the function block diagram of the REMS.

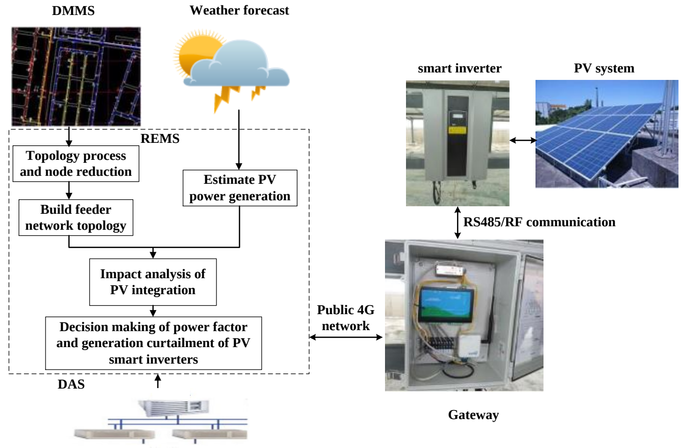

Fig. 2. Function block diagram of the REMS.

Figure 3 shows the two-way communication topology of REMS. Field data such as solar irradiation, PV panel temperature, as well as the real power generation and reactive power compensation of smart inverters have been collected and sent to the gateway of each PV system with RS-485 or wireless RF. The gateway concentrates the above field data at the rate of one record per second, which is then transmitted and stored in the REMS server database.

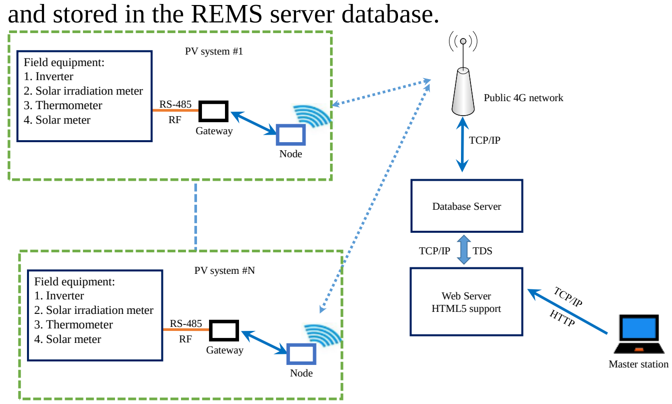

Fig. 3. Communication topology of REMS.

III. Voltage Control by PV Smart Inverter

The proposed variable power factor control method could be used as the normal state of operation for the smart inverters. Figure 4 shows the man machine interface for the proposed PV inverters. The control of power factor is executed by Taipower according to the level of real power output of the PV system. There are four setting points of (P, PF) for each control curve. The utility company determines the settings by adjusting the (P, PF) pairs in the mode configuration array by considering the installation location of each PV system to be controlled. Each array will have a variable number of points to define the piece-wise linear curve of the desired Watt-Power factor behavior. In the example of Fig. 4, there are 4 points, labeled P1 through P4. The P-values of the array will be the real power output, expressed as the percentage of maximum nameplate real power output. The PF values of the array will be the setting of power factor corresponding to the real power output. The leading power factor is used by the smart inverter

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to generate the reactive power to raise the voltage level when the real power generation by the PV system is less than P2. On the other hand, the lagging power factor is used by the smart inverter to absorb the reactive power when the real power generation by the PV system is larger than P3. When the real power generation of the PV system varies between the range of 20% to 80%, the power factor of 1.0 is applied and there will be no reactive power control required since the voltage variation at the PCC is within the operation constraints.

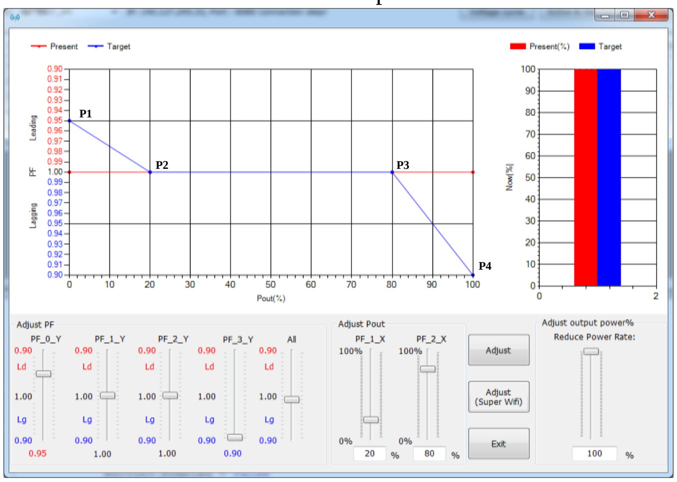

Fig. 4. Array setting of Watt-Power factor for control of a smart inverter.

To determine the array setting of the Watt-Power factor for all PV systems integrated in a distribution feeder, the REMS performs three-phase load flow analysis to solve the voltage magnitude at the PCC. If the voltage magnitude is greater than 1.05 pu, the power factor of smart inverter is adjusted first. If the power factor has reached its limit while the overvoltage violation still occurs, the real power output of the PV system must be curtailed. Figure 5 shows the overall process proposed for controlling both the power factor and real power curtailment for the smart inverter of each PV system.

IV. FIELD TESTING OF PV SYSTEM WITH SMART INVERTERS

To demonstrate the effectiveness of REMS in controlling the smart inverters to achieve good service voltage quality for distribution feeder with high penetration of PV systems, the actual distribution feeder RA11 for Taipower Penghu District is selected for field testing and computer simulation. Figure 6 shows the one-line diagram of the test feeder. There are five PV systems with total capacity of 820 kWp installed at different buses respectively. The rooftop PV system with capacity of 352 kWp at Bus 13 is selected for a case study in this paper. A gateway is installed at the study PV system for collection of power output of 29 smart inverters with capacity of 12 kVA each. The total power generation of the PV system is then reported to the REMS database. When the gateway receives the control command from REMS, the broadcasting control of power factor and real power generation for all inverters is executed.

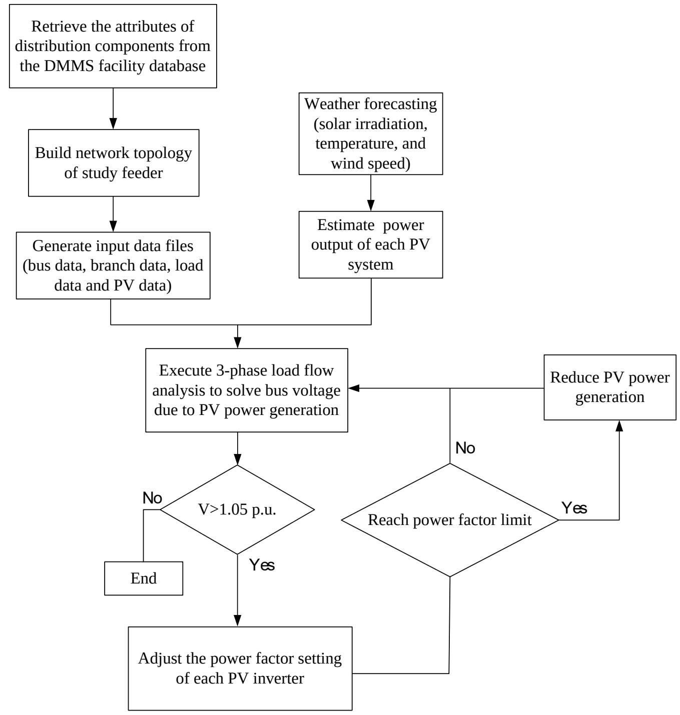

Fig. 5. Decision making process of power factor setting and real power curtailment for control of PV smart inverters.

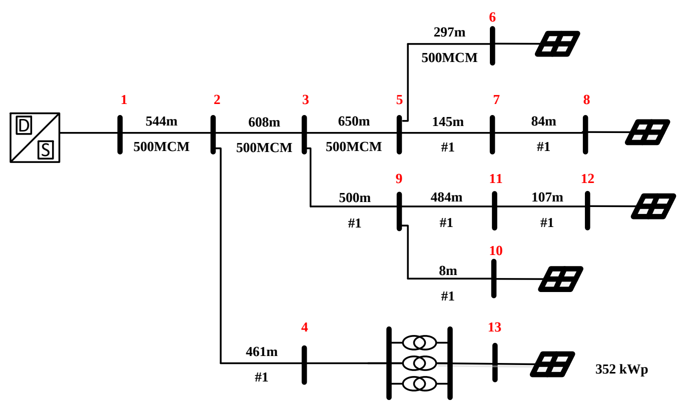

Fig. 6. One-line diagram of test feeder RA11.

Figures 7 and 8 show the profiles of real power generation, reactive power generation and voltage of the PV system after the execution of power factor control and real power curtailment with the data sampling interval every 0.2 seconds. There are 7160 data records collected during the test period for the control of smart inverters. Before the execution of smart inverter control, the real power generation by the PV system is 262 kW and the voltage level at PCC is 226.3 V. For period I, the power factor is adjusted from 1.0 to 0.9 lagging to absorb the reactive power of 124 kVAR. It is found that the real power output of the PV system remains unchanged, while the bus voltage has been reduced to be 224 V by power factor control. Then the power factor of the smart inverter is controlled back to 1.0 in period II, and the voltage is restored to 227 V. During this time period, real power generation of the PV system experiences a fluctuation of 85 kW due to sudden cloud effect, which also causes a dramatic voltage variation. For period III, the power factor is adjusted from 1.0 to 0.9

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leading to generate more reactive power by the smart inverter. The bus voltage reaches 229 V due to the excessive reactive power injection of 135 kVAR by the inverter. For the test period IV, the smart inverter is shut down. With the real power generation of PV system being reduced to be zero, the bus voltage is decreased from 229 V to 225 V. For period V, the smart inverter restore its normal operation with power factor equal to 1.0, the voltage is then increased from 225 V to 226.7 V.

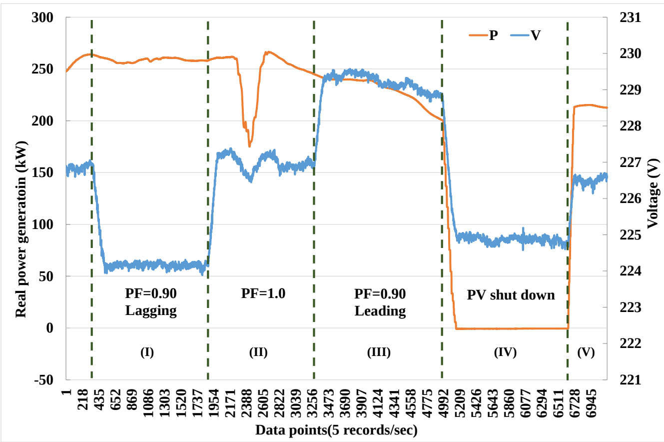

Fig. 7. Profiles of real power generation of PV system and PCC voltage after control of smart inverter (2015/06/25-10：30AM).

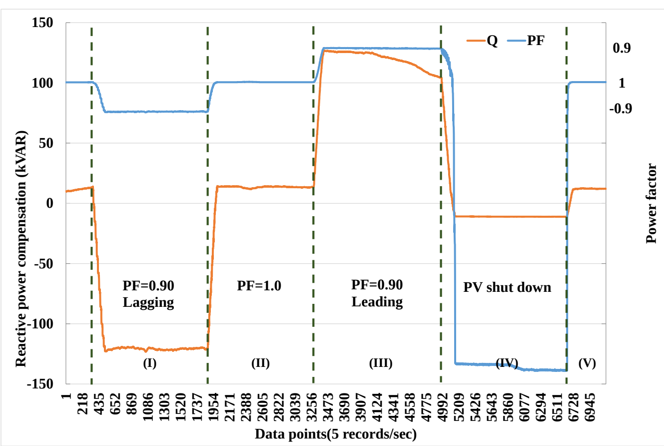

Fig. 8. Profiles of reactive power compensation and power factor (2015/06/25-10：30AM).

In this paper, the computer simulation of the test feeder is executed by using the actual real power generation of a PV system and the reactive power compensation of the smart inverter for different test periods in Fig. 7 and Fig. 8. Table I shows the voltage variations of field measurement at PCC and the results of computer simulation for different control scenarios of smart inverters. It is found that the voltage variations solved by the impact analysis of PV integration in REMS for three scenarios are very close to those of the field measurements. This supportive evidence shows that REMS has good capability to resolve the effectiveness of smart inverters to maintain good power quality for the distribution system with high penetration of PV system.

TABLE I
VOLTAGE VARIATIONS OF FIELD MEASUREMENT AND COMPUTER SIMULATION FOR CONTROL OF SMART INVERTERS

Feeder RA11 (PV=355 kWp)	Voltage variations (Δ V)		PV output (KW) (before control)
	Field measurement	simulated	
PF=1.0→PF=0.9 (lagging)	2.3	2.3	260
PF=1.0→PF=0.9 (leading)	4.0	3.9	260
PV shutdown →PV on (PF=1.0)	1.7	1.8	215

V. MITIGATION OF VOLTAGE VARIATION FOR FEEDERS WITH HIGH PV PENETRATION

In this study case, a practical Taipower distribution feeder with a large solar farm is selected for computer simulation to demonstrate the effectiveness of smart inverters to increase the PV penetration without violating the system overvoltage constraint. Figure 9 shows the test feeder with a large PV farm with capacity of 3750 kWp being installed at Bus 4. The hourly power generation of the PV system has been derived by considering the solar irradiation over the daytime period. The real power generation by the test PV system is increased during the morning session and reaches the maximum value of 3000 kW at 1 PM as shown in Fig.10. Without applying the smart inverters for voltage control, the bus voltage at PCC will exceed 1.08 pu because too much real power is generated and injected by the PV system. Without applying the smart inverters, the real power generation of the PV farm must be curtailed from 9 AM to 4 PM to solve the overvoltage problem due to high PV penetration. For instance, the real power generation is reduced from 3000 kW to 1680 kW at the solar peak hour of 1 PM. The total curtailment of solar energy over this one day period reaches 6519 kWh for the solar farm, so that the bus voltage can be reduced from 1.08 pu to 1.05 pu to comply with the operation regulation of the distribution system. Therefore, the solar energy collection is deteriorated dramatically due to the voltage violation problem for high penetration of PV system.

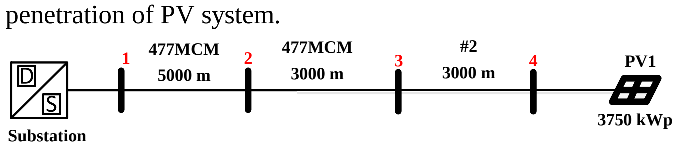

Fig. 9. One line diagram of test Taipower feeder.

To reduce the real power generation curtailment of PV system and maintain good service voltage quality at the same time, the smart inverters with the two functions of power factor control and real power curtailment are proposed for this large PV farm. The smart inverters have the capacity to adjust its power factor from 0.95 leading to 0.95 lagging. To maintain the voltage level at PCC without violating the operation constraint, the power factor of the smart inverters is adjusted from 9 AM to 4 PM as shown in Fig. 11. For the solar peak hours of 12 PM and 1 PM, the reactive power compensation cannot be increased any further because the power factor has

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reached its limit of 0.95. Therefore, real power curtailment of PV generation must be implemented in these time periods so that the problem of voltage violation can be completely solved. The power generation curtailment of the PV system is reduced by 118.9 kW and 150 kW for 12 PM and 1 PM respectively. By comparing Fig. 10 and Fig. 11, it is found that curtailment of real power generation of the PV system at 1 PM has been reduced for 1320 kW to 150 kW when the REMS is applied for control of the smart inverters to regulate the reactive power compensation and perform the real power curtailment during the solar peak hours. The total energy curtailment of the PV system over a daily period has also been reduced from 6519 kWh to 269 kWh. The advantage of using smart inverters to enhance PV penetration in a distribution system for better collection of solar energy has therefore been verified by this case study.

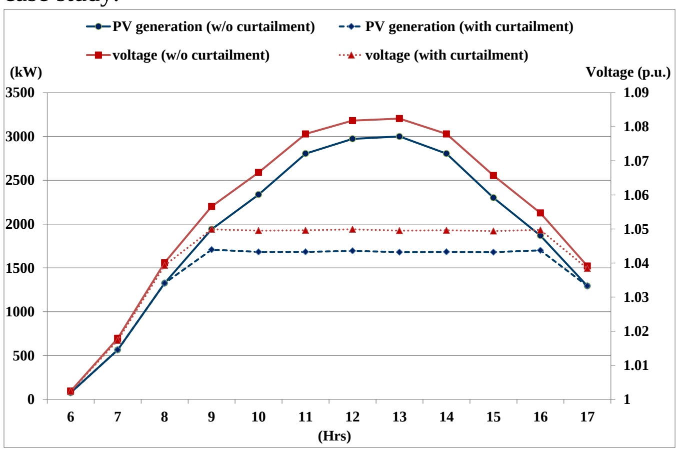

Fig. 10. Profiles of real power generation and bus voltage of test PV farm (using real power curtailment).

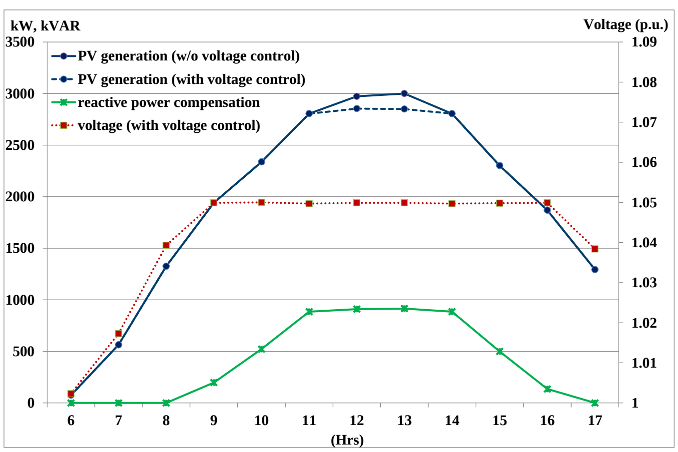

Fig. 11. Profiles of real power generation, reactive power compensation and bus voltage of test PV farm (using smart inverter).

VI. Conclusions

A renewable energy management system has been proposed in this study to provide the highly effective control of PV smart inverters to enhance the utilization of solar energy and to prevent the overvoltage problem for distribution system with high penetration of PV systems. The real power generation by each PV system connected in the distribution feeder is determined according to the installation capacity, the hourly solar irradiation forecasting and the PV panel temperature. An impact analysis software has been embedded in the REMS system, which will retrieve the attributes of distribution components from the facility database to build the network topology of study feeder and generate the input data files for impact analysis. The decision making for the control of PV inverters has been derived to adjust the power factor setting and real power generation curtailment for the PV system when the service voltage exceeds the operation constraint. To verify the accuracy of the impact analysis due to PV integration and to demonstrate the effectiveness of the proposed REMS, a rooftop PV system with capacity of 352 kWp has been selected for field testing and computer simulation. It is found that the voltage variation at the PCC after the control of power factor and real power curtailment by the smart inverters is very consistent with the results of impact analysis of PV system integration.

To investigate the effectiveness of the proposed REMS in maintaining the voltage quality of a distribution system with high PV penetration, a large PV farm with capacity of 3750 kWp, which has been installed in an actual feeder, is used for a case study. When the traditional PV inverters with fixed power factor of 1.0 are used, the PV power generation must be curtailed by 1320 kW at 1 PM to prevent the voltage violation of 1.05 pu and the total energy curtailment over a daily period will reach 6519 kWh to maintain good quality of service voltage. With the proposed Watt-Power factor control method, only 140 kW of PV power generation has to be curtailed at 1 PM after the reactive power compensation of 915 kVAR by the smart inverters. It is concluded that the implementation of REMS for the control of smart inverters can increase the PV penetration dramatically in a distribution system to enhance the solar energy harvesting without causing voltage violation problem.

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VIII. Biographies

Chih-Chieh Yeh received the M.S. degree in Electrical Engineering from Southern Taiwan University of Science and Technology, Tainan, Taiwan, in 2011. He is currently pursuing the Ph.D. degree in Electrical Engineering at National Sun Yat-sen University, Kaohsiung, Taiwan.

Chao-Shun Chen (M’84-SM’06) received the B.S. degree from National Taiwan University in 1976 and the M.S, Ph.D. degree in Electrical Engineering from the University of Texas at Arlington in 1981 and 1984 respectively. From 1984 to 1994 he was a professor of Electrical Engineering department at National Sun Yat-Sen University.
From 1989 to 1990, he was with Empros Systems International. Since Oct. 1994, he works as the Deputy Director General of Department of Kaohsiung Mass Rapid Transit. From Feb.1997 to July 1998, he was with the National Taiwan University of Science and Technology as a professor. From August 1998 to January 2008, he was with the National Sun Yat-Sen University as a professor. From February 2008, he is with I-Shou University as a chair professor and with National Sun Yat-Sen University as a joint professor. His majors are computer control of power systems, electrical and mechanical system integration of mass rapid transit systems.

Te-Tien Ku (S'2009-M'2014) received the M.S. and Ph. D. degree in Electrical Engineering from National Sun Yat-Sen University in 2006 and 2012 respectively. He is presently an assistant professor at National Penghu University of Science and Technology. His area of interest is smart grid and applications to distribution systems.

Chia-Hung Lin(S’95-M’98-SM’13) received the B.S. degree from National Taiwan Institute of Technology in 1991, M.S. degree from University of Pittsburgh in 1993, and Ph. D. degree in Electrical Engineering from University of Texas at Arlington in 1997.
He is presently a full professor at National Kaohsiung University of Applied Sciences. His area of interest is distribution automation and computer applications to power systems.

Cheng-Ting Hsu (M’90) was born in Taiwan in 1963. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from National Sun Yat-Sen University, Kaohsiung, Taiwan, in 1986, 1988, and 1995, respectively. From 1990 to 1992, he was a Power Electronics Engineer with Phoenixtec Power Company Limited, Taipei, Taiwan, developing uninterruptible power supply equipment. He is currently a Professor of electrical engineering at Southern Taiwan University, Yung-Kang City, Taiwan.

Hui-Jen Chuang(S’98-M’02) received the B.S. and M.S. degree in Electrical Engineering from National Taiwan University of Science and Technology in 1990 and 1992 respectively, and Ph. D. degree in Electrical Engineering from National Sun Yat-Sen University in 2002.
He is presently a Professor at Kao Yuan University, Lu Chu, Taiwan. His research interest is in the area of load flow and power system analysis of mass rapid system.

Hung-Yi Yu received the M.S. degree in electrical engineering from The University of Queensland, Australia in 2010 and his Ph.D. degree of Electrical Engineering from The University of Sydney, Australia in 2015. He is now the head of intelligent distribution section, department of power distribution in Taiwan Power Company. He has more than twenty years of working experience in Taiwan Power Company in different fields of design, protection, intelligent electronic devices (IED), circuit breakers, smart grid and renewable energy resources particularly in photovoltaic power in distribution system.