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Integration of Photovoltaic Systems into Distributed Grids without Battery Energy Storage

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ABSTRACT

Integration of photovoltaic systems (PVs) without battery energy storage into distributed grids is considered in this paper to evaluate of this generation to their operating parameters. System structure (including power converter, measurement and control system) and working modes of PVs will be introduced and analyzed to show the its power variation. The system of bus power balance and Newton-Raphson algorithm is also established in this paper to determine operating parameters of the microgrid. A 35-kV distributed grid is simulated by the ETAP software corresponding to a fixed value for load buses and varied values of power of solar irradiance. Simulation results showed the change of power flows in branches and the increase of bus voltage in cases of having power participation of PVs at a bus (enough power of solar irradiance). Due to working as a distributed generator, research results are useful for dispatchers to make operating plans for whole power system and implement PVs at other buses or change transmission lines with suitable sections.

Keywords: ETAP software, maximum power point, Newton-Raphson, photovoltaic system, power converter, system of power balance equations.

INTRODUCTION

PVs is a system harnessing power from photovoltaic generator (PVG) through power converters. The integration of PVs into distributed grids can affect to operating system parameters. It must be evaluated by using mathematical and simulation tools to make suitable operating plans for whole power system at any time [1].

Power participation of PVs depends on the capability of photovoltaic conversion corresponding to each type of PVG, power of solar irradiance (G), temperature (T) at p-n junction and control method [2]. To harness power from PVs and connect to the power system, power converters play an important role to regulate PVG [3]. They can help to harness maximum power from PVG, integrate PVG and energy storage (option), synchronize to the grid and generate power to the grid. At each time, dispatchers must find out characteristics of PVs to exactly determine integrating power between PVs and the grid as nature or requirement that help to hold stability for whole system.

To have information about power flows in branches and bus voltage, Newton-Raphson method was proposed to solve the system of power balance equations in power system. Approximate solutions can be determined by classifying type of buses and using impedance matrix. Because the value of solutions is near to rated value, this method has a fast speed of convergence and is often chosen to determine operating parameters of power system by computer [4], [5].

Corresponding to above analysis, it must be made clear about the method to harness power, the integration between PVs and the grid at any time and the effect of PVs into operating parameters of distributed grids. To execute this purpose, the next section will represent the structure and characteristic of system harnessing PVG. Section III will introduce contents of Newton-Raphson method applied to determine operating parameters of the grid. Section IV will show some simulation results for a grid example in some scenarios of G. The last section will give out some conclusions.

POWER STRUCTURE AND CONTROL FUNCTIONS OF PVs

In grid-connected systems, PVG can be harnessed and synchronized by DC/DC and DC/AC converters. Power structure and control functions of PVs are described in Fig. 1 [3].

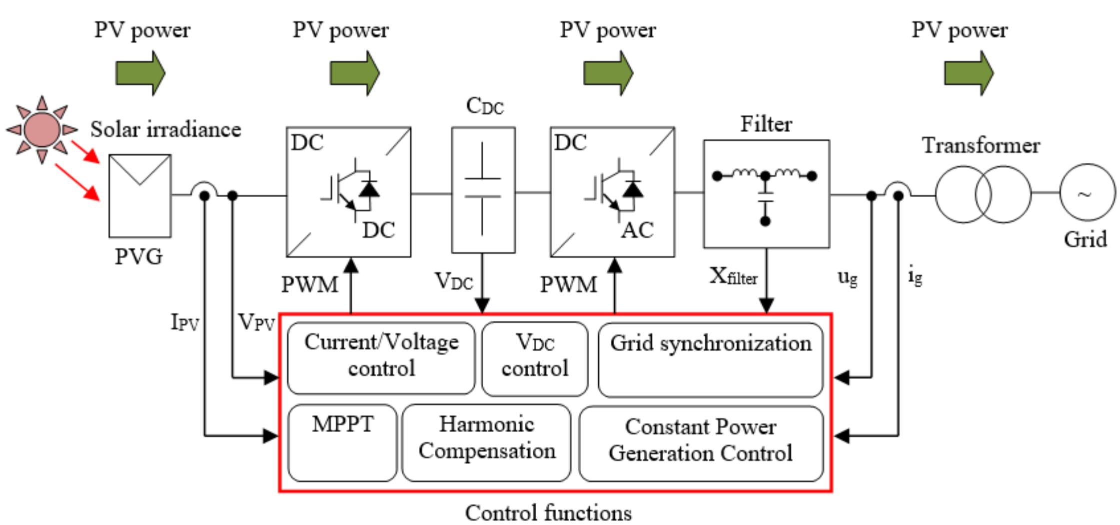

Fig. 1. Power structure and control functions of PVs

Power structure of this system has some main units such as C_{dc} capacitor, DC/DC and DC/AC power converters, filter and transformer. C_{dc} capacitor helps to charge and discharge energy instantaneously that contributes to hold stable voltage at DC bus. The DC/DC converter regulates PVG to harness maximum power from this generation at any time. The DC/AC helps to synchronize with the grid and generate PV power to the grid. The filter and transformer play an important role to filt high order harmonic of the current integrating between PVs and the grid. Output voltage of the transformer is also suitable for the requirement of the grid. Due to having no energy storage and small power loss, almost PV power runs through the DC/DC and DC/AC to the grid without charging. For this reason, power from PVs always fluctuates corresponding to the variation of G.

Some main measurement quantities are voltage and current at output terminals of PVG; voltage at DC bus; voltage and current at point of common coupling with the grid. These quantities must be collected in this structure to execute control functions, such as control current or voltage at output terminals of PVG to operate it at maximum power point; regulate voltage at DC bus at a reference value; control to compensate high order harmonic or regulate power integration between PVs and the grid.

Although power generating from PVG depends on many factors but it only varies much in case of much variation of G. Peak points, called maximum power point (MPP), moves up or down instantaneously and immediately corresponding to the change of G as described in Fig. 2 [2].

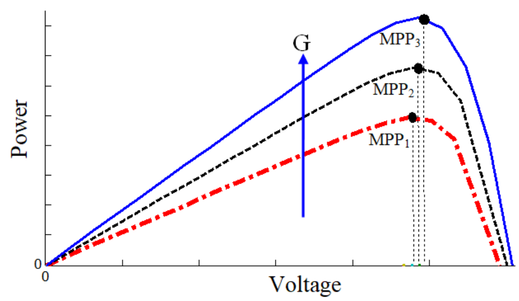

Fig. 2. Movement of MPP corresponding to the change of G

Power integrating between PVs and the grid is zero or near zero when G is very small. It also reached to rated value at any time in daytime if standard test condition exists. Due to always fluctuation and large range variation, power generating from PVs can affect much to the grid and must be evaluated more detailed through simulation process before having decisions to dispatch whole system.

EFFECT PVs WITHOUT ENERGY STORAGE TO POWER FLOWS AND BUS VOLTAGE IN DISTRIBUTED GRIDS

A simple grid with the participation of PVs at bus B is considered in Fig. 3.

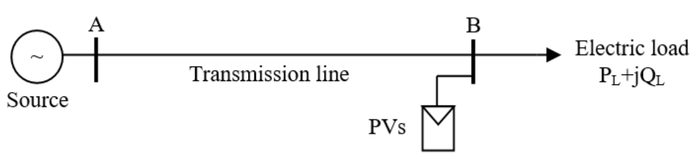

Fig. 3. A simple power system

In this system, active and reactive power losses in transmission line can be determined by (1) [5]:

$$\begin{cases} \Delta P_{line} = \dfrac{(P_L - P_{pv})^2 + Q_L^2}{U_A^2} R_{line} \times 10^{-3} \\ \Delta Q_{line} = \dfrac{(P_L - P_{pv})^2 + Q_L^2}{U_A^2} X_{line} \times 10^{-3} \end{cases} \quad ◎◎◎$$

where, P_L and ΔP_{line} (kW) are active power of load and active power loss in transmission line,
P_{pv} (kW) is the integration power between PVs and the grid,
Q_L and ΔQ_{line} (kVAr) are reactive power of load and reactive power loss in transmission line,
U_A (kV) is voltage at bus A,
R_{line} and X_{line} (Ω) are resistance and reactance of the transmision line.

Voltage at bus B can be determined by (2):

$$\Delta U_{line} = \frac{(P_L - P_{pv})R_{line} + Q_L X_{line}}{U_A} \qquad (2)$$

At night-time (without solar irradiance), power integrating between PVs and the grid is zero. This case is same as cases without implementing PVs at bus B. At daytime (having solar irradiance), PVs will help to reduce power mobilized from source, power and voltage losses (ΔP_{pv} and ΔU_{line}).

When the grid becomes more complex with many branches and buses, power flows in branches and bus voltage are also more difficult than above simple grid. In these case, Newton-Raphson method can be used to solve this problem due to fast convergence and high accuracy [4]. It means that the active effect of PVs to the grid will be made easier and clearer if it is implemented at many buses with suitable capacity.

To determine operating parameters for N-bus grid by using Newton-Raphson method, system of power balance equations at the i^{th} bus can be defined by (3) and (4) [5]:

$$U_i^2 y_{ii} \cos\psi_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{N} U_i U_j y_{ij} \cos(\delta_i - \delta_j - \psi_{ij}) = \Delta P_i \qquad (3)$$

$$-U_i^2 y_{ii} \sin\psi_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{N} U_i U_i y_{ij} \sin(\delta_i - \delta_j - \psi_{ij}) = \Delta Q_i \qquad (4)$$

where: $i = \overline{1, N}$; $\Delta P_i = P_{Li} - P_{Gi}$; $\Delta Q_i = Q_{Li} - Q_{Gi}$; $\dot{U}_i = U_i \angle \delta_i$; $Y_{ij} = y_{ij} \angle \psi_{ij}$

P_{Li} and Q_{Li} are active and reactive load power at the i^{th} bus; P_{Gi} and Q_{Gi} are active and reactive power of PVs at the i^{th} bus. Because PVs is considered as an active generator, integrating power between PVs and the grid at any time depends on G and T as defined by (5):

$$\begin{cases} P_{Gi} = P_{pv}\big|_{G,T} \\ Q_{Gi} = 0 \end{cases} \qquad (5)$$

In this problem, solutions are module and angle of bus voltage at the i^{th} bus. Solutions at the $(k+1)^{th}$ step can be determined by (6) [5]:

$$\begin{bmatrix} \delta_i^{(k+1)} \\ U_i^{(k+1)} \end{bmatrix} = \begin{bmatrix} \delta_i^{(k)} \\ U_i^{(k)} \end{bmatrix} + \begin{bmatrix} \Delta\delta_i^{(k)} \\ \Delta U_i^{(k)} \end{bmatrix} \qquad (6)$$

where, $\Delta U_i^{(k)}$ and $\Delta \delta_i^{(k)}$ are module and angle errors of bus voltage at the the i^{th} bus and the k^{th} step. These errors can be calculated by (7) at the k^{th} step [5]:

$$\begin{bmatrix} \Delta\delta_i^{(k)} \\ \Delta U_i^{(k)} \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P_i^{(k)} \\ \Delta Q_i^{(k)} \end{bmatrix}$$ ◎◎◎

where, J^{-1} is the inversed matrix of Jacobian matrix,

$\partial P_i^{(k)}/\partial \delta_i^{(k)}$, $\partial P_i^{(k)}/\partial U_i^{(k)}$, $\partial Q_i^{(k)}/\partial \delta_i^{(k)}$ and $\partial Q_i^{(k)}/\partial U_i^{(k)}$ are elements of Jacobian matrix.

$\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are active and reactive power errors at the k^{th} step

Newton-Raphson algorithm applied to determine operating parameters with the participation of PVs is described in Fig. 4 [5].

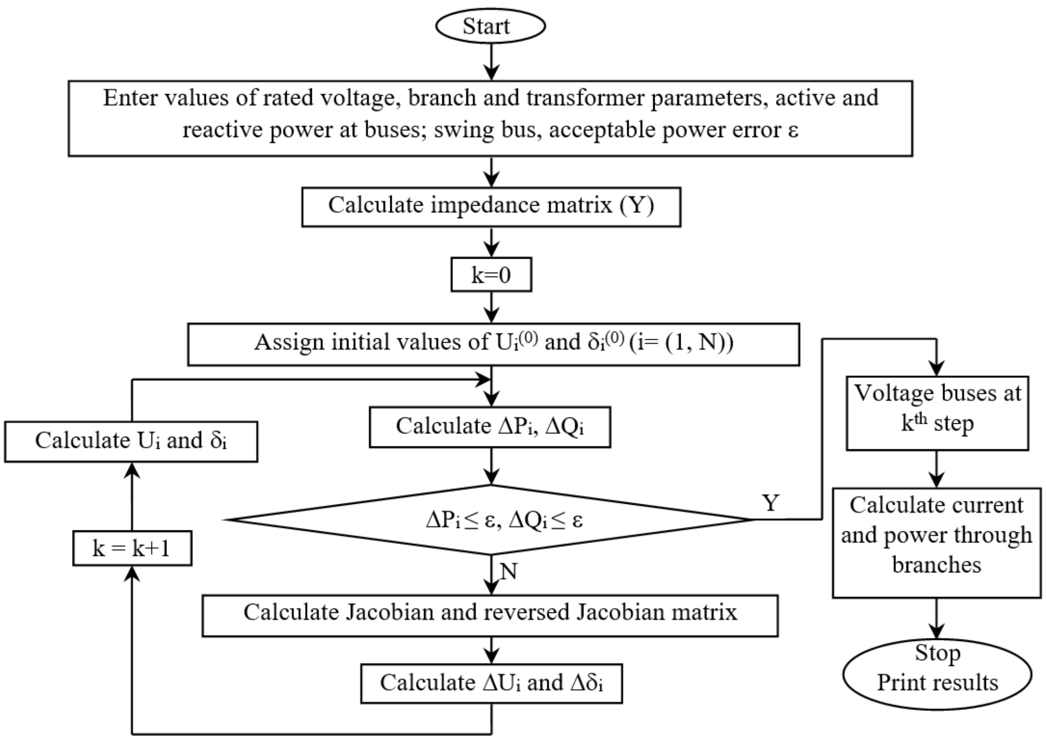

Fig. 4. Newton-Raphson algorithm to determine operating parameters in the grid

SIMULATION RESULTS

The diagram of the example grid with the participation of PVs at bus P4 is considered in Fig. 5.

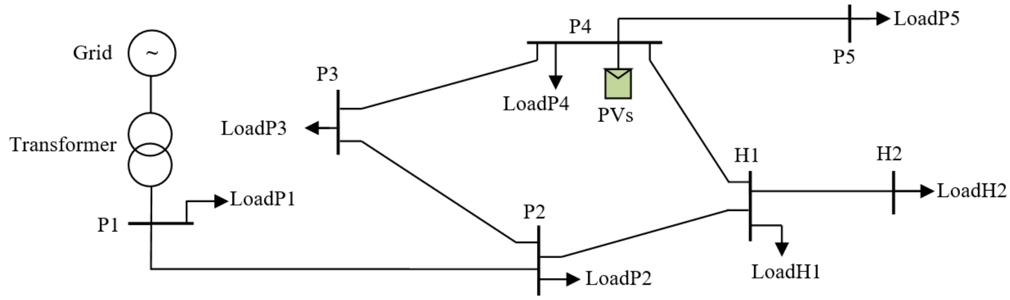

Fig. 5. Diagram of simulation grid

Known parameters to simulate include: source and transformer in Table 1, transmission lines in Table 2, electric load at bused in Table 3 and PVs in Table 4.

Table 1. Parameters of source and transformer

Type	Parameters
Grid	Rated voltage: 110 kV; Short-circuit power: 5000 MVA; Reactance/Resistance: ∞
Power transformer	Voltage ratio: 110/35 kV; Rated power: 25 MVA; Impedance: Z=10%; Reactance/Resistance: 20

Table 2. Parameters of transmission lines

Name	Sectional area (mm²)	Type	Length (km)	Name	Sectional area (mm²)	Type	Length (km)
P1-P2	183	Pirelli-twisted 19 strands	12	P3-P4	77.3	Pirelli-twisted 7 strands	8
P2-P3	111	Pirelli-twisted 7 strands	20	P2-H1	111		30
P4-H1	49.5		11	H1-H2	49.5		6
P4-P5	34.4		10				

Table 3. Parameters of electric load at buses

Name	Apparent power (MVA)	cosφ	Type	Name	Apparent power (MVA)	cosφ	
LoadP1	2	0.85	80% constant kVA, 20% constant Z	LoadP5	2	0.85	80% constant kVA, 20% constant Z
LoadP2	1.5	0.8		LoadH1	3.6	0.8	
LoadP3	1.2	0.8		LoadH1	1.5	0.8	
LoadP4	2.5	0.8					

Table 4. Parameters of PVs

Type	Parameters
A Sharp NE-Q5E2U panel	P_{mppstc}=165 W; V_{mppstc}=34,6 V; I_{mppstc}=4,77 A; V_{OCstc}=43,1 V; I_{SCstc}=5,46 A
PVs	Power at standard test condition: 3960 kW; An array: 80 panels in series; 300 arrays in parallel

Simulation results representing some operating states of PVs to evaluate bus voltage and power flows in whole grid are shown in Fig. 6, Fig. 7 and Fig. 8.

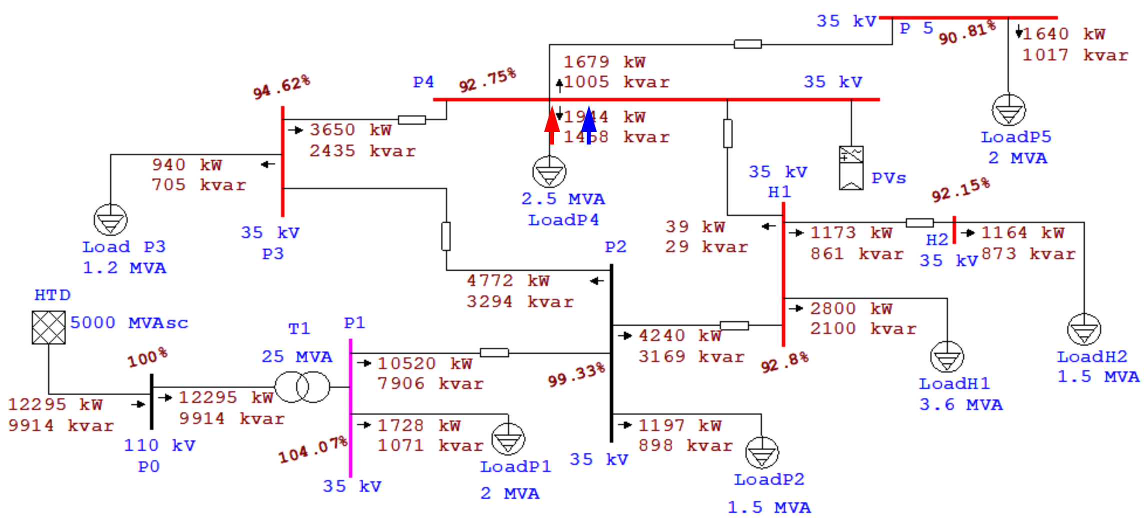

Fig. 6. Without solar irradiance (G=0)

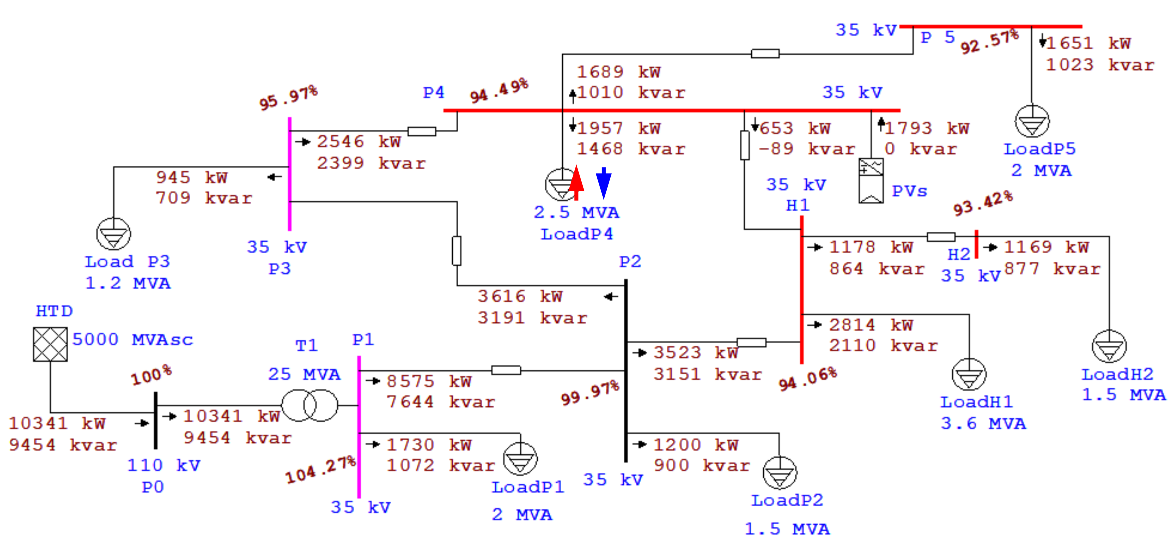

Fig. 7. Power of solar irradiance is 500 W/m²

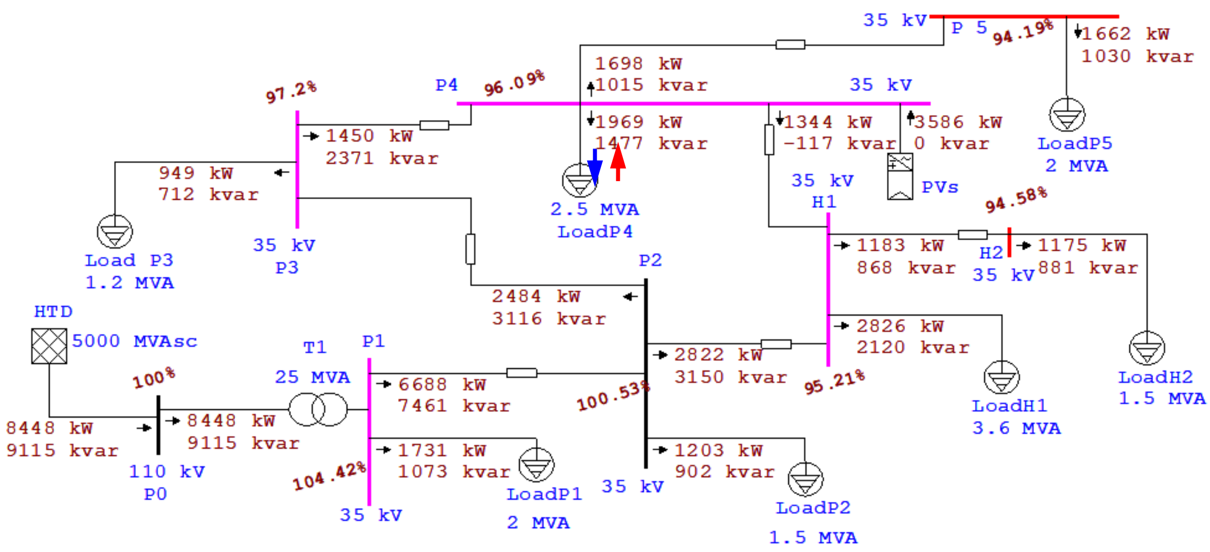

Fig. 8. Power of solar irradiance is 1000 W/m²

From simulation results in Fig. 6, Fig. 7 and Fig. 8, the change of power flows in transmission lines is represented in Table. 5.

Table 5. The change of power flows in transmission lines

Power flows (kW+jkVAr) / Transmission lines	G=0 W/m²	G=500 W/m²	G=1000 W/m²
P1-P2	10520+7906j	8575+7644j	6688+7461j
P2-P3	4772+3294j	3616+3191j	2484+3116j
P4-H1	-39-29j	653-89j	1344-117j
P4-P5	1679+1005j	1689+1010j	1698+1015j
P3-P4	3650+2435j	2546+2399j	1450+2371j
P2-H1	4240+3169j	3523+3151j	2822+3150j
H1-H2	1173+861j	1178+864j	1183+868j
P0-P1	12295+9914j	10341+9454j	8448+9115j
Total power loss	881,8 +1973,3j	668,5+1295,2j	519,7+920,6j

Results in Table 5 showed that power flows in whole grid change very much although designed power of PVs at standard test condition only has 27.7% in total load's possession with the participation of PVs only at bus P4. With the integration of PVs at the end the transmission line, power mobilized from source and power transmitted through the transmission line near source decreased very much. When G increased from 0 to 1000 W/m², the integration of PVs helped to decrease total power loss in whole grid upto 51.1% (from 2161.4 kVA to 1057.2 kVA). Moreover, power flows going through P4-H1 transmission line changed: direction of active power reversed (increased 3446%) and reactive power increased 403%. From above comment, it must be noted when choosing sectional area for P4-H1 line to adapt requirements of transmitted power with the participation of PVs at bus P4.

Working the same as above operating states in Fig. 6, Fig. 7 and Fig. 8, simulation process will continue with other states corresponding to T=30⁰C and 200 W/m² for each step of G. The change of voltage at bus H1, H2, P2, P3, P4 and P5 is represented in Fig. 9.

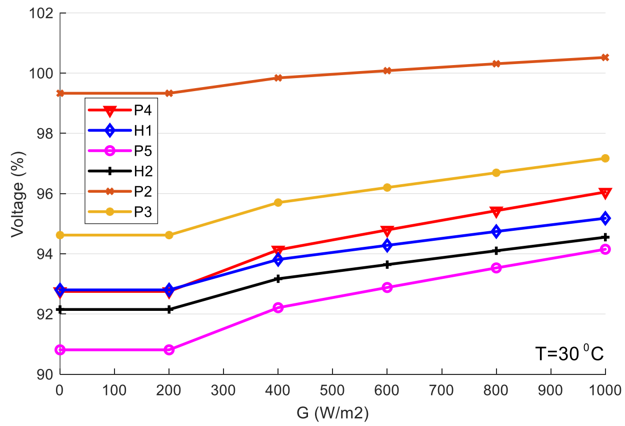

Fig. 9. Change of bus voltage (T=30^{0}C and G varies)

Simulation results in Fig. 9 showed that the integration of PVs helped to improve voltage quality of all load buses whenever having solar irradiance. When G=0, values of voltage at all load buses were below 95%U_{rated}. When G increased and reached to 1000 W/m^2, values of voltage at almost load buses noticeably increased higher than 95%U_{rated} (except P5 and H2 buses are near 95%U_{rated}). It means that PVs can help to improve voltage quality for whole grid and it needs to have participation of PVs at more buses to continue higher improvement.

CONCLUSION

The important contribution of this paper is to show the effect of PVs to operating parameters in distributed grids, including power flows in transmission lines and bus voltage. This paper showed the power structure and detailed control functions of a PVs. Moreover, characteristic of PVs was represented to provide some evaluations to dispatchers about the integration of this generator to operating parameters. These contributions can help to give out solutions to hold power balance and improve voltage quality for whole grid.

Carried out by ETAP software, power flows in transmission lines and voltage at all buses at any operating state can be determined exactly. By using simulation tool, all working states of loads and variations of G can be evaluated in detail to make operating plans or forecast the development of the grid clearly.

The integration of PVs can be continued to evaluated when having participation of other generations such as small hydro plant, wind generator, capacitor. Operating parameters of electrical grids can be improved if these distributed generations are implemented. It means that optimal locations and optimal capacity for each generation are next research directions to have the best effective operation.

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Conflict of Interest

The authors declare that there are no conflicts of interests.

Peer-review

External peer-review was done through double-blind method.

Data and materials availability

All data associated with this study are present in the paper.

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