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Research Article

The bus selection based on PV curve for the photovoltaic integration into power grid

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Abstract: Thanks to cost reduction, efficiency improvement, and fast advancement in power electronics, renewable energy, particularly solar power is increasing exponentially in the global energy sector. On the one hand, the integration of solar energy into the electricity is subject to a number of technical and non-technical challenges. Technical challenges include uncertainty of output power, system stability, imbalance between supply and demand, lack of reactive power, harmonics, angular stability, etc. The non-technical challenges include environmental, social and economic issues. On the other hand, the voltage profile in the weak nodes of the system is improved by the integration of solar power. The main purpose of the work is to identify buses which are suitable for the solar plant integration in the Albanian Power System (APS) based on the Power – Voltage (PV) curve method. The APS is modelled as an 18-bus grid (220 kV and 400 kV). The system simulation has been performed in the software PSS/E. Based on the critical point values of the PV curves methodology, two buses are identified as the most suitable for solar plant integration in the applications.

Keywords: *Photovoltaic plants, Power system stability, PSS/E software, Renewable energy*

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1. INTRODUCTION

Nowadays, Renewable Energy Sources (RES) utilization increases rapidly and attracts many attentions from decision-makers worldwidely. There are a number of technical and non-technical challenges to the integration of RES into the electricity system, as many studies have been encountered in the literature. These challenges include the uncertainty of output power, system stability, imbalance between generation and demand/frequency response, lack of reactive power, harmonics, angular stability, etc.

To overcome the technical challenges involved in integrating RES on a large scale into the electricity grid, a major transformation of the grid needs to be undertaken. This means that a transformation from the traditional networks to the smart grid ones should be achieved [1]. A smart grid would be an intelligent system designed to allow high penetration of renewable energy sources like solar, wind, geothermal, etc., into the electricity grid without causing any blackouts. Moreover, large-scale RES will have a substantial impact from a power system stability standpoint [2]. It is seen via several studies that photovoltaic power integration can significantly improve the total network voltage stability [3]. Furthermore, static and transient analysis is a tool to study the impact of photovoltaic power on power systems.

A large number of methods related to the analysis of the voltage profile at different levels of RES integration have been performed in the literature. In Ref. [3], the static voltage stability impact of solar power generation on power systems is reported by using the PowerWorld simulator PV (active power - voltage) and QV (reactive power - voltage) curves to explore the performance suitability of the renewable energy generator model. The percentage change in voltage - power sensitivity has been used to determine the location for solar power integration on the grid, and the feasible penetrations have been defined for a selection of system buses [3]. In Ref. [4], the PV curve method is used to investigate the impact of a wind turbine on the voltage stability of the electrical power system. The PSD-BPA software is used [4]. In order to explore the influence of RES on the voltage stability of the power system, Ref. [5] uses the CPF based PV curves method in the Power System Toolbox (PSAT) environment. A framework based on the contingency analysis to estimate the effect of large-scale solar power integrated into a conventional grid is discussed in Ref. [6]. The PV curve is a tool to study the voltage stability by evaluating the total active power limit before the voltage collapse point.

This paper presents the PV curve method for the assessment of the weakest buses based on critical point values of the PV curve and critical contingencies for the photovoltaic power integration into the power network [7]. Furthermore, the identification of the weakest buses may be a reference for planners to integrate photovoltaic systems into APS. The paper is structured as follows: In Section 2, the system under the study or the test system, the PV curve, and Power System Simulation for Engineers (PSS/E) software are discussed. The voltage magnitudes at the main buses of Albanian Power System (APS) before and after photovoltaic systems integration are discussed in Section 3. Finally, in Section 4, a summary of the main conclusions and findings of the paper are presented.

2. MATERIALS AND METHODS

2.1. System

The simulations are performed based on the APS by using PSS/E Software. The single line diagram of the High Voltage (HV) APS under study is shown in Fig. 1. It comprises exactly 13 buses at 220 kV voltage level, 5 buses at 400 kV voltage level, 13 generators (i.e. hydro generators) of 1350 MW installed capacity, 11 electrical loads of 1148.23 MW and 290.23 MVAr, 24 branches (220 and 400 kV), 4 three-winding voltage transformers, 13 two-winding voltage transformers, etc.

The main power generation capacities are concentrated in the north of the country. The APS is simulated based on the PV curves. Table 1 shows the main generation units and their installed capacity. Note that in this diagram, some small hydro generation units located in the north of the country are not considered. All generators are connected to the main transmission grid through their substations, whose voltage levels are 10.5 / 220 kV and 13.8 / 220 kV.

Table 1. The main generation units.

Nr.	Hydro power plants		
	Name	Generators (MW)	Installed capacity (MW)
1	Vau i Dejës	5 x 50	250
2	Koman	4 x 150	600
3	Fierza	4 x 125	500
Total			1350

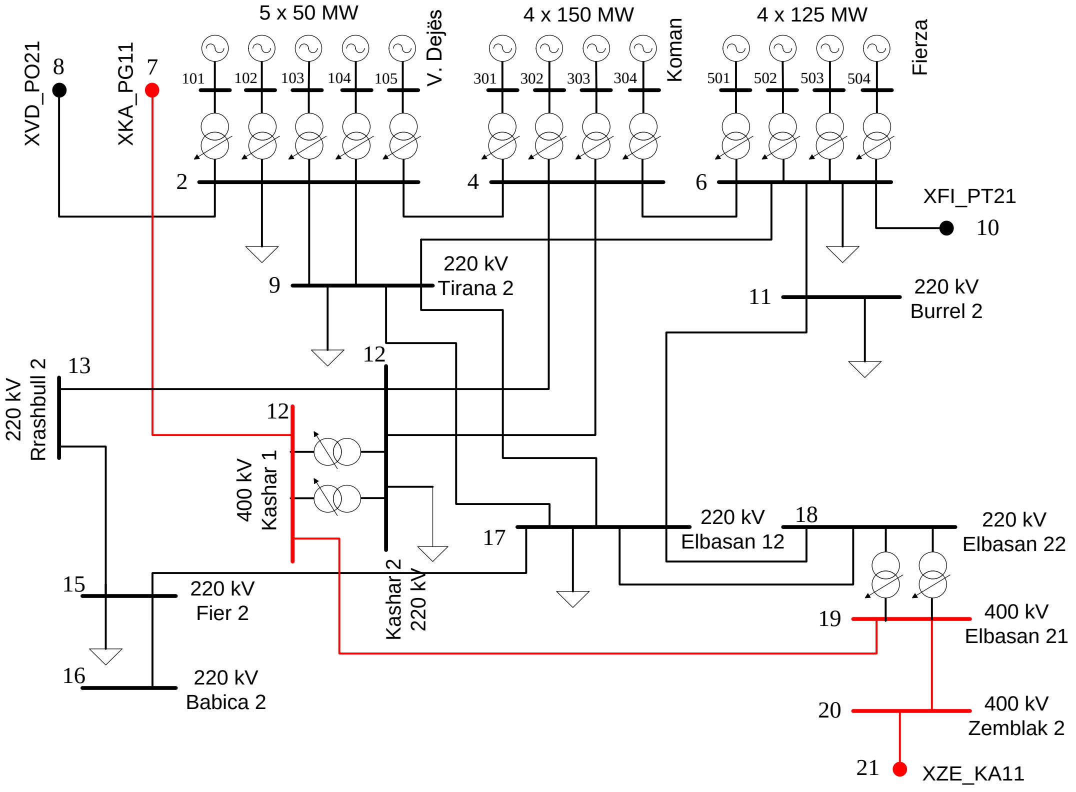

Figure 1. The single line diagram of high voltage APS.

Fig. 2 shows the structure of the transmission system in Albania. The Albanian electrical power transmission system consists of 400 kV, 220 kV, 150 kV, and 110 kV lines and transmission substations. Transmission system lines are 445.7 km at 400 kV, 1250 km at 220 kV, 34.4 km at 150 kV, and 1701 km at 110 kV.

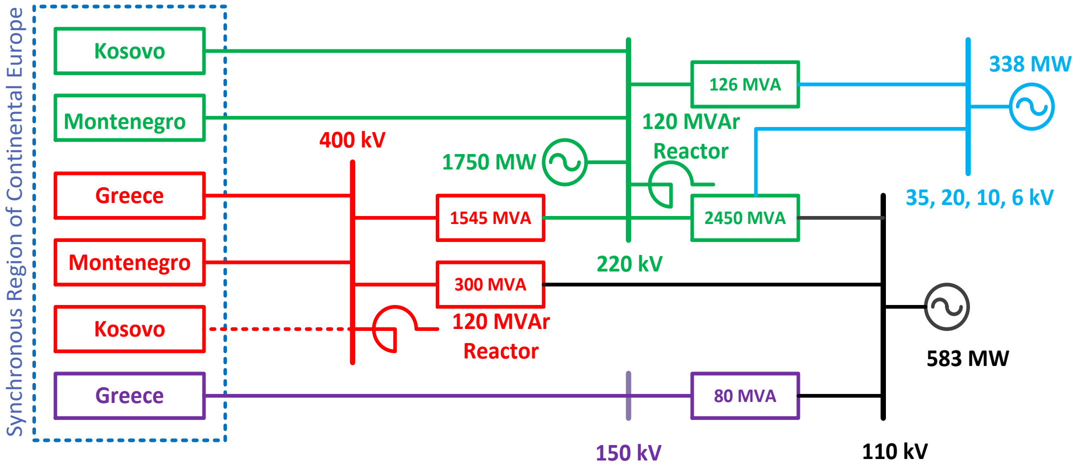

Figure 2. *Structure of the transmission system.*

The APS is interconnected with the neighboring power systems through transmission lines; through 150 kV and 400 kV with the Independent Transmission System Operator of Greece; 220 kV and 400 kV with the Montenegrin Electrical Transmission System; and 220 kV and 400 kV with the Transmission System of Kosovo as shown in Fig. 2.

2.2. Power – Voltage Curve Method

The PV curve [8] is an efficient tool for determining active power transfer limits in electrical power systems. Fig. 3 shows the PV curve, illustrating the voltage characteristics in terms of active power. The voltage at the system buses decreases as the active power transfer is increased. The low voltage value, or critical point value, corresponds to the maximal power transfer. A voltage collapse may occur when the power transfer continues to increase beyond the maximum value. This phenomenon is known as the voltage collapse transfer limit.

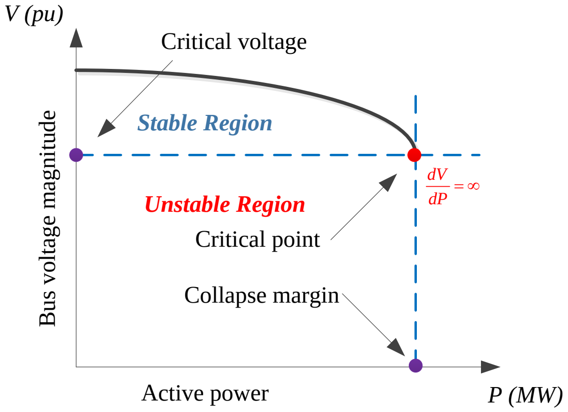

Figure 3. The PV curve for voltage stability analysis shows stable and unstable regions.

2.3. PSS/E Software

The Siemens PTI Power System Simulator (PSS/E) is a commercial simulation software intended for studies of transmission networks, generation, and distribution in steady - state and dynamic conditions. PSS/E has been used by many researchers in various studies [7], [9], [10], [11], [12], [13], [14]. The single line diagram of the system under study [15] is shown in Fig. 1 [16]. The hydro-generators are modeled as GENSAL (Salient Pole Generator Model), the exciters are modeled as ESST2A and EXPIC1, and the turbine governors are modeled as IEEEG3. Based on the Generic Renewable Generator/Converter Models and Generic Renewable Electrical Control Models, the photovoltaic plants in this study are modeled as REGCAU1 and REECAU1 respectively [17]. Other power system elements, including buses, transformers, transmission lines, and loads, are modeled based on their real technical parameters.

3. RESULTS AND DISCUSSIONS

3.1. Base Case

The APS, a large meshed grid is simulated as a base case and the PV curve analysis results are assessed in this regard. The PV curves are plotted for 14 buses (7 load buses). They represent the changes in the voltage when the active power transfer level increases.

One of the main concerns of the electrical power systems stability is the increase of power transfer at the load buses beyond the maximum level. The increased active power transfer may lead to instability, voltage collapse, and blackout. Furthermore, in this study, the critical point voltage values corresponding to the maximum power level at 14 buses are assessed. Table 2 represents the critical point voltage values. The maximum incremental power transfer level for the APS is found to be 325.00 MW based on PV curve analysis for all buses in 220 kV and 400 kV. From Table 2, it is observed that buses 15 and 17 (load buses), and buses 16 and 20 (no load buses) correspond to the lowest voltage at the critical point value of PV curves. These buses are considered the weakest with values of 0.828, 0.884, and 0.828 and 0.823 *pu* respectively. Figs. 4 and 5 show the PV curves for the APS at critical buses before the photovoltaic integration.

Table 2. Critical point bus voltage for Albanian power system.

Type	Bus	Rated Voltage (kV)	Critical point Voltage (pu)	Deviation (%)
Load buses	2	220	0.982	1.80
	6	220	0.988	1.20
	9	220	0.914	8.60
	11	220	0.931	6.90
	12	220	0.909	9.10
	15	220	0.828	17.20
	17	220	0.884	11.60
No load buses	4	220	0.993	0.70
	13	220	0.892	10.80
	14	400	0.863	13.70
	16	220	0.828	17.20
	18	220	0.884	11.60
	19	400	0.860	14.00
	20	400	0.823	17.70

The APS is simulated for several contingencies, and the PV curves are analyzed using PSS/E software. The critical point value based on each PV curve is estimated. In order to find the weakest buses in APS, we have identified the worst contingencies and have determined the critical point values of PV curves for each bus in the system. The identification of the weakest buses may help the operators to avoid system blackouts. One of the main actions that operators can take is photovoltaic integration.

Table 3. The critical point bus voltage under different contingency.

Cont.	Max.P (MW)	Load Buses							No Load Buses						
		2	6	9	11	12	15	17	4	18	13	14	16	19	20
2-4	281.25	0.978	0.990	0.918	0.935	0.913	0.835	0.890	0.997	0.980	0.897	0.868	0.836	0.866	0.831
2-8	312.50	0.980	0.987	0.914	0.932	0.909	0.828	0.884	0.992	0.997	0.892	0.863	0.829	0.860	0.823
2-9	250.00	0.989	0.980	0.896	0.920	0.894	0.816	0.870	0.990	0.970	0.878	0.849	0.816	0.846	0.811
2-9	250.00	0.989	0.980	0.896	0.920	0.894	0.816	0.870	0.990	0.970	0.878	0.849	0.816	0.846	0.811
4-6	306.25	0.976	0.990	0.916	0.936	0.911	0.832	0.889	0.993	0.979	0.895	0.866	0.833	0.863	0.827
4-12	237.50	0.976	0.980	0.894	0.917	0.883	0.808	0.865	0.993	0.970	0.868	0.841	0.809	0.839	0.803
4-12	237.50	0.976	0.980	0.894	0.917	0.833	0.808	0.865	0.993	0.970	0.868	0.841	0.809	0.839	0.803
6-9	243.75	0.973	1.006	0.891	0.930	0.890	0.813	0.867	0.990	0.996	0.875	0.846	0.813	0.843	0.808
6-10	325.00	0.995	1.011	0.934	0.954	0.929	0.851	0.906	1.005	0.000	0.913	0.884	0.851	0.882	0.846

6-11	243.75	0.978	1.003	0.901	0.852	0.896	0.811	0.862	0.993	0.993	0.878	0.847	0.812	0.842	0.807
7-14	325.00	0.998	1.006	0.942	0.957	0.938	0.862	0.916	1.007	0.996	0.923	0.895	0.862	0.892	0.857
9-12	312.50	0.984	0.989	0.919	0.932	0.899	0.824	0.884	0.991	0.978	0.884	0.857	0.824	0.855	0.818
9-17	300.00	0.982	0.985	0.915	0.922	0.906	0.817	0.869	0.992	0.974	0.887	0.854	0.817	0.849	0.812
9-17	300.00	0.982	0.985	0.915	0.922	0.906	0.817	0.869	0.992	0.974	0.887	0.854	0.817	0.849	0.812
11-17	262.50	0.980	1.002	0.903	0.996	0.898	0.814	0.866	0.993	0.992	0.881	0.849	0.814	0.845	0.908
12-13	268.75	0.980	0.984	0.908	0.920	0.909	0.741	0.867	0.991	0.973	0.744	0.856	0.741	0.851	0.815
13-15	262.50	0.979	0.982	0.906	0.918	0.907	0.732	0.863	0.990	0.971	0.907	0.854	0.732	0.848	0.812
14-19	262.50	0.980	0.983	0.907	0.919	0.908	0.817	0.865	0.991	0.972	0.889	0.867	0.818	0.827	0.790
15-16	325.00	0.981	0.986	0.912	0.929	0.907	0.824	0.882	0.991	0.975	0.890	0.860	0.000	0.857	0.820
15-17	250.00	0.983	0.991	0.915	0.940	0.901	0.697	0.897	0.993	0.981	0.857	0.865	0.697	0.865	0.831
17-18	325.00	0.982	0.987	0.914	0.931	0.908	0.827	0.884	0.992	0.976	0.892	0.862	0.827	0.859	0.821
17-18	325.00	0.982	0.987	0.914	0.931	0.908	0.827	0.884	0.992	0.976	0.892	0.862	0.827	0.859	0.821
19-20	325.00	1.015	1.020	0.974	0.985	0.973	0.902	0.954	1.019	1.010	0.959	0.934	0.902	0.935	0.000
20-21	325.00	1.022	1.026	0.988	0.997	0.988	0.920	0.972	1.025	1.016	0.975	0.957	0.921	0.960	0.965

Table 3 shows the worst contingencies. They occurred frequently on buses 15, 16, 17, and 20 under the (12–13), (13–15), and (15–17) contingencies. Buses 15 and 17 are fully loaded. The minimal voltage magnitude is 0.697, which appeared for buses 15 and 16 under the (15-17) contingency.

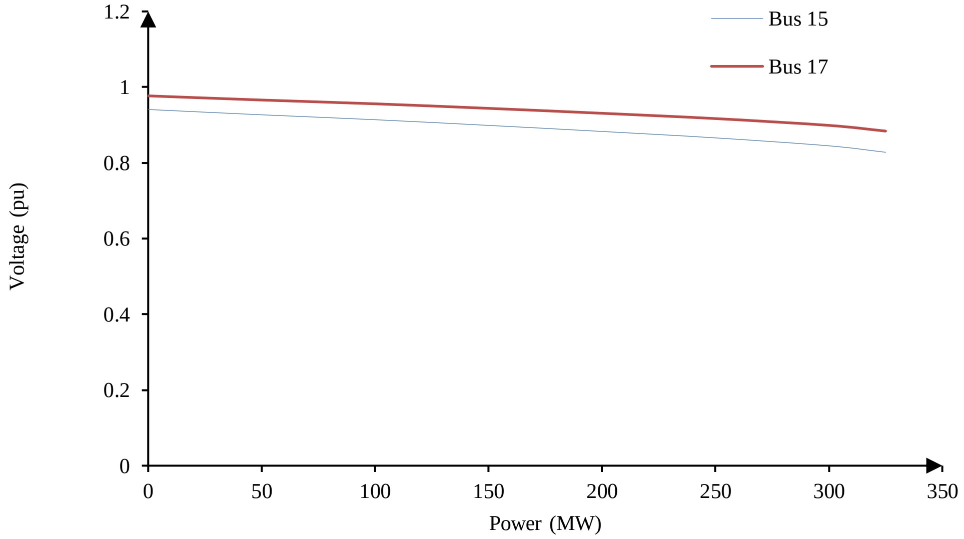

Figure 4. The PV curves for load buses 15 and 17.

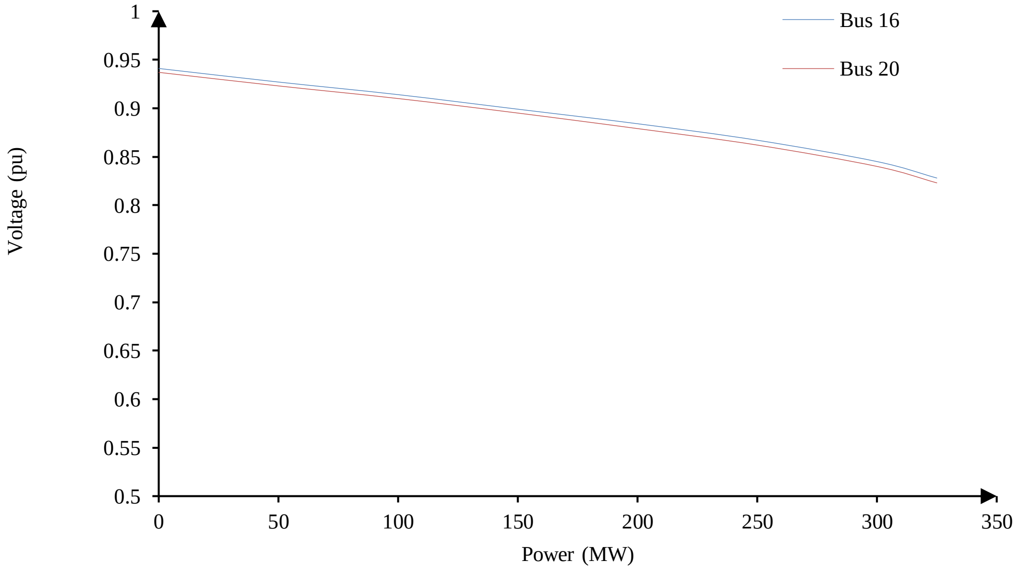

Figure 5. The PV curves for no load buses 16 and 20.

The PV analysis in the APS under contingency for the critical load buses is performed as well. It is clear that a significant impact on the operation of an electrical power system integrated with renewable energy resources can be detected during a line outage. In this study, the line (13–15) was tripped. The PV curve analysis for each load bus is observed after the line (13–15) outage. It was observed that the maximum incremental power transfer was decreased. This means that the maximum power transfer is reduced from 325.00 MW to 265.50 MW. The critical load buses are identified with a minimum voltage magnitude (pu). The minimum voltage magnitude corresponds to the maximal incremental power transfer. From the observation, it was found that under the contingency (13–15), the voltage level is 0.732 pu and 0.863 at buses 15 and 17, respectively. Buses 15 and 17 are found to be the weakest buses. Fig. 6 shows the PV curves at the weakest buses after the line (13–15) outage.

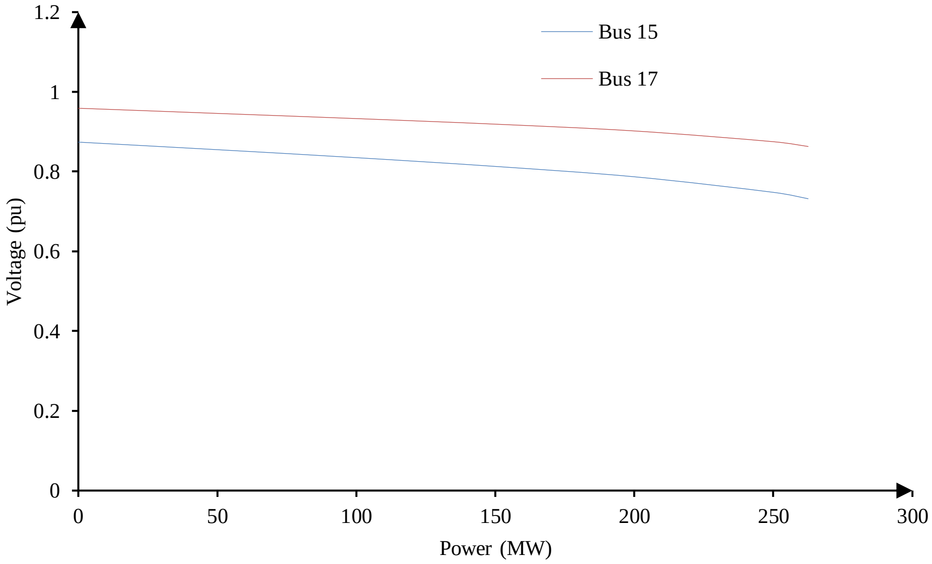

Figure 6. The PV curves for load bus 15 and 17 under the contingence (13-15).

It is obvious from Fig. 6 that the maximum incremental power transfer is 265.50 MW and the critical point corresponding to this maximum value is 0.732 and 0.863 pu. Furthermore, from the analysis, it was found that under the contingency (13–15), the voltage level is 0.732 pu at bus 16. Bus 16 is found to be the weakest bus without a load.

3.2. Photovoltaic Integration

The suitable integration of renewable energy generation units connected to proper power system buses plays a crucial role in the voltage profile improvement (Fig. 7). An improvement in the voltage profile means reliability and efficiency in the operation of an electrical power system. The issues such as voltage profile need to be analyzed before the renewable integration to prevent voltage instability leading to outages or system blackouts.

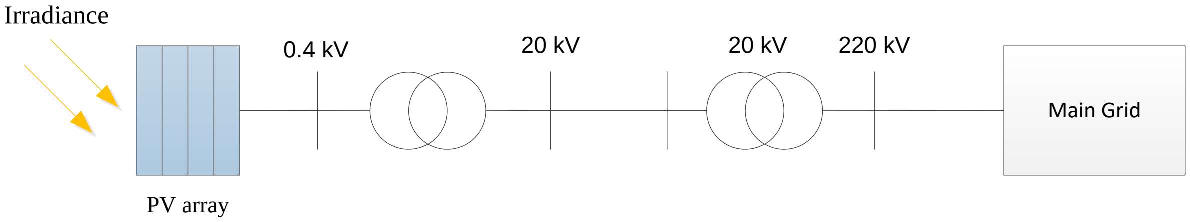

Figure 7. The simplified scheme for the photovoltaic power integration.

The photovoltaic module output power depends on air temperature, irradiance, and the technical parameters of the technology itself. However, the output power is calculated using Eq. (1) as follows [18]:

$$P_o = N\ FF\ V_y\ I_y \tag{1}$$

Here, P_o the output power of photovoltaic module, N is the number of photovoltaic module, FF is the Fill Factor, V_y and I_y are Voltage and Current during the state y .

Table 4. Critical point bus voltage for APS after photovoltaic integration.

	Bus	Rated Voltage (kV)	Critical voltage (pu)	Deviation (%)
Load buses	2.	220	0.991	0.90
	6.	220	0.998	0.20
	9.	220	0.930	7.00
	11.	220	0.946	5.40
	12.	220	0.925	7.50
	15.	220	0.864	13.60
	17.	220	0.904	9.60
No load buses	4.	220	1.000	0.00
	13.	220	0.913	8.70
	14.	400	0.878	12.20
	16.	220	0.867	13.30
	18.	220	0.903	9.70
	19.	400	0.876	12.40
	20.	400	0.835	16.50

The capacity factor of a module can be expressed as the average power P_{avg-pv} divided by the rated power P_{n-pv} of the photovoltaic module according to Ref. [19]:

$$CF_{PV} = \frac{P_{avg-pv}}{P_{n-pv}} \tag{2}$$

Based on the PV curve analysis, it has been observed that buses 15 and 17 are the weakest. These buses are suitable for photovoltaic integration. The APS under consideration in this study consists of 100 MW of solar panels connected in two buses of 50 MW each. The Albanian authorities have granted licenses to several investors for investments in excess of 50 MW of solar power shown in Fig. 1.

Table 4 represents the critical point voltage values after the photovoltaic power integration. From Table 4, it is observed that buses 15 and 17 (load buses) correspond to the lowest voltage at the critical point value of PV curves but with a significant improvement after the photovoltaic integration. The improvement expressed in percentage as a deviation is from 17.20 to 13.6% and from 11.60 to 9.60% for bus 15 and 17, respectively.

From Table 4, it is observed that buses 16 and 20 (no load buses) correspond to the lowest voltage at the critical point value of PV curves but with an apparent improvement after the photovoltaic integration. The improvement expressed in percentage as a deviation is from 17.20 to 13.30% and from 17.70 to 16.50% for bus 16 and 20, respectively.

Table 5. Critical point bus voltage under different contingency + Photovoltaic.

Contingency	Load buses						
	2	6	9	11	12	15	17
2-4	0.979	0.989	0.919	0.935	0.914	0.852	0.893
2-8	0.983	0.990	0.920	0.938	0.915	0.853	0.894
2-9	0.985	0.973	0.891	0.914	0.889	0.826	0.866

2-9	0.980	0.965	0.881	0.905	0.879	0.814	0.856
4-6	0.986	0.991	0.923	0.941	0.918	0.856	0.898
4-12	0.975	0.978	0.894	0.917	0.883	0.824	0.867
4-12	0.975	0.978	0.894	0.917	0.883	0.824	0.867
6-9	0.975	1.006	0.895	0.933	0.894	0.832	0.873
6-10	0.998	1.014	0.942	0.960	0.937	0.877	0.917
6-11	0.979	1.000	0.902	0.854	0.897	0.828	0.865
7-14	1.003	1.010	0.952	0.966	0.949	0.891	0.930
9-12	0.989	0.994	0.929	0.941	0.909	0.852	0.897
9-17	0.985	0.987	0.920	0.927	0.911	0.841	0.878
9-17	0.985	0.987	0.920	0.927	0.911	0.841	0.878
11-17	0.980	1.000	0.905	0.992	0.899	0.831	0.869
12-13	0.982	0.985	0.913	0.926	0.912	0.785	0.877
13-15	0.981	0.983	0.911	0.924	0.910	0.776	0.874
14-19	0.981	0.982	0.909	0.920	0.910	0.836	0.869
15-16	0.990	0.996	0.928	0.945	0.923	0.861	0.902
15-17	0.984	0.990	0.918	0.939	0.907	0.760	0.898
17-18	0.991	0.997	0.929	0.946	0.924	0.863	0.904
17-18	0.991	0.997	0.929	0.946	0.924	0.863	0.904
19-20	1.017	1.022	0.982	0.992	0.981	0.928	0.967
20-21	1.024	1.028	0.996	1.003	0.997	0.946	0.984

3.3. Impact of Photovoltaic Integration

The supposed photovoltaic power plants are connected at two buses in the APS under study. The total installed capacity after photovoltaic integration changes from 1350 MW to 1450 MW in this case. The generation capacity added to the system is almost 7.4% of the total power generation. Bus 15 and 17 were selected for renewable energy (solar) integration based on the critical point of PV curve studied in steady state and under contingencies.

Under different contingencies, the critical point bus voltages after the photovoltaic integration are shown in Table 5. It is seen from Table 5 that the lowest critical point of voltage magnitude under the (15-17) contingency appeared at the bus 15, it consists of 0.760 from 0.697 without photovoltaic power. Furthermore, other low value appeared in bus 15 under the contingency (12-13) and (13-15), 0.785 and 0.776 respectively. The impact of photovoltaic power integration into APS is positive for the voltage stability. It improves the voltage profile at the weakest buses under the worst scenarios avoiding system blackout.

4. CONCLUSION

In the present work, a methodology based on PV curve under critical contingency to determine suitable buses for photovoltaic integration into Albanian power system has been used and analyzed. The Power-Voltage analysis is performed by using the Power System Simulation for Engineering software. The most suitable location for the photovoltaic integration is selected based on critical point of voltage profile. The most favorable large-scale photovoltaic integration load buses are 15 and 17. A scenario with 7.4% photovoltaic power plant has been studied. It was seen that the integration of solar energy into APS has a significant positive impact on voltage profile and its stability. In future studies, the power quality of the electrical power system can be made under the high penetration of solar power.

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