Influence of Wind Power Plant on P-V and Q-V Curves in Transmission System

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Abstract. Recently, an increasing number of wind power plants (WPP) or wind farms have been connected to transmission systems around the world. In this paper, the influence of wind farms on P-V and Q-V curves, which are related to voltage stability, is investigated. For the purpose of the aforementioned research, the IEEE 24 bus Reliability Test System (RTS) was modeled in the PowerWorld Simulator program. The model is then used for the calculation of P-V and Q-V curves for different scenarios of WPP location and size. For every scenario voltage profile (voltage magnitude for each of 24 buses in the system) is calculated as well as P-V and Q-V curves. The results are compared with the Base Case (i.e. the case in which WPP is not connected to the system). Also, results for the scenarios are compared and conclusions are made.

Keywords: P-V curve · Q-V curve · Wind power plant · Voltage · Transmission

1 Introduction

The large increase in the connection of wind power plants (WPP) to the transmission system rise the question of how such power plants will affect the voltage stability of the system. Recently, many research studies on the mentioned topic are available in the scientific literature. The literature [1] analyzes the voltage stability (P-V and Q-V curves) of a transmission system with a connected charging station for electric vehicles and a WPP in which different types of wind turbines are implemented. In the literature [2], the authors examine the voltage stability of the transmission system at the point of connection of the battery charger for electric vehicles and the distributed energy source (renewable energy source—WPP and solar power plant). For the benchmark of the transmission system. IEEE 14 bus system [3] is used. The influence of wind power plants on voltage and transient stability has been investigated in the literature [4]. The test was performed on a power system with 9 buses modeled in GE Positive Sequence Load Flow Analysis (PSLF) software [5]. Characteristics of different wind turbine generators used in modern WPP are presented in [6]. Some types of wind turbine are suitable for voltage regulation and thus can positively affect the voltage stability of the system. Evaluation of P-V and Q-V curves in inverter based (mainly WPPs) power system is presented in [7]. IEEE 9 bus test system is used as a model of transmission system [8].

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In this paper IEEE 24 bus test system [9] is used for investigation of WPP influence on the P-V and Q-V curves of the transmission system. The test system is modeled in PowerWorld Simulator [10] which is used for calculation of the P-V and Q-V curves as well. The WPP is connected to different location (defined by the different simulation scenarios) and bus voltage, active power losses and the P-V and Q-V curves are calculated respectively. Obtained results are finally compared and discussed.

The rest of the paper is organized as follows: used model and all the input data are presented in Sect. 2. Simulation scenarios and calculation results are given in Sect. 3. Comparison of the results is presented in Sect. 4 and conclusion is given in the last section.

2 Network Model and Input Data

2.1 Network Model

The IEEE 24 bus test system [9] is chosen as a representative example of transmission system. Although the original test system is made for testing various reliability analysis methods, it is also used for various voltage analysis [11]. For the purpose of the calculations that are made, the IEEE 24 bus network is modeled in PowerWorld Simulator. The single line diagram of the modeled system is depicted in Fig. 1.

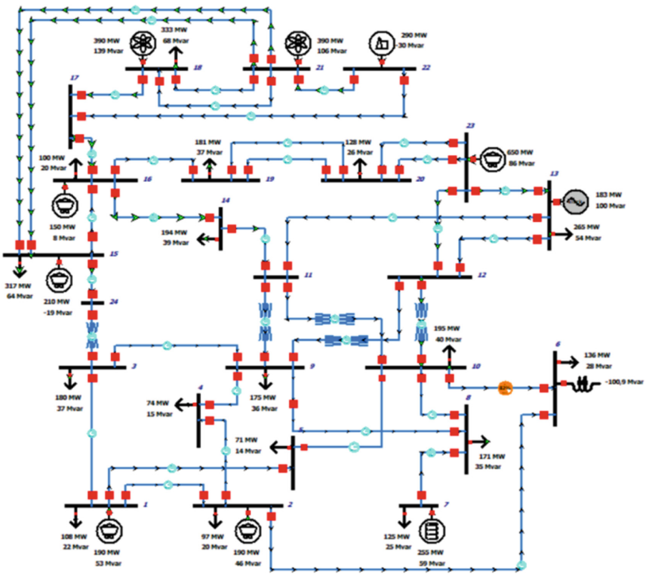

Fig. 1. PowerWorld single line diagram of the modeled IEEE 24 bus test system.

Table 1. Generators data.

Bus number	Output active power [MW]	Voltage regulator set point [p.u.]	Active power limit [MW]	Reactive power limit [MVAr]
1	190	1.035	192	−50 + 80
2	190	1.035	192	−50 + 80
7	255	1.025	300	0 + 180
13	n/a	1.020	n/a	n/a
15	210	1.014	215	−50 + 110
16	150	1.017	155	−50 + 80
18	390	1.050	400	−50 + 200
21	390	1.050	400	−50 + 200
22	290	1.050	300	−60 + 96
23	650	1.050	660	−125 + 310

2.2 Input Data

Set points for generators in the system (output active power, voltage regulation set point as well as active and reactive power limits) are shown in Table 1.

Bus 13 is selected as slack bus of the system and thus the data for output active power as well as active and reactive power limits are not applicable. The data for active and reactive consumption are listed in Table 2. The total active power consumption in the system is 2850 MW.

Table 2. Bus consumption data.

Bus number	Consumption active power [MW]	Consumption reactive power [MVAr]	Bus number	Consumption active power [MW]	Consumption reactive power [MVAr]
1	108	22	13	265	54
2	97	20	14	194	39
3	180	37	15	317	64
4	74	15	16	100	20
5	71	14	18	333	68
6	136	28	19	181	37
7	125	25	20	128	26
8	171	35			
9	175	36			
10	195	40			

3 Simulation Scenarios and Results

3.1 Simulation Scenarios

In order to investigate the influence of the WPP on the P-V and Q-V curves, five (5) simulation scenarios are defined as follows:

Scenario 1—base case scenario. There are no WPP integrated and in this scenario bus voltages are observed. The input data for generator production and load consumption are mentioned in Tables 1 and 2.

Scenario 2—200 MW WPP is integrated on buses 3, 4, 5 and 6. WPP participates in voltage regulation. In this scenario the best location for WPP integration is determined based on obtained Q-V curves.

Scenario 3—200 MW WPP is integrated on a bus 3 and two cases are analyzed. In the first case there is no reactive power regulation and in the second case WPP participates in reactive power regulation. PV and QV curves and bus voltages are given for both cases.

Scenario 4—WPP is integrated on a bus 3 and in first case installed power is 600 MW. There is no voltage regulation and bus voltages are observed and compared with Scenario 1. In second case, WPP power increases to 1045 MW and WPP participates in reactive power regulation. PV curves, QV curves and bus voltages are given for both cases.

3.2 Results

Power flow calculation is performed and results are obtained for each scenario. In base case scenario, operating point is changed in comparison to original IEEE 24 bus. As a result of decreased generator power, bus voltages are in range between 0.78 and 1.05 p.u.

Scenario 1 results. Bus voltages for scenario 1 are given in Fig. 2. If voltage limits are set within $\pm$ 10%, it can be noticed that some buses have voltages lower than desired limit. Lowest voltage is on bus 2, 0.79843 p.u. and the buses 18, 21, 22 and 23 have the highest voltage (1.05 p.u.).

In addition to huge voltage drops, there is also increased current in cables resulting in higher losses. Total losses in this case are 87.5 MW.

Scenario 2 results. In this scenario, the best location for WPP integration is determined based on bus voltages after integration. As shown in Fig. 3, voltages are higher on all buses after 200 MW additional power is integrated in system.

After results are obtained, set of results for bus 3 is taken and analyzed for various WPP power and ability to maintain voltage stability.

Scenario 3 results. First location for implementation of 200 MW WPP is bus 3. WPP does not participate in voltage regulation. After WPP is integrated, bus voltages increase since additional power is added to the grid, Fig. 4. The biggest increase is noticed on busses near place of WPP integration. WPP increases voltages near its location. Power flows have changed in a manner that total system losses decrease to 82.6 MW as well as cabel overload.

Fig. 2. Bus voltages, scenario 1.

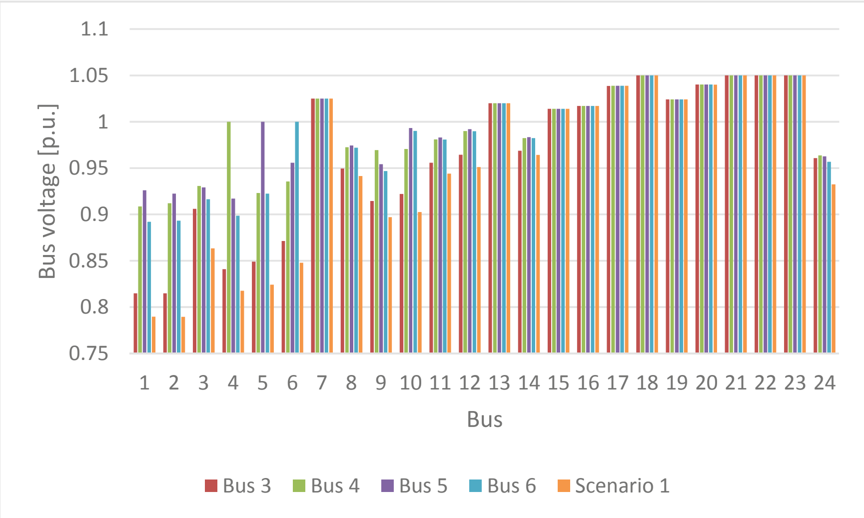

Fig. 3. Bus voltages, scenario 2.

In second case, WPP can participate in voltage regulation and it is integrated on bus 3. Voltage on bus 3 is set to 1 p.u. Fig. 5 shows that, in comparison to Scenario 1, voltages are higher on all buses as WPP increases voltage on all neighbouring buses. Losses are 75.8 MW and cable overload (cabel connecting buses 6 and 10) is still present.

Scenario 4 results. In the forth scenario two cases are analyzed. In the Case 1, WPP has installed power of 600 MW and WPP does not participate in voltage regulation.

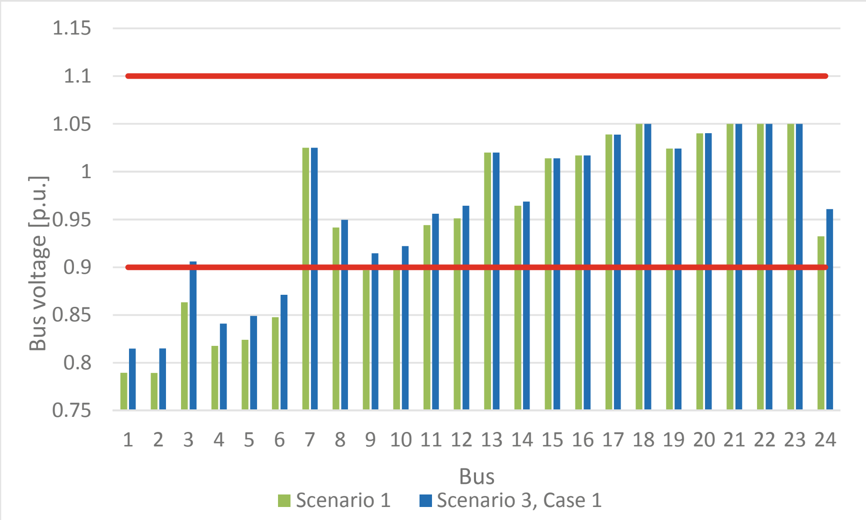

Fig. 4. Bus voltages, scenario 2 without voltage regulation.

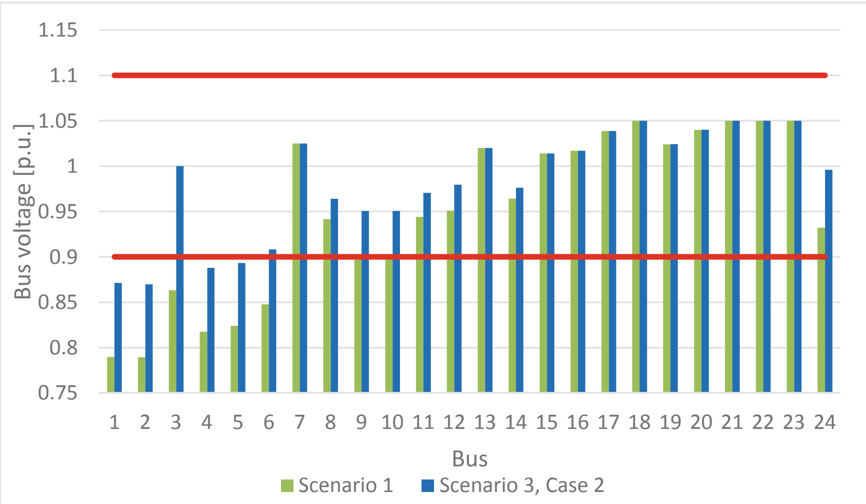

Fig. 5. Bus voltages, scenario 3 with voltage regulation.

Higher active power installed on a bus 3 results in higher bus voltages on the place of integration. Bus voltages are shown in Fig. 6. With higher active power, resulting power flows change and with higher power in system, losses increase. This results with lower bus voltages in comparison to scenario 1. This impact is mostly highlighted od busses 1 and 2.

System losses now have a value of 125.8 MW. Cable loadings have changed and cables that were overloaded in Scenario 1 (cable connecting buses 6 and 10) are now

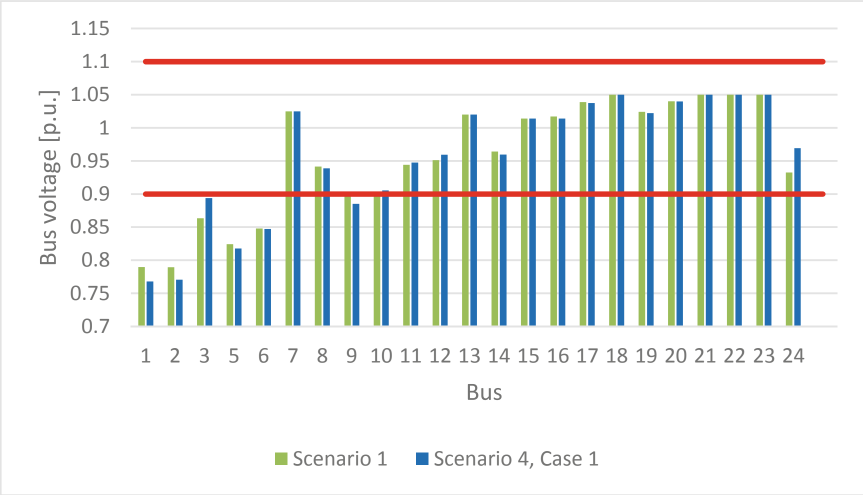

Fig. 6. Bus voltages, scenario 4 without voltage regulation.

under their loading limits. On the other hand, cables connecting busses 3–1 and 3–9 have increased loading, up to 55% of their rating. High WPP power can affect bus voltages in a negative way as it was shown in this scenario.

Results for Case 2 are given in Fig. 7. In this scenario, 1046 MW WPP is integrated on bus 3 and it can participate in voltage regulation. Local bus has higher voltage than in Scenario 1 but voltage decreases on other buses. In this case higher power is integrated on a bus in order to run WPP near its stability limits.

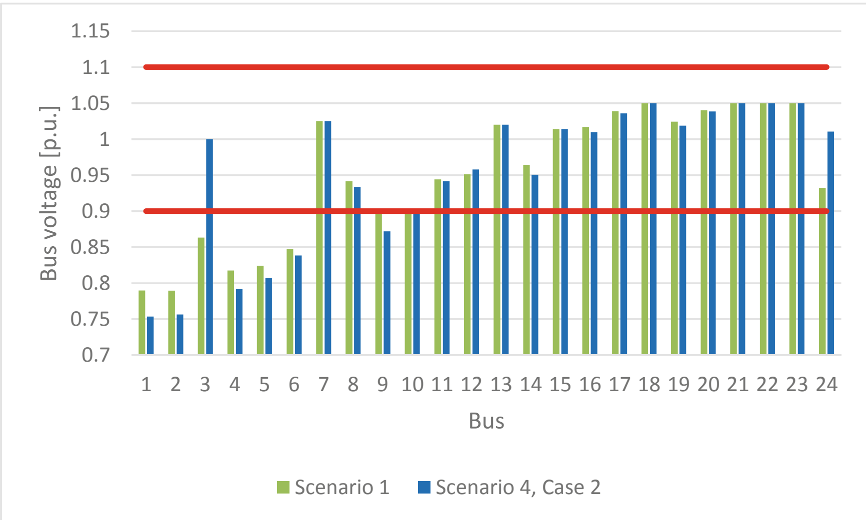

Fig. 7. Bus voltages, scenario 4 with voltage regulation.

Total losses have also increased and now have a value of 212.1 MW. Cabel between buses 6 and 10 is still overloaded as well as cables connecting buses 3–1 and 14–16. This change is a result of increased power flows due higher active power in system.

4 Discussion

P-V and Q-V curves are main tool in analyzing system stability. Some specific points in P-V curves are normal operating point, and voltage collapse point. In this paper, stability margin is set on 0.85 p.u. (red line). If voltage decreases under this value it is considered that voltage stability cannot be maintained.

Scenario 2—Q-V curves. Since WPP participates in voltage regulation, voltage is set to 1 p.u. Maximum active power that can be transferred is determined by WPP power. With increased power this margin also increases. On the other hand Q-V curves give insight in voltage stability in case that voltage is fixed (Fig. 8).

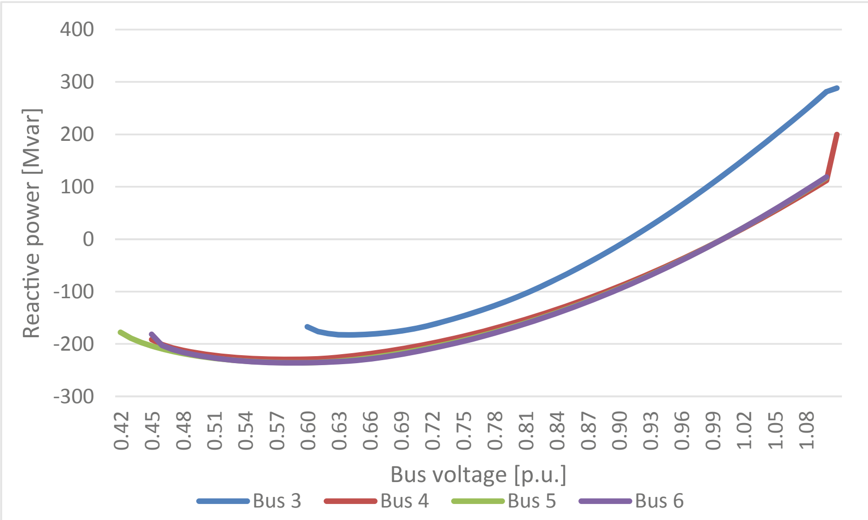

Fig. 8. Q-V curves, scenario 2.

The lowest margin is for WPP integrated on bus 3. Due this, the most interesting set of results is obtained for WPP on bus 3. Increasing active power results in lowering stability margin and it can even lead to instability.

Scenario 3—P-V and Q-V curves. P-V curve for both cases is shown in Fig. 9. In Case 1 initial voltage is 0.906 p.u. and active power increases in steps of 1 MW. As active power increases, voltage begins to decrease. Critical point is 0.85 p.u. and it is considered to be a point after which voltage stability cannot be maintained. As it can be seen, active power corresponding to knee point is 587 MW and after this point voltage increases rapidly. When active power reaches value of 601 MW, voltage decreases to 0.833 and after this voltage collapse occurs.

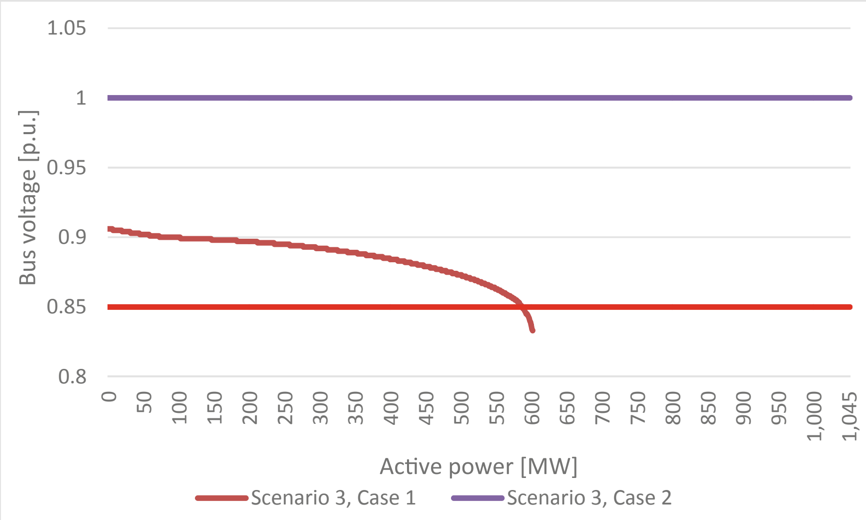

Fig. 9. P-V curves, scenario 2

In Case 2 WPP participates in voltage regulation. PV curve changes in comparison to previous scenarios and now it has fixed value of 1 p.u. No matter how much active power increases, voltage remains 1 p.u. Maximum power that can be transferred before voltage collapse is 1045 MW.

QV curve for given case is shown in Fig. 10. In Case 1, maximum loading before collapse is around 190 Mvar. System is stable as increase in reactive power results with increased voltage. System stability can also be confirmed by applying dQ/dV criteria as its derivative is greater than 0.

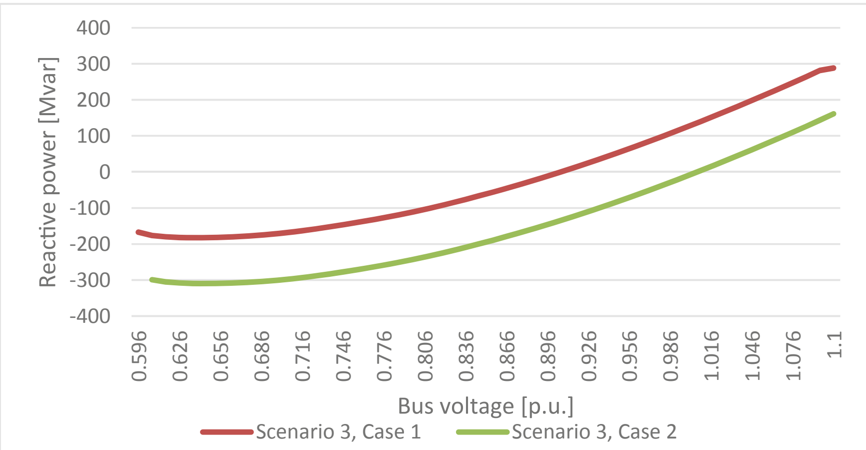

Fig. 10. Q-V curves, scenario 3.

QV curves also differ in Case 2. Reactive power margin with 300 Mvar is lower in comparison to Case 1. Voltage stability is enhanced in comparison to previous scenarios. Also, stability margins have increased in this case.

Scenario 4—P-V and Q-V curves. In Scenario 4, WPP works near its stability margin. The biggest change can be noticed when PV curves are observed. In previous Scenario, maximum power that can be transferred is 600 MW. With higher integrated power stability margin decreases and voltage collapse happens when active power increases to 320 MW (Fig. 11).

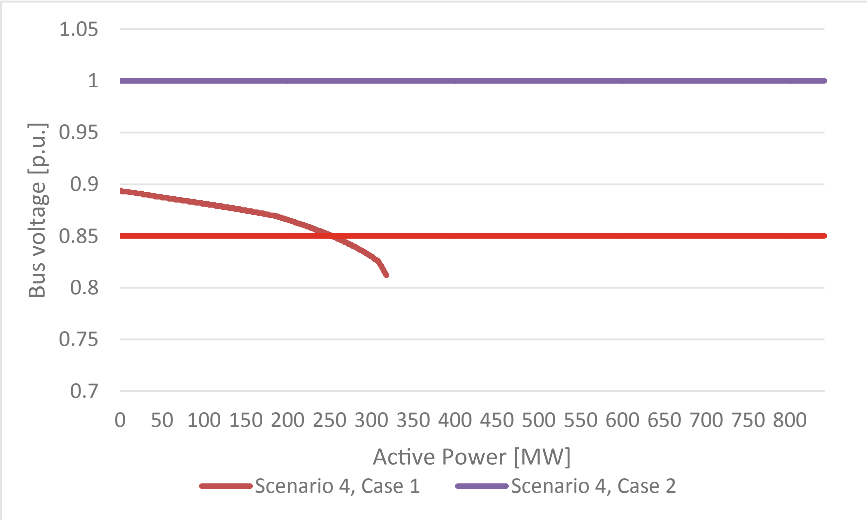

Fig. 11. P-V curve, scenario 4

Since WPP participates in voltage regulation, PV curves have a specific value of 1 p.u. WPP maintains this value on a given bus and maximum power that can be transferred is 840 MW. After this value, voltage collapse occurs. If regulation is not possible, maximum active power is 600 MW.

In comparison to Scenario 3, stability margins have decreased, Fig. 10. The minimal reactive power has decreased and stability margins are also smaller. System is stable in both scenarios, as $dQ/dV > 0$ and operating point is located to the right of the minimal point. Reactive power before collapse is now 100 Mvar. In both cases, reactive power limit is negative but higher value is preferable (Fig. 12).

In this scenario there are two possible equilibrium points. In order to determine which point is operating point dQ/dV criteria needs to be applied. First point (intersection of curve with 0 Mvar, voltage 0.86 p.u.) is not stable since $dQ/dV < 0$. Other intersection point (0 Mvar, 1 p.u.) is stable because $dQ/dV > 0$. In comparison to all previous scenarios, this scenario has the narrowest stability margins and only 60 Mvar are needed to collapse voltage.

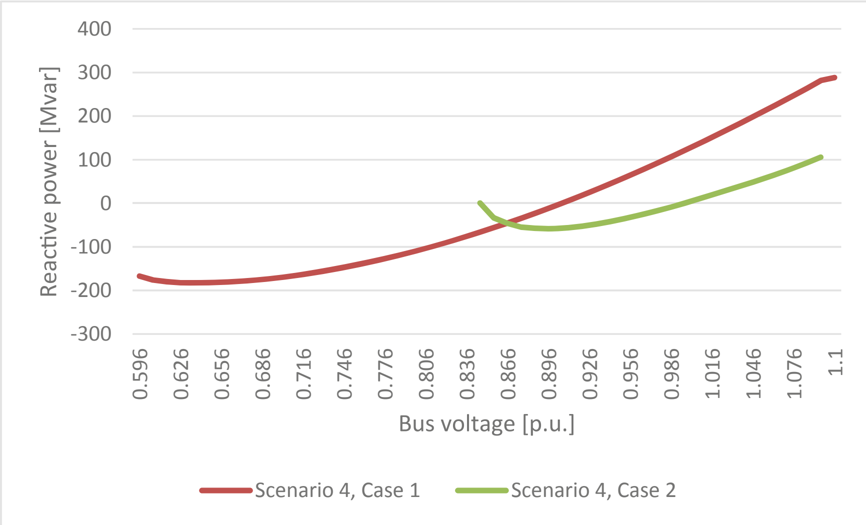

Fig. 12. Q-V curves, scenario 4.

5 Conclusion

Maintaining voltage stability is important task and various methods are used to achieve it. The transition to green energy has led to an increased integration of RES. The integration of RES can affect the stability of the system. Positive effect on voltage values and consequently reduced losses can be achieved by good selection of location and proper sizing of RES. WPP, as one of the most common RES, can adapt to any grid and enhance all aspects of stability. Installation close to the point of consumption can raise the voltage locally and reduce currents in the network, which will consequently reduce losses. High installed power can also have a negative effect, since power flows increase with higher active power, which results in greater voltage drops. This influence can also be considered from the stability point of view by studying the PV and QV curves. If WPP is integrated in the system, the voltage stability is improved. However, high integrated power leads to a breakdown in voltage stability. If RES is already integrated into the system, stability can be further improved by enabling voltage regulation. The voltage regulation is coupled with the reactive power of the generator, i.e. it is enough for the WPP to provide certain amounts of reactive power and thus affect the voltage magnitudes. When WPP participates in voltage regulation, the limits of voltage stability increase. Using WPP in voltage regulation is desirable, however, high active power with demand to participate in voltage regulation can become new source of instability. In order to comprise these requirements, detailed studies need to be performed for each given grid configuration.

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