ELEKTROTEHNIŠKI VESTNIK 85(5): 229-234, 2018
ORIGINAL SCIENTIFIC PAPER

Voltage stability analysis of the interconnected Italian – Slovenian power system

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Abstract. The objective of this paper is to study the possibility of voltage instability on the border section between Italy and Slovenia. At present, the Italian and Slovenian power systems are interconnected by two overhead lines, one at the nominal voltage of 380 kV and the other at 220 kV. Referring to the classic voltage stability analysis, the paper investigates possible large overload conditions on the 220 kV interconnector, caused by an outage of the 380 kV interconnector when the power flows between the two countries are at their highest level. After a brief description of the characteristics of the power system in the considered section, the real network is approximated to match the model used in the classic analysis of voltage stability. The performed load-flow calculations relevant to the (real) power system under heavy operating conditions allow for an evaluation of the effects of the used approximations and validation of the results of this study.

Keywords: Voltage stability, Interconnected power systems, Load-flow calculations

Analiza stabilnosti elektroenergetskega omrežja na mejnem območju med Italijo in Slovenijo

V članku analiziramo možnost pojava napetostne nestabilnosti na mejnem območju med Italijo in Slovenijo. Trenutno sta slovensko in italijansko napetostno omrežje povezana z dvema nadzemnima vodoma 380 Kv in 220 Kv. Študija v obliki klasične analize napetostne stabilnosti raziskuje visoke preobremenitve 220 kV interkonekcijskega voda v scenariju maksimalnega pretoku energije med državama in hkratnem izpadu 380 kV interkonekcije. Kratki predstavitvi karakteristik elektroenergetskega sistema sledi opis predlaganih približkov za uporabo modelov, uporabljenih pri analizi napetostne nestabilnosti v resničnem omrežju. Izračun pretokov energije močno obremenjenega elektroenergetskega omrežja nam omogoča potrditev dobljenih rezultatov in oceno vpliva predlaganih približkov.

1 INTRODUCTION

The classic voltage stability theory [1] shows that instability phenomena can take place in heavily stressed systems and/or under unusual conditions characterized by a combination of a very weak network, very high load demand and low lagging power factor. Generally, during a normal operation in a sufficiently strong power system, these conditions do not occur. Extreme operating conditions can take place in special cases, for example in the N-1 operation, and these situations require a careful evaluation of the voltage stability.

In this paper, the classic voltage stability theory is applied to the border section between Italy and Slovenia. At present, the power systems of the two countries are interconnected by means of two overhead lines, one at the nominal voltage of 380 kV and the other at 220 kV. These two lines constitute a “section”, that is a border region between neighbouring areas of the European interconnected power system in which the interconnection lines carry mainly unidirectional power flows. To this regard, note that, among all the European countries, Italy is the greatest importer of electricity [2]. Accordingly, on the border sections between Italy and the neighbouring countries, power flows are directed (during most of the time) toward Italy. This is valid also for the section between Italy and Slovenia.

As a rule, the power system sections need a coordinated management of the TSO involved in order to guarantee a sufficient robustness to face possible critical conditions caused by faults or disturbances in the power system. At the section between Italy and Slovenia, critical operating conditions can take place in case of an outage of the 380 kV interconnection line since, at a large power exchange between the two countries, this event can heavily overload the 220 kV interconnection line. The aim of the study presented in this paper is to investigate if the high currents flowing in this line under the considered N-1 condition can lead to voltage instability phenomena.

The paper is organised as follows. Section 2 describes the main characteristics of the power system at the border section between Italy and Slovenia and also between Italy and Austria, as the latter might experience large extra power flows under the N-1

Received 9 July 2018
Accepted 23 August 2018

operating condition. Section 3 presents the classic voltage stability theory. In Section 4, the theory is applied to the specific case of the border section between Italy and Slovenia with the 380 kV interconnection line out of service, the relevant power system characteristics are computed and the results are discussed and compared with those obtained by load-flow calculations.

2 POWER SYSTEM CHARACTERISTICS

In the Italian North-Eastern geographical region, the electric power network is interconnected with the Slovenian and Austrian networks.

Figure 1 illustrates the 380 kV and 220 kV networks at the border between Italy and Slovenia. The two networks are linked by two interconnection lines: the 380 kV line between the Redipuglia (Italy) and Divača (Slovenia) stations and the 220 kV line between the Padriciano (Italy) and Divača (Slovenia) stations. These lines form a border section between Slovenia and Italy, which normally imports energy from Slovenia.

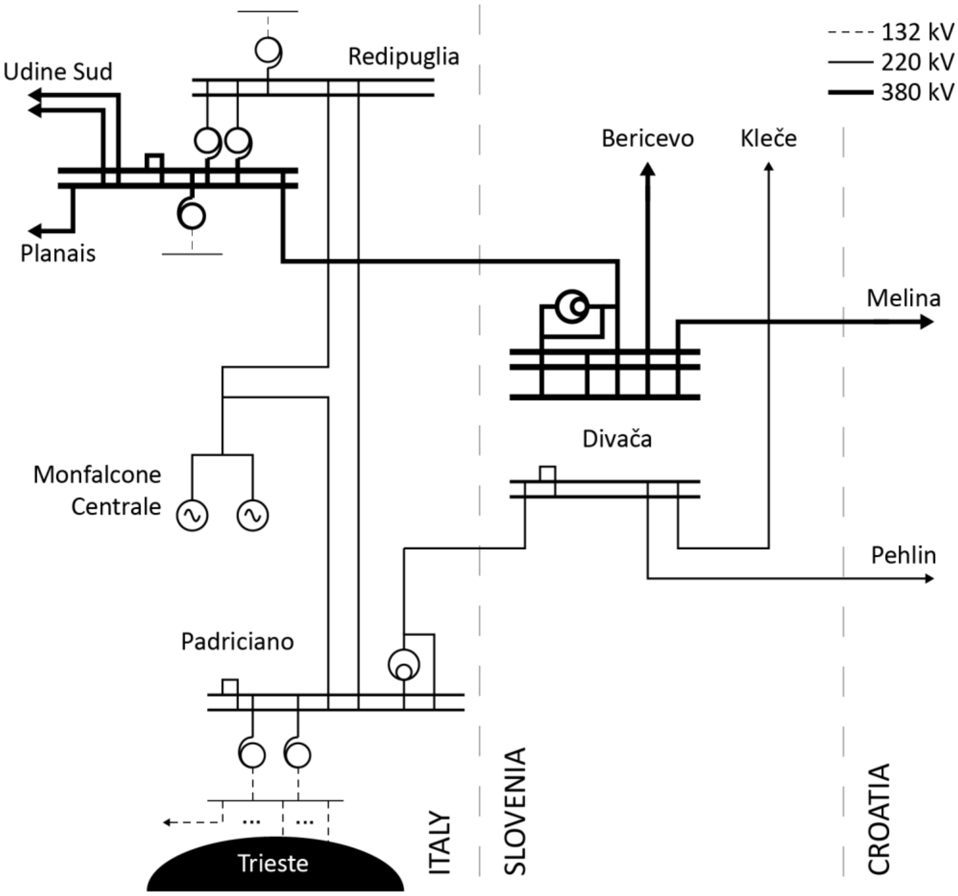

Figure 1. 380 kV and 220 kV networks at the section between Italy and Slovenia.

The power flows between Italy and Slovenia are controlled by Phase Shift Transformers (PST) installed on both interconnection lines. Two PSTs of 600 MVA each are installed at the Divača station on the 380 kV interconnector to Redipuglia, and one PST of 370 MVA is installed at the Padriciano station on the 220 kV Padriciano-Divača interconnector (see Fig. 1 where, for the sake of simplicity, only one PST is represented at Divača). All these PSTs are manually controlled by Terna, the Italian TSO. The PSTs limit the power transmission capability of the Redipuglia-Divača and Padriciano-Divača lines to 1200 MW and 370 MW[1], respectively.

The total power flowing from Slovenia to Italy can really exceed 1500 MW, which is about 5 times more than in the case of the power flowing between Austria and Italy.

Also the border section between Austria and Italy is composed of two interconnection lines: the 220 kV line

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[1] More precisely, on the Padriciano-Divača line the current limits are: the summer thermal limit of the conductor is 900 A; the winter thermal limit of the conductor is 960 A; the PST thermal limit is 929 A.

between the Soverzene (Italy) and Lienz (Austria) stations, and the 132 kV merchant line between Tarvisio (Italy) and Greuth (Austria). The power flowing in these interconnectors are controlled by two PSTs, both installed on the Austrian side (at Lienz and Greuth) and controlled by APG, the Austrain TSO. At present, these PSTs keep the power flows at a constant value by automatic controllers. The 220 kV Soverzene-Lienz line transports 210 MW, whereas the 132 kV Tarvisio-Greuth merchant line transports 85 MW during the winter and 65 MW during the summer period.

Speaking in terms of power transmission capacity, the 380 kV Redipuglia-Divača interconnector is by far the most important line in the two considered border sections of the North-East area of the Italian trasmission network. In case of an outage of the Redipuglia-Divača line, the two interconnection lines between Austria and Italy are not subject to significant power changes. This is due to the relatively low development of the 380 kV and 220 kV power systems in the entire area; these lines are therefore relatively far from the border section between Italy and Slovenia. Moreover, at steady-state the power flows resume the values set by the PST controls.

In case of an outage of the Redipuglia-Divača line, the above conditions give rise to large overloads on the 220 kV Padriciano-Divača line and can overload also other power system components (lines, transformers) present in the area.

3 THE CLASSIC VOLTAGE STABILITY ANALYSIS

This section briefly recalls the basic concepts related to voltage instability. Voltage stability is concerned with the “ability of a power system to maintain acceptable voltages to all buses in the system under normal conditions and after being subject to a disturbance. A system enters a state of voltage instability when a disturbance, increase in load demand or change in system condition, causes a progressive and uncontrollable decline in voltage” [1].

It is known that voltage instability problems in an electric power system may take place under operating conditions characterized by a very high load and system weakness. Let us consider the simple system model shown in Fig. 2 that includes an "infinite power" bus (whose voltage $\bar{E}_P$ is assumed constant) and a transmission line (whose impedance is $\dot{Z}_L = Z_L e^{j\beta}$) feeding a load (whose impedance is $\dot{Z}_C = Z_C e^{j\varphi}$). This simple model neglects the power system transversal admittances.

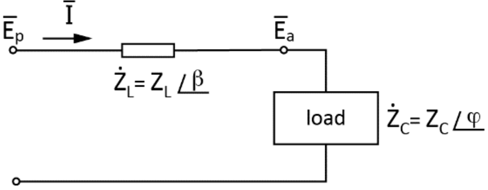

Figure 2. System model for voltage stability analysis.

For the receiving end voltage of the transmission line, E_a, the following equations are valid:

$$E_a = Z_c \cdot I = Z_c \cdot \frac{E_p}{|\dot{Z}_L + \dot{Z}_C|} \tag{1}$$

$$E_a = \frac{Z_C}{Z_L} \cdot \frac{E_P}{\sqrt{1 + \left(\frac{Z_C}{Z_L}\right)^2 + 2 \cdot \frac{Z_C}{Z_L} \cdot \cos(\beta - \varphi)}} \tag{2}$$

The active power transmitted to the load, P_a, can be expressed as:

$$P_a = \frac{3 \cdot E_P{}^2 \cdot Z_C \cdot \cos\varphi}{Z_L{}^2 \cdot \left[1 + \left(\frac{Z_C}{Z_L}\right)^2 + 2 \cdot \frac{Z_C}{Z_L} \cdot \cos(\beta - \varphi)\right]} \tag{3}$$

When the load demand increases while keeping the power factor constant (cosφ=constant), the active power P_a trasmitted to the load reaches its maximum value, P_{max}, when $|Z_C| = |Z_L|$. The maximum power results in:

$$P_{max} = \frac{3 \cdot E_P{}^2}{2 \cdot Z_L} \cdot \frac{\cos\varphi}{1 + \cos(\beta - \varphi)} \tag{4}$$

In correspondence with P_{max}, the voltage E_a on the load bus assumes the critical value:

$$E_{cri} = \frac{3 \cdot E_P{}^2}{\sqrt{2 \cdot (1 + \cos(\beta - \varphi))}} \tag{5}$$

The critical voltage E_{cri} of the load bus corresponds to the voltage stability limit. If the load demand further increases, the voltage drop determined by the increased current in the transmission line leads to a reduction of the transmitted power P_a.

For any given power factor value, changing the load demand one obtains in the plane P_a-E_a the well-known steady-state characteristic, or “nose curve”, of the power system. In order to guarantee a sufficient power system operating security, a proper voltage stability margin, expressed in percent of the maximum power P_{max}, is required. For example, in [3] the authors limit the load power at 95% P_{max}. This corresponds to a 5% voltage stability margin.

4 APPLICATION TO THE INTERCONNECTIONS BETWEEN ITALY AND SLOVENIA

In this section, the classic voltage stability theory presented in Section 3 is applied to the border section between Italy and Slovenia to investigate if voltage instability problems can be expected as a result of an outage of the Redipuglia-Divača interconnection, or if they can be excluded.

To use the simple model shown in Fig. 2 the following approximations are applied.

1) As the 380 kV and 220 kV busbars are not connected at the Divača station (see Fig. 1), the link between the 220 kV Divača busbars and the 380 kV network mainly consists of the 380/220 kV autotransformers located at the Beričevo (Slovenia) and Melina (Croatia) stations. As seen from the simplified network scheme shown in Fig. 3, these stations are connected to the Divača station by 220 kV lines passing through the Klece (Slovenia) and Pehlin (Croatia) stations. The other lines connected to the 220 kV Klece and Pehlin busbars are not indicated in Fig. 3. The first approximation used in the study is to neglect these lines and their effect on the power flow between Slovenia and Italy.

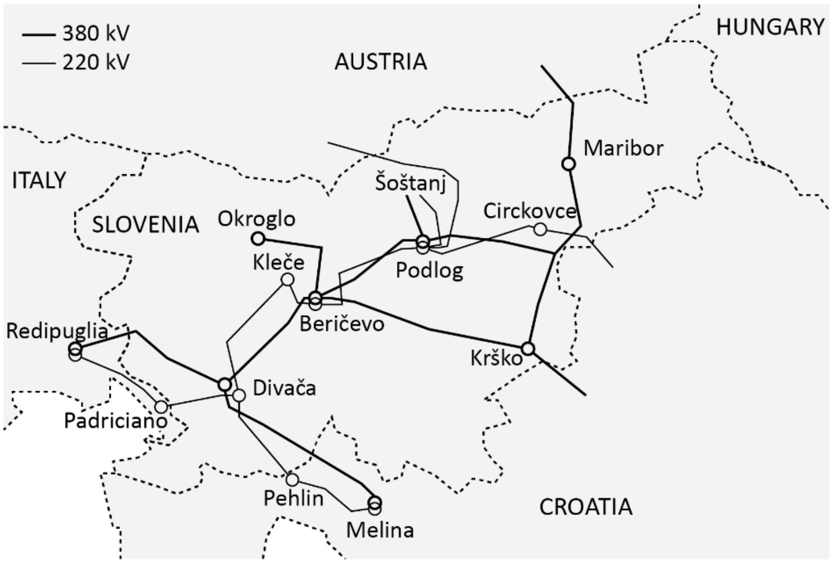

Figure 3. Simplified scheme of the Slovenian 380/220 kV transmission network.

2) The load-flow calculations carried out for different load conditions show that the voltages of the 220 kV busbars at the Beričevo and Melina stations have similar values for both the modulus and angle. For example, at a maximum power flow of 1573 MW toward Italy (this power, observed on March 8, 2017, corresponds to the sum of the transmission capacities of the two interconnectors) and assuming the Redipuglia-Divača interconnection out of service, we obtain:

- 220 kV Beričevo busbar: E=228.4 kV with a 15,60° angle;
- 220 kV Melina busbar: E=230.1 kV with a 15,77° angle.

This justifies the second approximation used consisting of the direct connection of the 220 kV Beričevo and Melina busbars at the same node of the equivalent network.

3) Finally, the 220 kV busbars of the Beričevo-Melina "artificial" station are assumed to be an "infinite power" bus with a constant voltage of 230 kV.

In this way, the Beričevo-Melina node corresponds to the left-side node of the Fig. 2 system model, with a constant voltage E_P=230 kV. The load in Fig. 2 corresponds to the Italian network fed (through the Padriciano-Divača interconnection line) by the 220 kV Divača busbars, which correspond to the right-side load bus with voltage E_a.

In conclusion, the effects of these approximations are shown in Figure 4, where the real power system is adapted to the simple system model of Fig. 2 used to analyze the voltage stability. Figure 4 highlights the 220 kV transmission lines of the power system between the Beričevo-Melina artificial node and the Divača load node.

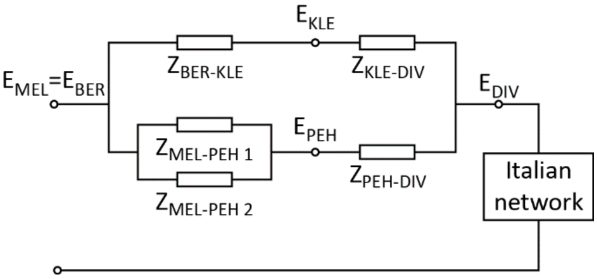

Figure 4. Adaptation of the studied network to the reference scheme shown in Fig. 2.

The series impedances of the five 220 kV lines involved are:

- Bericevo-Klece: $\dot{Z}_{BER-KLE} = (0.78 + j5.27)\,\Omega$
- Klece-Divača: $\dot{Z}_{KLE-DIV} = (3.93 + j17.31\,)\,\Omega$
- Melina-Pehlin 1: $\dot{Z}_{MEL-PEH\,1} = (1.08 + j7.18)\,\Omega$
- Melina-Pehlin 2: $\dot{Z}_{MEL-PEH\,2} = (1.10 + j5.75)\,\Omega$
- Pehlin Divača: $\dot{Z}_{PEH-DIV} = (3.13 + j22.07)\,\Omega$

Following the above, the total impedance between the end nodes shown in Fig. 4 is $\dot{Z}_L = 13.78e^{j81.37}\,\Omega$.

Once the starting voltage $E_{MEL-BER}$=230 kV and the line impedance Z_L have been assigned, equations (2) and (3) are used to determine the power system steady-state chracteristics, i.e. the curves of the load bus voltage E_{DIV} as a function of the power P_{ITA} imported from Slovenia by the Italian power system.

For different power factor values, these characteristics are plotted in Fig. 5.

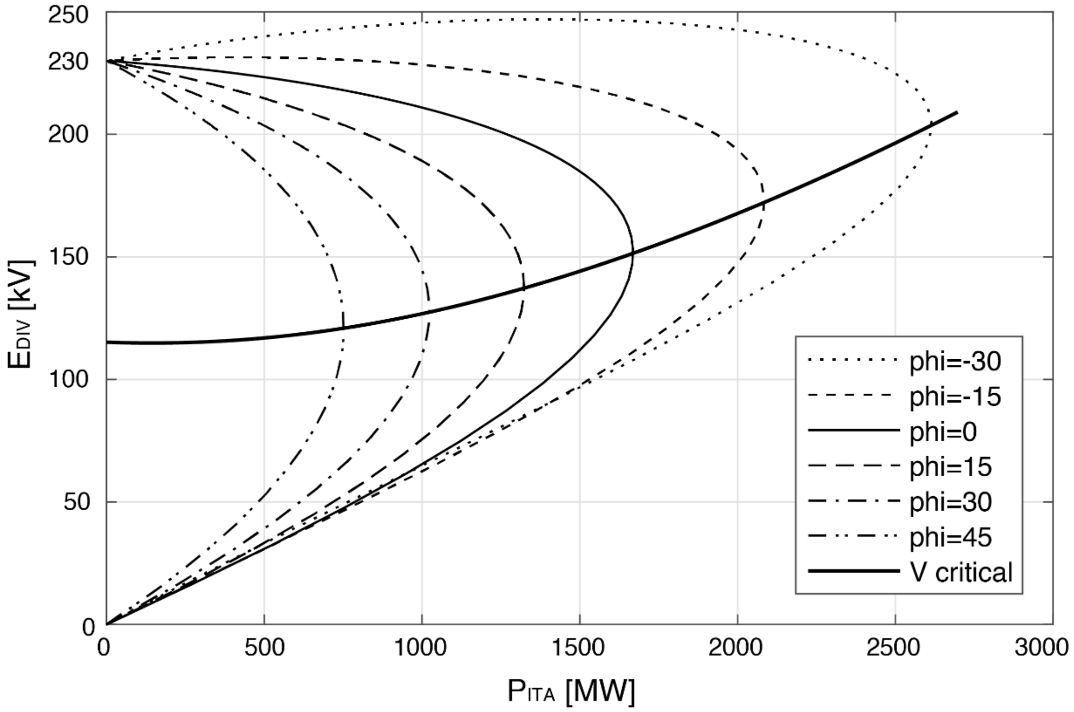

Figure 5. Voltage-power characteristics for the studied transmission system.

The curve connecting the critical points (maximum transmissible power P_{max} - critical voltage E_{cri}) determines the limit between the regions of a stable and possible unstable operation and, consequently, the voltage stability limit. Below the voltage stability limit, the voltage at Divača E_{DIV} may or may not progressively decrease depending on the load behaviour [1].

Figure 5 shows that the voltage stability limit can be reached only at power values much higher than the 370 MW transmission capacity of the Padriciano-Divača line. However, the outage of the Redipuglia-Divača interconnection in an operating condition of a high power import to Italy can determine on the remaining Padriciano-Divača interconnection a (temporary) power flow definitely higher than its transmission capacity[2]. To this regard, it should be noted that temporary overloads are permissible provided they do not increase the risk of discharge and conductor aging. In other words, the conductor thermal limit, i.e. rated current, is a limit that can be exceeded for short time periods. For example, the Italian Standard CEI 11-60 [4] specifies two (among the infinite possible) operating modes that withstand temporary overloads.

To check that there will be no voltage instability problems on the Padriciano-Divača line under the most critical operating conditions, load-flow calculations are made for the highest power flow from Slovenia to Italy, i.e. 1573 MW. The Redipuglia-Divača line is assumed to be out of service and the PST installed at the Padriciano station is assumed in operation with the maximum boost tap (maximum import to Italy)[3]. Assuming E_p=230 kV, the voltage of the 220 kV Divača

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[2] In what follows, according to the classic analysis of the power system voltage-power characteristics, the system protections expected to get activated when the currents are too high and/or the voltages too low, are neglected.

[3] The network model includes the new double circuit 380 kV line Redipuglia-Udine Sud (indicated in Fig. 1), which started operation in October 2017.

busbar E_{DIV} is 187 kV (0.85 p.u.). Accordingly, the voltage drop between E_p and E_a is close to 20%. The power of the Padriciano-Divača line is 840 MW with the load angle close to 18° lagging ($\cos\varphi = 0{,}95$). The current of the Padriciano-Divača line is 2736 A, which is 304% of the rated current.

There is a reasonable matching between these results and the system characteristics reported in Fig. 5 and obtained by using the above approximations. Indeed, in Fig. 5, the operating point P_{ITA}=840 MW, E_a=187 kV is located on the curve corresponding to a load angle of about 22° instead of the 18° angle provided by the load-flow calculation[4].

The voltage stability margin of about 25% of this operating point (as can be deduced from Fig. 5) is fully satisfactory.

We can also observe that, for the load power P_{ITA}=840 MW, the voltage stability limit reported in Fig. 5 crosses the system characteristic relevant to a load angle of about 35° lagging. Viceversa, for the load angle of 18° lagging, the voltage stability limit corresponds to the load power of about 1250 MW.

The above results prove that:

- the approximations used in order to evaluate the voltage stability of the border section between Italy and Slovenia introduce reasonably small errors and, therefore, can be considered acceptable;
- also under extreme conditions on the Padriciano-Divača line when the currents are thrice the rated ones, due to the high power factors observed under normal operating conditions the system would operate sufficiently far from the voltage stability limit.

5 CONCLUSION

This paper anlyzes the robustness of the power system on the border section between Italy and Slovenia, which includes only two often heavily loaded interconnection lines. The classic voltage stability analysis is used to calculate the transmission system characteristics (also known as 'nose curves') assuming that the most important interconnector, i.e. the 380 kV Redipuglia-Divača line, is forced out of service. At a large power import from Slovenia to Italy, the N-1 state can considerably overload the smaller 220 kV Padriciano-Divača interconnector.

Using the results of load-flow calculations, the network is simplified to be adapted to a simple system model enabling the classic voltage stability analysis and to calculate the transmission system nose curves under the N-1 operation.

The conclusion drawn by the analysis performed is that the challenging conditions considered can give rise to large overloads and unacceptable voltage drops withoud jeopardizing the voltage stability. Indeed, for the most critical operating condition, a comfortable 25% voltage stability margin is calculated.

As to the future work, the study can be extended to investigate operation of the network protections used to open the Padriciano-Divača interconnector when overloaded, thus separating the two Italian and Slovenian power systems. Also to be done with this respect is to ensure proper management of the consequent power unbalances.

ACKNOWLEDGEMENT

The author acknowledges Mr. Michele Poli and Mr. Andrea Piller for their kind support and valuable contribution in realization of this paper.

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[4] The voltage-power characteristics drawn in Fig. 5 can be regarded as conservative owing to the fact that, for lagging angles, the larger is the angle, the smaller is the stability margin.