Analiza vpliva umestitve predvidene SVC naprave v slovenski elektroenergetski sistem s stališča dušenja ENTSO-E med-sistemskih nihanj

URBAN RUDEŽ & RAFAEL MIHALIČ

Povzetek V procesu načrtovanja morebitnih bodočih investicij v slovenski elektroenergetski sistem se je pojavila potreba po obsežni analizi vplivov naprave iz družine FACTS na dušenje nizkofrekvenčnih med-sistemskih nihanj v ENTSO-E kontinentalni interkonekciji, in sicer statičnega var kompenzatorja (SVC). Po prvotni zamisli bi bila SVC naprava predvidena ureditvi lokalnih stacionarnih napetostnih razmer na 220 kV in 400 kV napetostnih nivojih v regiji. Ker napravo odlikuje hiter dinamičen odziv, je bilo smiselno preveriti tudi možnost uravnavanja razmer v širši električni okolici, torej na obratovanje ENTSO-E interkonekcije, katerega del je tudi slovenski elektroenergetski sistem. Analiza je bila izvedena na kompleksnem modelu omrežja za analizo dinamičnih pojavov, sestavljenega iz javno dostopnega ENTSO-E modela ter interno izdelanega (ter v preteklosti preverjenega) modela elektroenergetskega sistema Slovenije. Modeliranje omenjene naprave je bilo izvršeno na podlagi objavljenih raziskovalnih publikacij tako tujih kot domačih raziskovalcev. Z upoštevanjem preproste regulacijske strategije so rezultati v splošnem pokazali na pozitiven vpliv na stabilnost za majhne motnje ter identificirali tista med-sistemska nihanja, katerih dušenje je mogoče z napravo, priključeno na visokonapetostno omrežje Slovenije, uspešno dušiti.

Ključne besede: • elektroenergetski sistem • FACTS • dušenje • nizkofrekvenčno • med-sistemsko • nihanje • interkonekcija •

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Impact of Considered SVC Implementation in the Slovenian Power System on Inter-Area ENTSO-E Oscillation Damping

URBAN RUDEŽ & RAFAEL MIHALIČ

Abstract During the planning process of possible future investments into the Slovenian power system, a need arose for the comprehensive analysis related to low-frequency inter-area oscillation damping of a static var compensator (SVC) device. The SVC device was initially considered for solving local steady-state voltage issues on highest 220 kV and 400 kV voltage levels in the region. As the SVC device features fast dynamic response, it seemed reasonable to verify whether its implementation benefits the operation of the entire ENTSO-E interconnection as well. The presented analysis was performed using a complex model for dynamic studies, comprising publicly available ENTSO-E model and internally constructed Slovenian power-system model, which was successfully tested and verified in the past. Modelling of the SVC device was achieved by means of available research publications dealing with the subject, both foreign as well as domestic. By implementing a simple damping strategy, the results showed a positive effect on a small-signal stability and indicated which inter-area oscillations can be successfully damped when considered devices are connected to the Slovenian high-voltage transmission network

Keywords: • power system • FACTS • damping • low-frequency • inter-area • oscillation • interconnection •

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1 Introduction

It has been decades since national power systems in continental Europe started to interconnect in order to increase the level of operational security of individual power systems. However not until the introduction of Wide Area Monitoring Systems (WAMS) were Transmission System Operators (TSOs) able to monitor the operation of the entire ENTSO-E (European Network of Transmission System Operators for Electricity) interconnection as a whole, as it has grown significantly since then, encompassing almost the entire European continent. Relatively poor number of interconnections between countries compared to strong electrical connections within the countries themselves, resulted in conditions that often lead to low-frequency inter-area oscillations, which are electromechanical in their nature. There are a few publication available that study those periodically re-appearing such as [1] and [2].

Recently, ENTSO-E announced the availability of initial dynamic study model of the continental Europe [3], being prepared in several commercially accessible simulation software tools. The model exhibits three most often reoccurring inter-area oscillations, covering both oscillation directions: west-to-east and north-to-south. At the moment, this model appears to represent the best possible public-domain means for analysing the potential of low-frequency oscillation damping in ENTSO-E interconnection by applying different devices and control strategies.

Authors of this work did no concentrate on providing most suitable control strategy for achieving best possible impact of damping. Rather, the focus was put on finding out whether Slovenian power system's location within ENTSO-E interconnection is suitable for fast-acting devices, such as static car compensator (SVC), to impact the damping of inter-area oscillations significantly. The original idea for the installation of an SVC device however, originates in the need for solving steady-state voltage issues in the region, encompassing Slovenian and Croatian power system. It has been observed lately that during the low system loading, the operational voltage on 220 kV and 400 kV voltage levels reach alertly high values that might endanger the equipment in time. So the question arose whether the installation of fast-acting device instead of simple (static) reactors would have any positive consequences that would reach beyond the national borders.

To this end, a previously verified dynamic model of the Slovenian power system [5] was implemented into the already mentioned dynamic study model of ENTSO-E. Then one of targeted interconnection-wide oscillations was triggered. In the final phase, a model of an SVC device with a simple and straightforward control strategy for power oscillation damping (POD) was being relocated across several European countries of interest in order to see how impact on the damping changes with the location.

2 Applied Dynamic Models

2.1 ENTSO-E interconnection dynamic model (Dynamic Study Model)

In the last two years or so, the initial dynamic model of continental Europe was made publicly available by the European Network of Transmission System Operators for Electricity (ENTSO-E) [3].

The model-building process introduced several specifics, which limits the model's application solely to representing:

- mean frequency transients (spinning reserve, primary control),
- general oscillatory behaviour (i.e. modal analysis), which was monitored by European Wide-Area Monitoring Systems in the last couple of years. As was published in [1], three inter-area modes can be mostly detected in ENTSO-E, referred to as the "north-south" mode with the approximate frequency of 0.35 Hz and two "east-west" modes with the approximate frequencies of 0.13 Hz and 0.19, respectively. After performing a special tuning process on the model, it is said to exhibits all three modes, even though it turned out they are slightly different ("north-south" being 0.40 Hz instead of 0.35 Hz and "east-west" being 0.09 Hz instead of 0.13).

This means that by following the foreseen appropriate use of the model it should be able to reflect the typical (average) dynamic behaviour of the whole continental Europe. As a result, if studies other than that mentioned in the above two bullets are to be carried out, more detailed (correct) model of the local-system configuration is to be used. This is why national power systems corresponding to individual countries are modelled separately, in order to easily replace them with detailed model (however, load-flow convergence might not be that straightforwardly achieved). This was done in the presented analysis, where a detailed model of a Slovenian power system (presented in section 0) was applied. Authors assume that this might be one of the reasons for slightly different oscillation frequencies (see the second bullet above).

Among above-mentioned specifics of the model, the following are most evident:

- only machines with the active-power production above 250 MW (in the selected steady-state conditions) are modelled as synchronous machines, the rest are considered as a constant (negative) impedance. As a result, only approximately 9 % of all machines are appropriately modelled,
- synchronous machine models are equipped with a simplified (standard) models for control devices, encompassing automatic voltage controller, governor and power-system stabilizer,
- only machines with the active-power production above 0 MW (in the selected steady-state conditions) include the full set of control models (otherwise, only automatic voltage controller is considered),
- multiple parallel generation units connected to the same busbar are aggregated into a single machine,
- parallel transmission lines are aggregated into a single equivalent line,
- the system topology and steady-state data correspond to year 2020 (authors cannot be completely sure of that since in [4] this is written quite dubiously),
- etc.

More detailed information about the model itself and its verification can be found in [4]. However, there is another feature that should be separately mentioned as the authors find it quite important: the naming of all power-system elements (synchronous generators, transformers, transmission lines, busbars, etc.) is coded in such a way that only the country of origin is evident (using international country codes such as "SI" for Slovenia or "DE" for Germany). The rest of the name does not follow the currently enforced data exchange format prescribed by the ENTSO-E. Instead, an unknown coding procedure produced something one might also refer to as “random numbers”.

One is able to access the model by submitting a special request form to ENTSO-E in which a commitment is made to inform ENTSO-E about the result of the specific study or a project which requires the model. At the time of writing this paper, the model is available in several formats corresponding to different widely used simulation tools, such as PowerFactory, Netomac, PSS/E, etc.

2.2 Slovenian power-system dynamic model

The dynamic model of the Slovenian power system was developed at the University of Ljubljana, encompassing not only the 400 kV, 220 kV and 110 kV network levels of the Slovenian power system but certain parts of 400 kV and 220 kV networks of neighbouring countries as well (north of Italy, south of Austria, Hungary, Croatia, Bosnia and Herzegovina and Serbia). The model became especially valuable after being successfully verified for several contingencies that took place in the past:

- nuclear power plant Krško outage (March 2011),
- phase-shifting transformer in substation Divača outage (April 2011),
- transition into island operation of the 110 kV north-wester part of the Slovenian power system (June 2011),
- etc.

The verification process was conducted by comparing the model response with WAMS captured real-system response for the same contingency [5]. After some tuning the model adequately represented the system response for the whole variety of contingencies, without any additional changes in the model. Lately, the model was additionally verified for a special transient phenomenon that took place in substation Krško in 2015 [6]. It was a case of a long-lasting sympathetic inrush current phenomenon, which was also successfully reconstructed by considering Phasor Measurement Unit model together with current transformer saturation characteristics.

2.3 Static VAR compensator equivalent model

The dynamic simulations were performed in a so-called stability (commonly known as RMS) calculation mode, where symmetrical conditions between phases are assumed. Therefore, a detailed model of the SVC device was not required. Instead, an *equivalent* model was constructed by using a variable-admittance element (referred to as “VAR-Y”), as shown in the left part of Fig. From the scheme it is evident that the equivalent model of an entire SVC device consists of two parallel elements: fixed capacitance and a variable inductance, which is a model representation of a thyristor controlled reactor (TCR). As the TCR technology is not indented for a direct connection to voltage levels above 35 kV, a power transformer is included in the model as well.

The SVC control strategy is implemented within the “VAR-Y” controller. The model enables two kinds of controls, i.e. *voltage control* (at the specified bus) and *power-oscillation damping* (POD) control. The first is determined by device’s static characteristics (presented on the right-hand side of Figure 20.1), which determines the injection of capacitive and inductive currents for different values of the busbar voltage. So clearly, the SVC device is able to operate in either capacitive or inductive regime as long as the limitations of the TCR part are not exceeded. After that, TCR either operates in a fully closed or opened mode. The POD control on the other hand was modelled in terms of a differential control block with a limitation. This means that a kind of a bang-bang strategy was employed, which periodically bounces the SVC's operating point from one limit to another with the frequency of the present oscillation. As the control input variable, active-power flow on the selected transmission line was used.

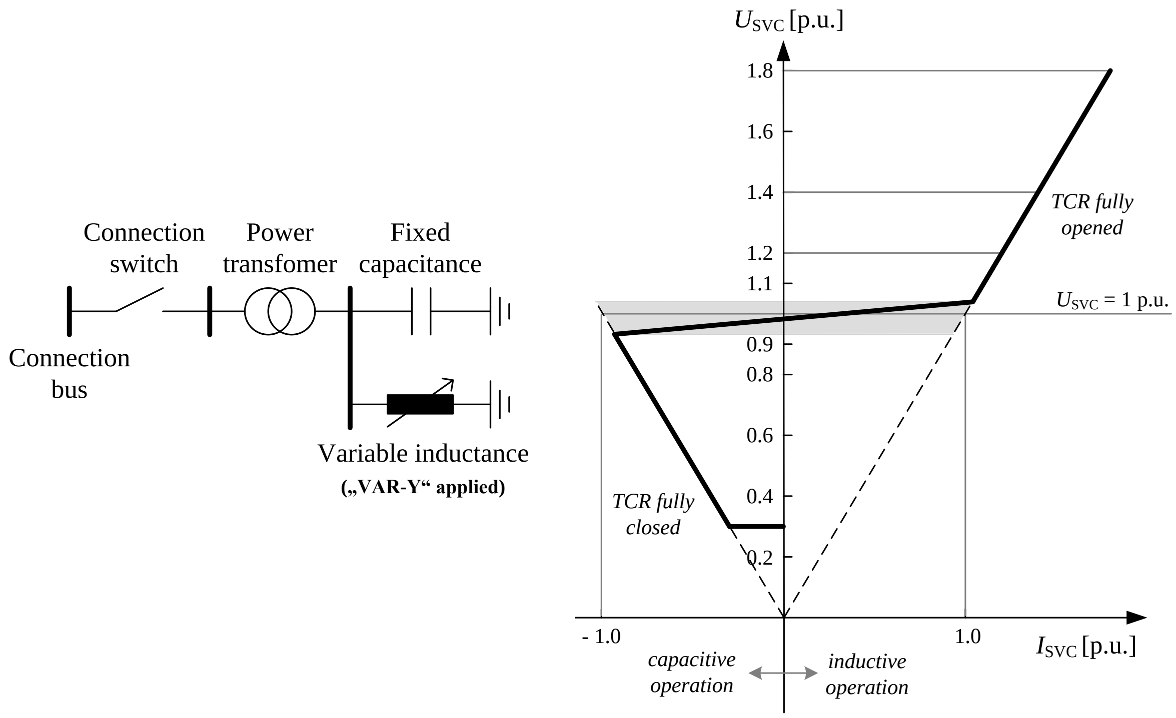

Figure 20.1: left: equivalent SVC model, right: static SVC characteristics

3 Inter-Area Oscillation Damping Analysis

3.1 Stimulating the appropriate oscillation

According to [7] and [8], the active-power oscillations in the power system can be categorized into two groups, depending on the source or the mechanism of its occurrence:

- *free oscillations (or negative-damping oscillations)*, resulted by negative damping ratio of power systems. Their appearance coincides with situations, when the excitation control starts to counteract the positive damping of generators' damping windings (this is usually the case when the reactance of transmission system is large or power output of generators is high). Damping of such oscillations is usually dealt with installation of power-system stabilizer (PSS) control,
- *forced oscillations*, which are explained by the resonance mechanism. The presence of a small but periodic disturbance with the frequency near any of the system's natural frequencies, causes quite fast increase in oscillation amplitudes. Similarly, the removal of the disturbance quickly results in oscillation annulation. This is why most commonly used approach to diminish forced oscillations is to separate the source of the disturbance.

In the presented study, the ENTSO-E power system model exhibits a very strong damping of its natural inter-area oscillations. This is why in the *first step*, appropriate changes were made to excitation-control parameters in order to decrease the damping. In case of north-south oscillations, these changes were applied to synchronous generators on northern and southern parts of Europe and similarly, in case of west-east oscillation, same changes were done to generators on western and eastern parts of Europe.

In the *second step* however, the targeted oscillation with the selected frequency was stimulated by insertion of a sine-shaped active-power injection in the north or west, respectively. The frequency of the injection followed the targeted frequency. After several periods, the power injection was withdrawn, but the oscillation with the exact selected frequency was sustained for an arbitrary amount of time. An example of such process for the stimulation of north-south oscillation with the frequency of 0.40 Hz is depicted in Figure 20.2. The upper graph represents the rotor angle deviation (from its steady-state values) of a Slovenian nuclear power plant Krško, whereas the lower graph depicts the same quantity corresponding to two other synchronous machines – one in Denmark (thin solid line) and the second in Italy (thick solid line). Due to anonymization of ENTSO-E dynamic model it is difficult to clearly specify which two generation units are in question.

Several conclusions can be drawn from Figure 20.2:

- the sine-shaped active-power injection appears at about *t* = 2 seconds and lasts for approximately 20 seconds,
- after active-power injection elimination the oscillations with the frequency of 0.40 Hz is sustained until the very end of the simulation (i.e. until *t* = 130 seconds),
- without performing any interventions, the oscillation amplitude remains constant throughout the simulation,
- generators from Italy and Denmark oscillate with an approximate 180° phase shift. As they are located at the very northern and southern physical ENTSO-E limits, this means that the oscillating energy exchange is indeed between the northern and southern groups of synchronous generators.

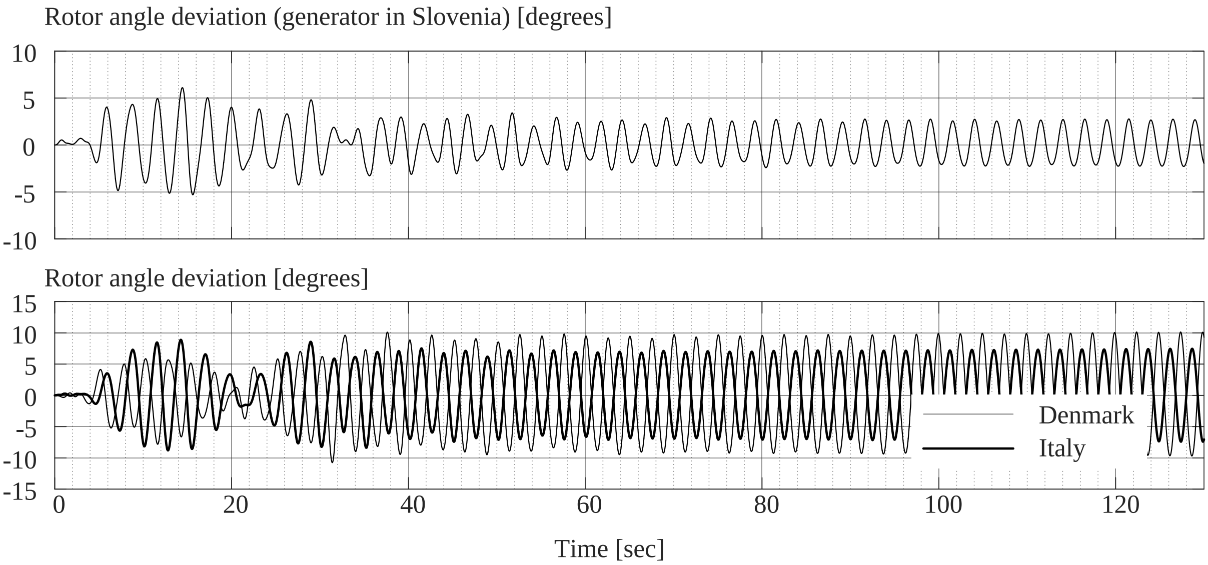

Figure 20.2: stimulating the north-south ENTSO-E sustained oscillations

3.2 SVC impact

In order to verify whether the SVC device, placed in the high-voltage Slovenian network, can indeed improve the damping of described inter-area oscillations, first the appropriateness of modelling had to be confirmed. To this end, the reactive-power rating of SVC was set to $200_{cap}/100_{ind}$ Mvar, the SVC connection point was varied across most of the ENTSO-E network and the SVC impact to oscillation amplitude was observed for:

- damping of west-east oscillation in the following countries: Greece, Bulgaria, Bosnia and Herzegovina, Slovenia, Austria and Switzerland (results presented in Figure 20.3),
- damping of north-south oscillation in the following countries: Netherlands, northern part of Germany, southern part of Germany, Czech republic, Slovenia and Italy (results presented in Figure 20.4).

In Figure 20.3 and Figure 20.4, a rotor angle oscillation with respect to time is depicted for two cases: without POD activation (grey oscillating curve) and with a POD activation at t = 90 second (black oscillating curve). In case of east-west oscillation (Figure 20.3), a rotor angle of a machine in Spain is depicted, whereas in case of north-south oscillation (Figure 20.4) a machine in Denmark is under investigation. Along with two oscillating variables, a set of thick black lines is provided as well. These lines correspond to oscillation amplitude with respect to time for different SVC placement among the already provided list of countries.

It can be clearly seen from the simulation results that closer the SVC is located to the very borders of oscillation (so closer to the group of generators having the highest mode shape), faster the oscillation amplitude can be decreased. Even though such conclusion was expected, it was interesting to find out that by placing the SVC to the very electrical centre of the oscillation, absolutely no damping effect can be detected. In terms of west-east oscillation, Austria appears at the centre of oscillation, whereas Slovenia is located just slightly towards the east. Consequently, regardless of POD controller activation, the SVC in 400 kV network of Austria has no noticeable effect on oscillation damping. On the other hand, SVC in the Slovenian 400 kV network has some slight influence on damping, as can be seen from Figure 20.3. Similarly, the oscillation centre in terms of north-south swings appears to be somewhere in the south of Germany. For the reader’s convenience it is reasonable to mention that in the first step of north-south oscillation modelling (see section 0) a perfectly-sustained oscillation was hard to achieve due to a strong sensitivity of oscillation on changes in excitation control parameters. Consequently, author’s had to be satisfied with increasing oscillation amplitude for cases with no interventions (no SVC) that eventually lead to small-signal instability.

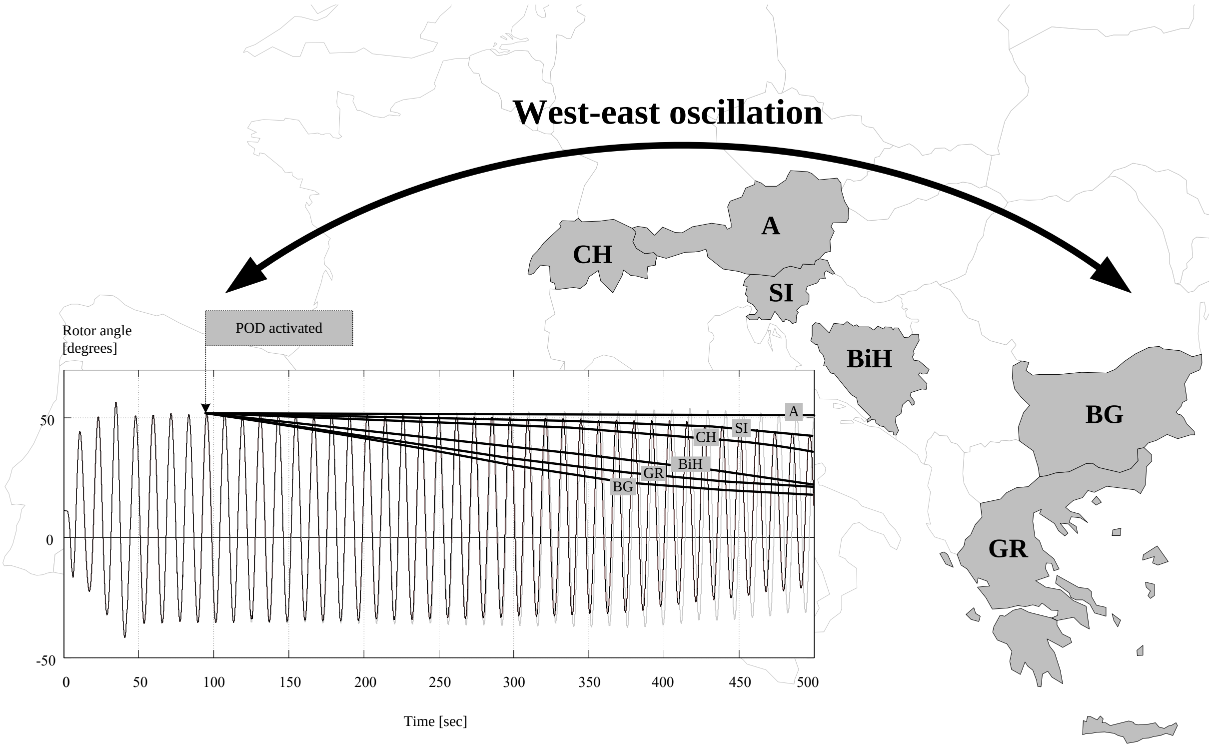

Figure 20.3: Impact of SVC device on east-west ENTSO-E oscillation damping

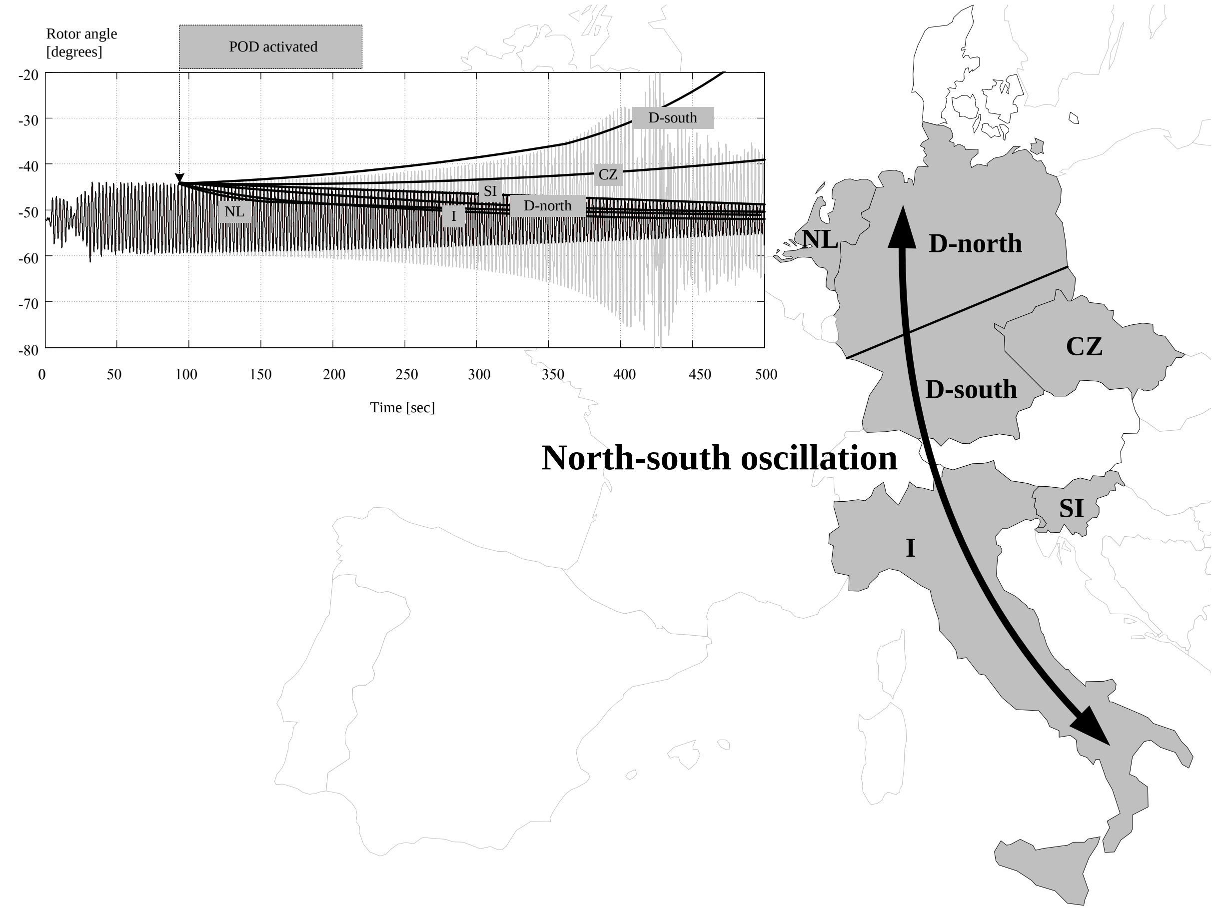

Figure 20.4: Impact of SVC device on north-south ENTSO-E oscillation damping

The results confirmed that the installation of an SVC device of a reasonable rating into 400 kV Slovenian network can have a significant effect on at least certain ENTSO-E oscillations. In addition, the analysis also showed (results not proved due to space limitation) that a similar effect can be achieved regardless of the SVC position within Slovenian 400 kV network.

4 Conclusions

Interconnecting smaller power systems into large interconnections might improve several operational aspect, but can as well be a trigger for appearance of new problems, one of them being small-signal stability. In the last couple of years, TSO's across Europe managed to detect and monitor characteristic inter-area oscillations that repeatedly appear in ENTSO-E, with the help of their national WAMS systems. As a result of consequential construction of a dynamic ENTSO-E model, TSOs and researchers are able to analyse these oscillation even further. It turned out that while trying to find answers to solving regional voltage issues in the Slovenian power system, the use of SVC device might contribute to small-signal stability issue in wider ENTSO-E sense as well, despite SVC's not being most appropriate for solving steady-state voltage problems. The presented analysis showed that Slovenia's almost central location within ENTSO-E is *in general* not that favourable for damping of oscillations, emerging from the very outer ENTSO-E limits. Nevertheless, *in specific scenarios* (i.e. north-south ENTSO-E oscillation) it might contribute to damping significantly.

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