The France-Spain Border: A Case Study Advocating for the Use of Simplified Time-Domain Simulations for Steady State Calculation

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Abstract—The fast evolution of transmission systems, induced by the massive integration of high voltage direct current links, special protection schemes and renewable energies, has a strong influence on the system’s behaviour and the steady state it reaches after one or several events. The power flow tools that are currently used to calculate steady states after some events are not adapted any more to such changes. A case study advocating for the use of simplified time-domain simulations for steady state calculation instead of fully static tools is presented here. This case study is simulated using DynaFlow, a new simulation tool that does a simplified time-domain simulation whose final state is given as a result. It focuses on the France-Spain border, and it is shown that the dynamic parameters of the special protection schemes have a strong impact on the steady state that cannot be easily captured by classical power flow tools. A sensitivity analysis is also done to illustrate this.

Index Terms—Time-domain simulation, Modelica, Steady State, Special Protection Schemes, Power Flow

I. INTRODUCTION

A. Motivations and background

Nowadays transmission systems are strongly evolving with the massive introduction of High Voltage Direct Current (HVDC) links, Special Protection Schemes (SPS) [1] and Renewable Energies (RE) [2]. This has an influence on the dynamic behaviour of the system and on its steady state following one or several events. Power flow tools [3] are classically used to calculate the system’s new steady state after a change but they rely on heuristics and external loops to try to mimic the controllers actions. Such an approach cannot capture all the complexity and interactions existing between all the different controls, especially when they interact with each others with different temporalities [4]. Discrete interactions between SPSs could in theory be taken into account by a classical power flow tool, at the cost of complex and error-prone external loops, but it is not the case for interactions driven by continuous dynamics.

B. Contributions

To cope with that, a new open source implementation (called DynaFlow) based on a simplified time-domain simulation has been proposed in [4]. Following this new approach, a case study is presented here, focusing on the France-Spain border, where the interactions of SPSs, together with HVDC dynamics, strongly impact the steady state. In particular, the interactions among Phase Shifter Transformers (PSTs), HVDC operated in an AC emulation mode [5] [6] and the over-current protections, show that a classic static approach is not suitable to capture all the interactions. Moreover, if the discrete actions could in theory be captured by a static power flow tool using complex external loops, it would be impossible to mimic the continuous behaviour of some components. The study presented here highlights all the benefits of using a simplified time-domain simulation to analyse cases with a lot of SPSs.

C. Paper organisation

In section II, the specificities of the France-Spain border are introduced along with the modelling choices done in DynaFlow [4] and the parameters chosen. In section III an in depth analysis of the behaviour and the interactions of SPSs following a few impacting events is presented. Furthermore, the analysis is stressed to present the influence of the system initial conditions (e.g. increasing the commercial exchange between France and Spain). In section IV, the influence of the SPSs different temporalities and of the simulation set-up on the obtained results are shown via a parametric analysis. In conclusion, perspectives are presented on similar studies where a simplified time-domain simulation approach is needed to correctly represent complex interactions between controls.

II. THE FRANCE–SPAIN BORDER SPECIFICITIES

Figure 1 shows the grid map of the France-Spain border. This area is interesting as it contains a few AC lines crossing the border, two HVDC links in parallel in an AC emulation mode [7], two PSTs and over-current protections that can interact with each other because of their respective time constants. This area is therefore a good example where discrete
dynamics and continuous dynamics could interact with each other. In this section, it is explained how these elements are modelled in DynaFlow and which parameters have been chosen for each modelled component. More details can be found in [4].

A. AC lines and transformers models

As for the classical power flow tools, no time-domain model is used for the lines and transformers. They are modelled using a Pi model with a resistance, a reactance, side capacitances and for the transformers a ratio and a phase-shift. The dynamics at stake are indeed faster than the rest of the system’s dynamics, which makes it unnecessary to have a more detailed model.

B. HVDC links model

For this particular case, the HVDC links in parallel are modelled as Voltage Source Converters (VSC) HVDC links. They regulate the voltage at each terminal. A PQ diagram is taken into account for each converter so that reactive limitations are properly handled. The active power flowing through each link follows a set point to which a variable part is added that is proportional to the difference between the voltage angles at each terminal. These angles are filtered following a certain dynamic. This type of regulation is called AC emulation as it mimics the behaviour of an AC line. The losses (intended here as the losses of the DC cable and the converters losses) are also taken into account, which means that the active powers at each AC terminal are not exactly equal. This is summed up in (1), (2), (3) and (4).

\[ P_1 = P^* + K(\theta_1 - \theta_2) \]  
\[ P_2 = -\rho P_1 \]  
\[ t_{filter} \frac{d\theta_1}{dt} + \theta_1 = \theta_1^f \]  
\[ t_{filter} \frac{d\theta_2}{dt} + \theta_2 = \theta_2^f \]  

In these equations, \( t_{filter} \) is the time constant of the AC emulation, \( \theta_1 \) and \( \theta_2 \) are the voltage angles at terminal 1 and 2 (with the filtered angles \( \theta_1^f \) and \( \theta_2^f \)), \( P_1 \) and \( P_2 \) are the active powers at terminal 1 and 2, \( P^* \) is the active power set point, \( K \) is the AC emulation coefficient and \( \rho \) is the global loss coefficients. For the simulations considered in this paper, the time constant chosen for the HVDC links is \( t_{filter} = 50 \text{ s} \). As a consequence, the HVDC links behave like AC lines but with a slow dynamic that can have an impact on the final steady state.

C. Phase-shifters model

The PSTs are modelled in current limiting mode. The current flowing in the transformer is monitored. When it goes above a certain value \( I_{max} \) for a certain amount of time \( t_{first} \), a tap is changed and then others each \( t_{next} \) until it goes back under the limit (with a dead band). One should note that for this model, two time constants are of importance for each transformer: \( t_{first} \) for the first tap change and \( t_{next} \) for the successive tap changes after the first one. It is then possible to accurately model the differences in time constants between several transformers. Table I sums up the parameters chosen for the two PSTs of the France-Spain border area (called PST1 and PST2 in the following) considered in this paper.

In a classical power flow tool, the PSTs are modelled using external loops. One external loop can change the taps of all the transformers or successive external loops can be used, with a predefined order that is deduced by heuristics. The heuristics and external loops are complex and error-prone when there are several PSTs.

D. Over-current protection model

The over-current protection (CLA for Current Limiting Automaton in the following) that is modelled in the following test cases monitors the current flowing in a certain line or transformer. When it goes above a certain value for a certain amount of time \( t_{lag} \), the protection disconnects a given component to mitigate the over-current. For the simulation cases shown in sections III and IV , two CLAs are considered. A first one (CLA1) is monitoring the current on a line close to the border: if the limit CLA1\( I_{max} \) (CLA1\( I_{max} \)) is overcome, after \( t_{lag} \) (\( t_{lag} \)) a transformer is tripped. A second over-current protection is monitoring the current on PST1, if it is above the limit CLA2\( I_{max} \), PST1 is disconnected after \( t_{lag} \). Table II sums up the numerical values chosen for CLA1 and CLA2, respectively. For PST2 no CLA is considered: instead PST2

\[ \begin{array}{c|c|c}
\text{CLA}_1 & \text{CLA}_2 \\
\hline
I_{max} & 1476 & 1476 \\
t_{lag} & 20 & 33 \\
\end{array} \]

is locked at current tap position when its monitored current is above 2185 A (8.5 pu).

Fig. 1: ENTSO-E grid map showing the France-Spain border.
E. Summary

The brief description of all the elements modelled in this case study shows that several time constants are of concern. These time constants have different values, which means that the different elements can interact with each other and the order in which they act when an event occurs cannot be predefined. This can have a strong impact on the final steady state reached by the simulation as it is shown in the next section.

III. Simulation Results Analysis

The base case considered in this paper is the French transmission system, together with a part of the Spanish transmission system close to the border. An export of 3500 MW from France to Spain is studied. A line tripping close to the border is applied at 200 s. Figure 2 shows the evolution of the PSTs currents (blue and red lines), the active power at one of the HVDC’s converters (yellow line) and the PSTs tap position (purple and green lines), with respect to time. When the line is tripped ((a) vertical dashed line) the current in PST1 is jumping above its limit: the first tap change occurs 26 seconds later. During this time interval, at about 220 seconds, the first Current Limiting Automaton (CLA1) trips a transformer close to the border ((b) vertical dashed line), bringing also PST2’s current above its limit. The current in PST1 starts decreasing before 220 seconds due to the dynamic of the HVDC link’s AC emulation. Starting from about 226 seconds, both PSTs start to move taps, following their $t_{next}$ time constants. PST1 moves from tap position 18 to tap 24 in order to reduce the current below its limit. Notice that PST2 is going from tap position 18 to 20 in about 8 seconds after CLA1 intervenes: a third tap position change (from 20 to 21) happens later. When PST1 increases its tap position, it increases the current in PST2: last PST1 tap position brings PST2 above its current again. Figure 3 shows similar informations when pushing the France to Spain export to higher values: for 3880 MW a similar behaviour as described above is observed. PSTs change tap position to retrieve acceptable values of monitored current. For export values of around 3990 MW the mutual influence of PSTs is even more important: PST2 tap position changes between 240 and 300 seconds are due to PST1 tap increasing. On the other hand, last PST1 tap position increase at 325 seconds is caused by a current overload induced by PST2 tap change at 300 seconds. When forcing the France-Spain export towards higher values, such as the 4090 MW case shown in Figure 3, when CLA1 acts, both PSTs currents are too high: PST1 is disconnected by CLA2 and PST2 is locked at initial tap position. This brings an overload of other lines close to border that trip a few seconds later, creating a cascade that does not allow one to find a solution using DynaFlow [4]. Table III sums up the sequence of discrete events as described above.

<table>
<thead>
<tr>
<th>Line tripping event</th>
<th>PST1 current above limit</th>
<th>CLA1 action</th>
<th>PST2 current above limit</th>
<th>PST1 action</th>
<th>PST2 action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 2: Evolution of PSTs currents (blue and red lines), HVDC active power (yellow) and PSTs tap position (purple and green), with respect to time.</td>
<td></td>
<td></td>
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</table>

Fig. 3: Evolution of PSTs currents (blue and red lines) and PSTs tap position (purple and green), with respect to time for different values of France to Spain export.

| Fig. 4: Evolution of PSTs tap position values against a classical fully static power flow. Figure 4 shows calculated tap position values using a static |
power flow (LoadFlow in legend) against ones evaluated using DynaFlow [4]: it is possible to observe that between 3500 MW and 3800 MW of export, both tools are able to find a solution (pink region). Notice that, introducing temporality of PSTs and HVDC brings to slightly different values of tap positions for both PSTs with respect to what calculated by the static power flow tool. It seems that taking into account the temporalities of the PSTs leads to steady states with less tap changes. Indeed, with a classical power flow tool, a first PST changes its taps to reduce its current, then the second one, and then it goes back to the first one if the second one tap changes have increased the current in the first PST. This way of calculating the tap changes can lead to a conservative state where too much taps compared to what was necessary have been changed. In addition to that, DynaFlow [4] is able to find a solution for even higher values of export (blue region). This is partly due to the fact that, in DynaFlow [4], loads are modelled as restorative loads with voltage limitations: after an event, the active and reactive powers of the load go back to their initial value following a certain time constant, unless the voltage is too low or too high, in which case the load behaves as a classical voltage-dependent load [4]. In the case of the static power flow tool used to obtain these results, loads are considered as fixed: this brings to issues related to voltage collapse close to some loads and maximal transmissible power issues on some lines, in particular when CLA1 intervenes. This has been proved forcing DynaFlow using fixed PQ loads, retrieving similar behaviour (both in terms of voltage collapse and available France to Spain export margins) as observed using a classical static power flow tool. The fact that the PST change less taps with DynaFlow [4], thus reducing the stress on AC lines in parallel compared to the classical power flow can also be an explanation for this bigger margin obtained with DynaFlow [4]. In this section, the impact of considering temporality on final results has been shown, in particular when PSTs and SPSs can interact together. The advantages of the DynaFlow [4] approach is even more noticeable when imposing higher values for the France-Spain export: for those cases, only DynaFlow [4] is able to find a solution. The results obtained here can have a strong consequence on the way the system is operated. When modelling and simulating the system in a better way, one can show that larger exports/imports are possible without having to take measure at the operation level. The system could in fact be operated even closer to its actual limits. In section IV, the impact of changing some time constants values for PSTs and HVDCs is shown, in order to highlight the influence of those on final results, advocating for the use of simplified time-domain simulators as DynaFlow [4] for the calculation of steady states.

IV. PARAMETRIC AND SENSITIVITY ANALYSIS

Attempting to decouple the influence of each time constant, some of the parameters shown in section II ($t_{\text{filter}}$ of PST1 and $t_{\text{filter}}$ of HVDCs AC emulation) are changed, one by one. The analysis focuses only on some values of France-Spain power exports, where the parametric analysis impact is stronger.

We conclude this section showing the France to Spain power export margins that can obtained using DynaFlow instead of a classic static power flow, on few French transmission snapshots.

A. Influence of reducing PST1 $t_{\text{first}}$ value

In section III it has been shown how the current monitored by PST1 is above its limit as soon as the line tripping occurs at 200 seconds. Values are even higher when CLA1 acts disconnecting a power transformer close to the border (Figures 2 and 3). In order to anticipate the tap change of PST1, $t_{\text{first}}$ is reduced to 5.5 seconds (same value than PST2). As expected and shown in Figure 5, PST1 tries to reduce its monitored current moving its tap already between 200 and 220 seconds. Compared to what is explained in Figure 3, this has as a consequence the reduction of the peak of the current in

![Fig. 4: Final value of tap position for PST1 and PST2 as calculated using a classic static power flow tool (cross) and DynaFlow (dots), depending on different values of France-Spain export. Pink region indicates values of export for which both power flow and DynaFlow are able to find a solution. Blue region refers to value of export where only DynaFlow is able to calculate a steady state solution.](image-url)
Fig. 5: Time evolution of currents and tap position of PST1 and PST2 when reducing $t_{\text{first}}$ of PST1 to 5.5 seconds.

this PST when CLA1 intervenes: this is particularly important when applying 4090 MW of export, as it prevents the trip of PST1, allowing the simulation to go further as PST1 current is not reaching CLA2 limit. As CLA2 is not acting, PST2 current values at 220 seconds are below locking current limit shown in section II, allowing PST2 to move tap to reduce its monitored current. Table IV outlines the discrete events sequence when considering $t_{\text{first}} = 26s$ and $t_{\text{first}} = 5.5s$ for PST1. For the 4090 MW case, the simulation stops anyway later as the power flows on border crossing lines are pushed by the PSTs towards the Eastern part of the border, overloading lines there that trip as above their temporary limits, bringing to a cascade of disconnections on the border. Another side effect of reducing PST1 $t_{\text{first}}$ can be observed when comparing Figure 3 and Figure 5 on the 3990 MW export case: the fact that PST1 is changing tap position earlier brings PST2 monitored current to start on slightly higher values when CLA1 acts at 220 seconds.

B. Influence of HVDCs $t_{\text{Filter}}$ values

In classical static power flow tools, no dynamics are taken into account when modelling HVDCs, whatever the considered operation mode. To see the impact of the introduction of HVDC dynamics in DynaFlow [4], the simulations results (for 3500 MW and 3990 MW of France-Spain export only) when $t_{\text{Filter}} = 0.01s$ are shown in Figure 6, that means that the HVDCs links are reacting almost instantaneously to phase variation on the converters sides, just like it would be the case with a classical power flow tool. The impact of small values of $t_{\text{Filter}}$ is particularly high on lower values of export: first plot of Figure 6 (3500 MW of export) shows that a fast response of the HVDCs AC emulation brings to delay the CLA1 action (from about 220 to 250 seconds) and PST2 tap position changes. For higher values of export, the impact is more limited. In Figure 7 the simulation results for 3500 MW and 3990 MW of France-Spain export are shown, but considering $t_{\text{Filter}} = 200s$. For 3500 MW export, the impact is mainly on PST1: the HVDCs AC emulation is now way slower than what was shown above and PST1 needs to change one tap more (final tap position here equal to 25 instead of 24 shown in section III) to reduce the monitored current above its limit. For the 3990 MW case, almost no PST1 monitored current reduction is happening between 200 second (line tripping) and 220 seconds (CLA1 power transformer tripping), bringing PST1 to be disconnected by CLA2 at 220 s. Due to the combination of these effects, at 220 s PST2 monitored current is jumping on higher values, but not high enough to be blocked: starting from about 225 seconds, PST2 tries to change tap position to reduce the monitored current without succeeding as it arrives at maximum value of tap position. Starting from this, overloaded lines start tripping creating a cascade that prevents DynaFlow [4] from finding a solution.

C. France to Spain export margins

In this last subsection the active power export results obtained using DynaFlow [4] and a classic static power flow tools are presented on a few 2021 French transmission grid snapshots. Figure 8 shows values of export from France
Fig. 7: Time evolution of currents and tap position of PST1 and PST2 when considering $t_{\text{filter}}$ of HVDCs link to 200 seconds.

Fig. 8: Maximum values of active power France to Spain export evaluated using a classic power flow tool (red crosses) and DynaFlow (blue dots), on few 2021 French transmission grid snapshots. Pink region indicates values of export for which static power flow and DynaFlow are both able to find a solution. Blue region refers to values of acceptable export that can be obtained introducing temporality of controls as done in DynaFlow.

to Spain calculated using static and simplified time-domain simulations, considering the same contingency and temporal constants as shown in sections II and III.

Larger margins of active power export are observed when introducing controls temporality as done in DynaFlow [4]. This can have a relevant impact on how an electric system is safely operated: larger margins allow one to avoid counter-trading and/or topological remedial actions when foreseeing a contingency as the one shown in this paper.

V. CONCLUSION AND PERSPECTIVES

In this paper some cases of study are presented, advocating the clear advantage of using a simplified time-domain approach. The simulations focus on the French transmission grid system, in particular around the France-Spain border, where the presence of PSTs together with HVDCs and SPSs makes the region of interest to study the interactions of these components with each others. The specificities of the France-Spain border have been introduced, along with the modelling choices and the parameters. The analysis of the simulation results has been conducted applying a contingency on a line close to the border and observing the impact of the interactions of PSTs, SPSs and HVDCs on the final PSTs tap positions and monitored current. It has been shown that taking into account temporality of controls allows one to properly catch the mutual influence of controls, in particular when stressing the values of active power export from France to Spain. Not only, the temporal interaction of controls allows DynaFlow [4] to retrieve a solution of interest on stressed cases, where classic static power flow tools would fail or would need very complex external loops to mimic the physics of the system. The importance of considering a simplified time-domain approach is even more evident when analysing the influence of time constants of controls on final results: it has been proved that, changing the time when one of the PSTs starts modifying its tap position strongly impacts the action of other controls and consequently the final steady state. Similarly, it has been shown that modifying the HVDC links response time has an impact on the final position of PSTs taps, both on low and high values of active power export from France to Spain. We also presented the range of active power export values for which a simplified time-domain simulator finds a solution, compared to what is obtained with a classic static power flow approach: larger margins of active power export are observed when introducing controls temporality. This has a strong impact on how an electric system can be safely operated.

In following studies, the analysis will be pushed considering multiple contingencies that can stress the system even more: the mutual influence of time constants of controls will be evaluated to show the stress limit of the system.

REFERENCES


