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Dynamic security regions in power systems with active overexcitation limiters

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ABSTRACT

This paper analyzes the impact of active overexcitation limiters (OELs) on the dynamic security assessment of power systems, with focus on transient stability. The analysis is concentrated on dynamic security regions evaluation, considering different OELs types, including the takeover and summed ones. Initially, the importance of the OEL modelling is exemplified in a study carried out on the Brazilian Interconnected Power System, where the OEL activation results in a significant transfer capability limitation. After that, the work explores the development of dynamic security regions in the IEEE New England system, showing how these regions can be distorted depending on the OELs representation.

1. Introduction

The demand growth associated with the intermittency of renewable generation and less investments on the transmission grid has brought more complexity to the power systems operation [1]. In this context, some operating scenarios may become less predictable and considerable stressed with some devices working close to their operational limits. This is the case, for example, of the overexcitation limiters (OELs) [2], which are fundamental to protect the field windings of synchronous machines from overheating [3].

With the increasing complexity of the power systems operation, online security assessment tools have become very important. Such tools indicate whether the system is or is not in a safe operation point, helping the operator in the decision making. Among the relevant online security assessment tools, security regions are very useful to the operators to point out safe redispatch directions based on static and dynamic security constraints [3]. In the dynamic security analysis, the main evaluation criterion is the transient stability.

Overexcitation limiters are devices with a slow dynamic behavior, commonly with an inverse time characteristic. These limiters act on the automatic voltage regulators (AVRs) in order to guarantee that the field current of synchronous machines will stay within the thermal limits. The most employed OELs are classified as summed or takeover type, depending on how its signal is introduced in the AVR. The OEL activation restricts the field current, decreasing the generator capability to provide reactive power to the system, which can lead to a voltage collapse [4,5]. Therefore, the analyses involving the activation of OELs are mainly concentrated in long-term stability studies [2]. However, the evolution of long-term variables may result in a reduction in the security margins associated with short-term instabilities, especially when operational limits are violated. In this case, a system with active OELs, which has its voltage control capacity reduced, is more propitious to a transient instability.

Usually, the control functions of overexcitation limiters are not considered in the database for transient stability studies [6]. In the database of the Brazilian Interconnected Power System, about 50% of the synchronous machines do not have the OEL control functions modelled. Nevertheless, the importance of the OEL modelling in transient stability analysis, especially in systems under stressed conditions, has already been the objective of previous research [2].

In this paper, the impact of active overexcitation limiters in the dynamic security assessment is analyzed with focus on security regions calculation. Initially, the importance of the OEL modelling is exemplified in a study carried out on the Brazilian Interconnected Power System (BIPS). The study shows how the activation of the OEL of an important synchronous condenser can affect the transient stability, limiting the power transfer capability. After that, the work explores the development of dynamic security regions in the IEEE New England system, showing how these regions can be influenced by the OELs representation.

The remainder of this paper is organized as follows. Section II describes the operation principle of overexcitation limiters, considering

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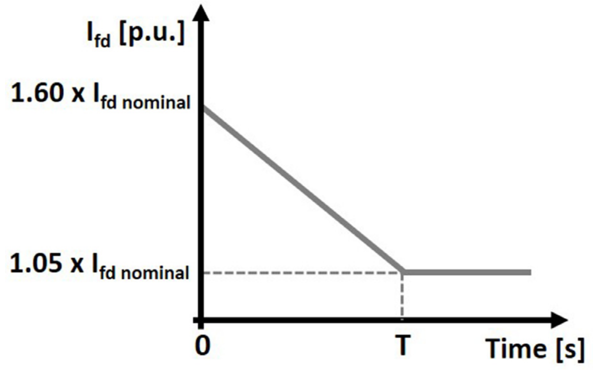

Fig. 1. Typical OEL inverse time characteristic.

different OEL models. Section III presents the basic concepts related to the dynamic security region development. In Section IV, results of the dynamic security assessment for BIPS and New England system are presented. Concluding remarks are discussed in Section V.

2. Overexcitation limiters

The overexcitation limiter (OEL) is a device that protects the synchronous machine's field winding from overheating caused by high currents [7]. Whenever the field current exceeds acceptable levels, the OEL must act to bring this current back to a safe operation point. The OEL activation principle is based on the thermal capability curve of the generator field winding, as defined by IEEE Std. C50.13 [8].

The overexcitation limiters commonly work with an inverse time characteristic [7] as exemplified in Fig. 1. If the filed current (I_{fd}) is lower than 105% of its nominal value, the OEL is not activated, i.e., an overcurrent of 5% is tolerated in the field circuit. However, if the field current is between 105% and 160%, the OEL acts to bring this current to the continuous limit (105%). In this range, the activation is inverse time, depending on the field current and the OEL settings [9]. In Fig. 1, the delay (T) may reach 30 s [9]. Finally, if the field current exceeds 160% of its nominal value, the limiter acts instantaneously, reducing the current to its continuous limit.

Once activated, the OEL output control signal will impact on the generator excitation system. The OEL can be classified into two main types, depending on how its signal is introduced in the AVR control loop [5]: summed type and takeover type.

2.1. Summed type OEL

In the summed type overexcitation limiter, the OEL output signal (V_{OEL}) is added to the summing junction of the AVR, with a negative sign [5], as indicated in Fig. 2. In addition to the OEL signal, the AVR is influenced by the machine terminal voltage (V_t), the reference voltage (V_{ref}) and the signal provided by the power system stabilizer (V_{PSS}).

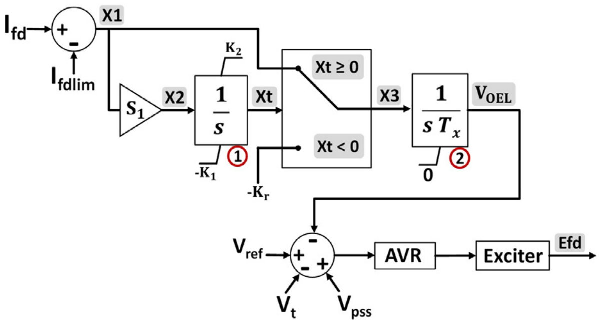

Fig. 2. Summed type overexcitation limiter.

Under normal operating conditions, the OEL output signal is equal to zero without impact on voltage regulation. On the other hand, when the OEL is activated, its signal has the effect of reducing the AVR reference voltage, dynamically forcing the field current to return to its limit value [4].

The summed OEL uses a field current integrator controller (Block #2 of Fig. 2), as well as the associated timer (Block #1 of Fig. 2). The operation principle begins by the comparison between the machine field current (I_{fd}) with the OEL limit (I_{fdlim}). Under normal operating conditions ($I_{fd} < I_{fdlim}$), the timer output signal (Xt) corresponds to its lower limit (-K1), such that the selector block remains in the lower position with a negative output signal (X3 = -Kr). Therefore, the OEL output (V_{OEL}) remains equal to zero, not impacting on the machine voltage regulation.

Under overexcited operating conditions ($I_{fd} > I_{fdlim}$), the current difference becomes positive, increasing the timer output. As soon as the timer output signal becomes greater than or equal to zero, the selector block switches to the upper position, activating the OEL. Consequently, V_{OEL} increases, reducing the field current to its limit according to (1).

$$V_{OEL} = \frac{1}{sT_X}\cdot(I_{fd} - I_{fd\,\mathrm{lim}}) \tag{1}$$

2.2. Takeover type OEL

Depending on the control characteristics, the takeover OEL can be represented by two schemes: control signal substitution (CSS) and error signal substitution (ESS) scheme.

Fig. 3 shows the detailed control function of the takeover OEL with the CSS scheme. The OEL signal overlaps the AVR output through the minimum block. In this way, the limiter directly controls the machine excitation system [5]. As a result, the power system stabilizer signal (V_{PSS}) becomes inactive and can substantially reduce the electromechanical oscillations damping [4]. The timer is represented by an integrator and its input (X2) depends on the difference between the field current (I_{fd}) and its limit (I_{fdlim}). The OEL is activated when this current difference is greater than zero and stops limiting when the difference is out of the dead band range [M, 0.0]. Within the dead band range, the timer input signal (X2) is equal to zero to avoid limit cycling issues [10].

The takeover OEL with the ESS scheme has a similar control logic as the CSS one, as presented in Fig. 4. However, in the ESS scheme, the OEL and the AVR have identical control laws [5]. Thus, if the AVR control function is G(s), the OEL signal is calculated by (2).

$$V_{OEL} = G(s)\cdot(I_{fd} - I_{fd\,\mathrm{lim}}) \tag{2}$$

The excitation system consists of an AVR and an exciter. To ensure the correctly system operation, the voltage regulator must be compatible with the overexcitation limiter [11]. Thus, for the simulations with the summed type OEL, the direct current excitation system IEEE DC1C [7] is considered. On the other hand, for takeover OEL simulations, an

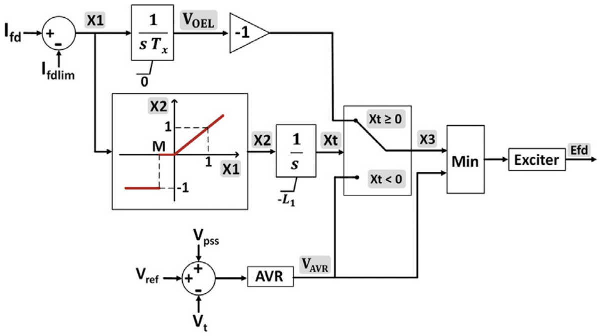

Fig. 3. Takeover type overexcitation limiter – CSS scheme.

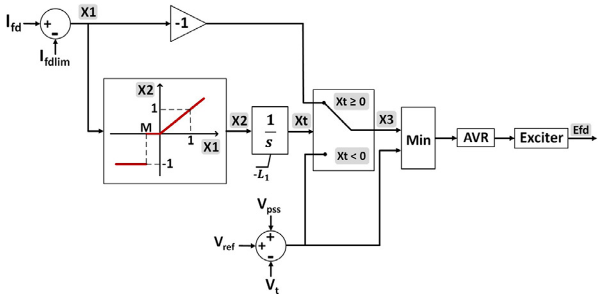

Fig. 4. Takeover type overexcitation limiter – ESS scheme.

IEEE ST1C static voltage regulator [7] is used.

3. Security regions

An important concept associated to the power system security assessment is the development of security regions [3]. The security regions are three-dimensional graphics that relate the active power generation in different areas of the system, indicating safe redispatch configurations. Through these regions, the system operator can identify how the active power transfer can be changed, preserving the system integrity.

The calculation of security regions is based on static and dynamic analysis, taking into account credible contingencies. The security criteria may include steady-state and transient voltage limits, thermal limits and transient stability.

In this work, the construction of security regions follows the procedure adopted in references [12] and [13]. Initially, three generation groups (Group 1, Group 2 and Group 3) are established, where one of them works as a slack group. Keeping the load fixed, a redispatch is considered in different directions as illustrated in Fig. 5. Each direction is defined by an angle (θ) that determines the generation in each group. Starting from an initial operation point and a certain direction, sequential redispatch steps are applied until violating a security criterion. For each mapped operating point along the redispatch directions, the system security is evaluated. If a criterion is violated, a step back in the redispatch is applied and a binary search is conducted until the limit is reached [13].

This method results in a three-dimensional graphic which contains the security boundaries with respect to the active power generation in each group. To simplify the visualization, three nomograms are plotted, considering the orthogonal projection into one of the generation planes. In Fig. 5, a nomogram that relates the active power generation of Group 2 and Group 3 is exemplified.

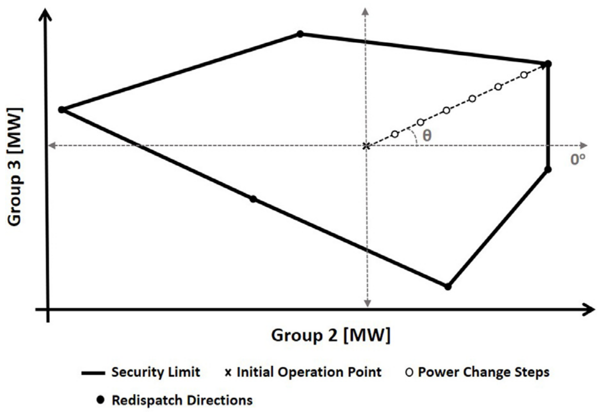

Fig. 5. Security nomogram: Group 2 x Group 3.

4. Results

In this section, the impact of active overexcitation limiters on the dynamic security assessment is analyzed. Initially, the importance of the OEL modelling is exemplified in the Brazilian Interconnected Power System, where transfer limits are explored. After that, the work evaluates dynamic security regions in the IEEE New England system in the presence of OEL modelling.

4.1. Brazilian interconnected power system

The impact of active OELs on transient stability is exemplified in a study carried out on the Brazilian Interconnected Power System. The database, provided by the Brazilian ISO, corresponds to a medium load scenario of October 2017 with 6342 buses, and includes full dynamic modelling. The study focuses on the OEL of an important synchronous condenser (SC) located at Ibiuna in the Southeast region. Ibiuna is a key substation since it is connected to the 765 kV transmission system that runs off the production from Itaipu power plant, located in South region. In this way, Ibiuna SC plays an important role in the transfer capability of the 765 kV network.

The excitation system of Ibiuna has a takeover OEL type with a CSS scheme. The OEL control is presented in Fig. 6. The OEL at Ibiuna SC has an instantaneous and a fixed time control. The instantaneous control compares the machine field current (I_{fd}) with the maximum acceptable field current (I_{fdlim1}), which value is 3.376 p.u.. Under normal operation conditions, the instantaneous limiter output (X45) is 1. On the other hand, when the limit is violated ($I_{fd} > I_{fdlim1}$), the instantaneous control is activated and the OEL signal takeovers the main control of the AVR. Therefore, the excitation is reduced instantaneously, ensuring that the field current does not exceed the associated limit.

The OEL timed control compares the machine field current (I_{fd}) with the maximum steady-state field current (I_{fdlim2}), which value is 2.329 p.u. Under normal operation conditions, the timed limiter output (X53) is 1. However, when the limit is violated ($I_{fd} > I_{fdlim2}$), the control is activated (X53 = X52) after a fixed time. If the signal control (X55) is less than or equal to zero, the OEL output signal (X56) takeovers the main control of the AVR, reducing the field current to the maximum acceptable steady-state field current.

The original operation point is modified to a get a more stressed condition that results in the OEL activation. Therefore, in the analyzed operating condition, the field current is lower than the instantaneous OEL limit (I_{fdlim1}), but higher than the timed OEL limit (I_{fdlim2}). Instead of stressing the system operation point, another alternative would be changing the OEL pickup to force its activation.

A three-phase short-circuit at the 765 kV system is studied under this stressed condition. The fault is simulated at t = 5.5 s and cleared after 100 ms by the opening of two 765 kV transmission lines.

In the first analysis, the OEL timed control is set with 1 minute, as modeled in the Brazilian ISO database. The field current behavior is

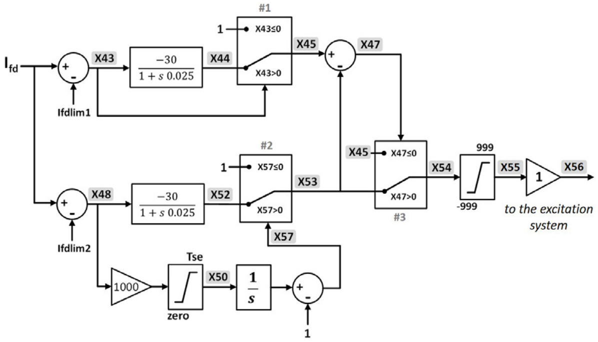

Fig. 6. Overexcitation limiter of Ibiuna SC.

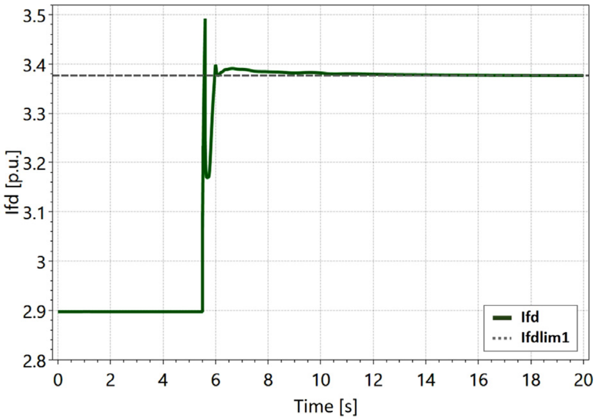

Fig. 7. Field current of Ibiuna CS: OEL timed control - 1 min.

depicted in Fig. 7. Before the fault simulation, the steady-state limit is already violated, but the OEL timed control is not active because of the 1-minute delay setting. When the short-circuit occurs, the instantaneous limit is violated, and the instantaneous control acts to reduce the field current to I_{fdlim1}.

Fig. 8 presents the rotor angle of important generators in the BIPS, including Itaipu power plant. Despite the severe contingency, the system remains transiently stable.

In order to consider that the OEL activation happened before the short-circuit occurrence, the simulation is repeated, changing the setting of the OEL timed control to 5 s. One should note that this setting change is just a computational strategy to reduce the processing time. Keeping a 1-minute delay would require the simulation to run for a long time before the short-circuit application. The results are shown in Figs. 9 and 10.

With the delay setting reduction from 1 min to 5 seconds, the filed current is limited before the fault occurrence (Fig. 9). As a result, the instantaneous control loop remains inactive, while the timed control is activated at t = 5 s. When the fault occurs with the OEL active, limiting the field current, the Itaipu power plant experiences a first swing instability (Fig. 10).

Reducing the Itaipu generation from 6000 MW to 5700 MW, the system remains transiently stable, even with the OEL timed control activation.

The results show that modeling the OEL timed control loop with a setting higher than the simulation time might lead to the false conclusion that the system is stable if the machine is in an overexcited condition with the OEL activated.

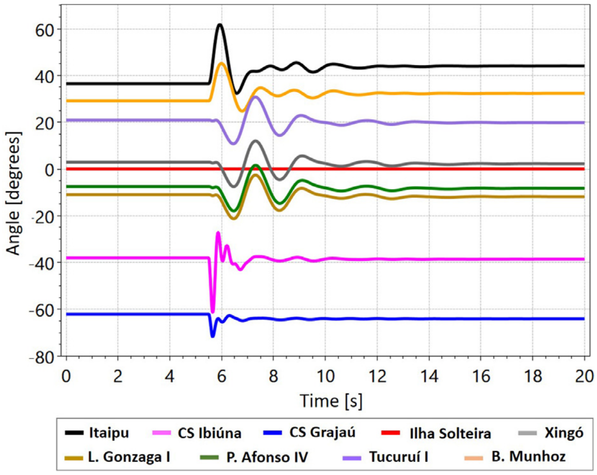

Fig. 8. Transient stability analysis: OEL timed control - 1 min.

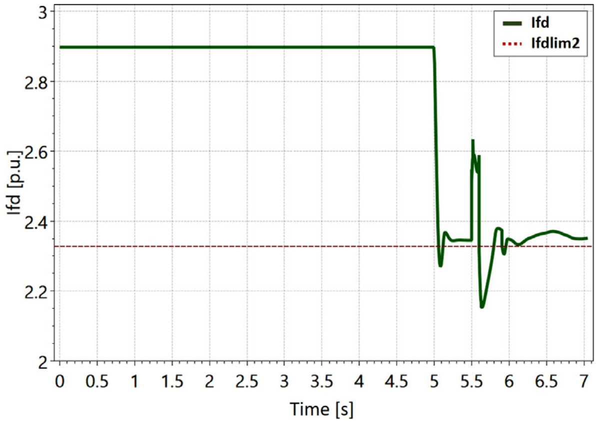

Fig. 9. Field current of Ibiúna 345 kV: OEL timed control – 5 s.

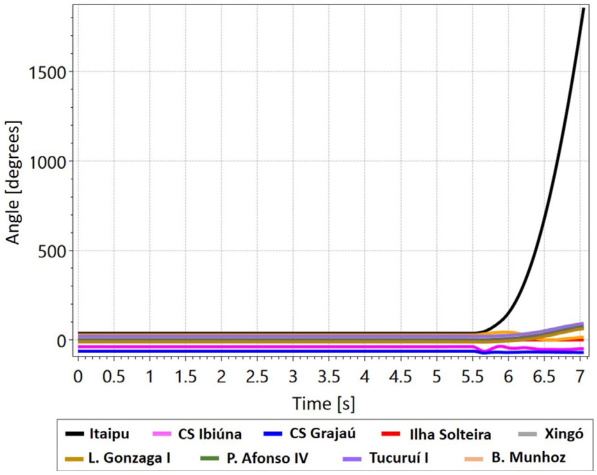

Fig. 10. Transient stability analysis: OEL timed control – 5 s.

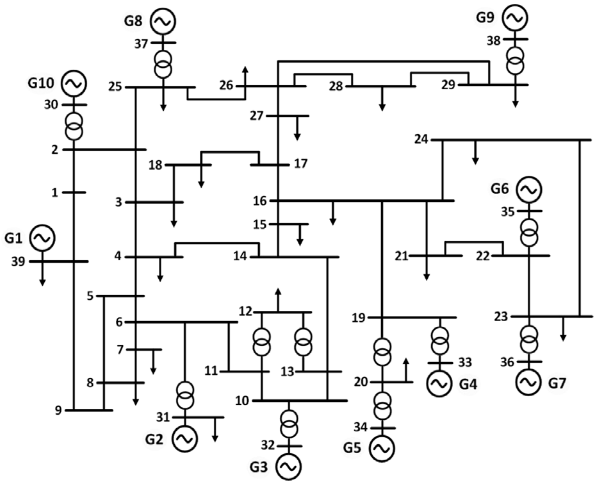

Fig.11. Single-line diagram of IEEE New England system.

4.2. Dynamic security regions

In this section, the security regions are developed for the modified IEEE 39-bus New England system [14], whose single-line diagram is depicted in Fig. 11. The main objective of this study is to show how these regions can be influenced by the overexcitation limiters representation and activation.

Initially, the generators are divided into three groups, considering

Table 1
Generation groups.

Group	*Generators*	*S [MVA]*	*P [MW]*	*Q [Mvar]*
1	G2; G3	1656.0	1490.4	721.8
2	G8; G9; G10	2208.0	1987.2	962.4
3	G4; G5; G6; G7	3312.0	2980.8	1443.6

their electrical proximity. Table 1 details the generation groups and their respective nominal, active and reactive power. Group 1 acts as the slack group, ensuring the power system balance through the nomograms construction. One should note that generator G1 is not included in Table 1 because it does not belong to any generation group. Only generators that participate in the reschedule process need to be part of a generation group. In this specific system, generator G1 is an equivalent and is kept with a fixed schedule.

The test system is stressed so that, in the initial operation point, the generators G5 and G6 (Group 3) are overexcited. From this operation point, 40 redispatch directions are considered. For each direction, the redispatch values of Groups 2 and 3 are performed using a sequential step of 1%.

Static and dynamic criteria are used in the security regions development. The static criteria include voltage limits, thermal limits, generation capacity limit and the load flow convergence (security limit). On the other hand, the dynamic criterion consists in the transient stability evaluation.

In this study, the static analysis has not shown security issues, i.e., the limitation is given only by the generation capacity of each group.

The dynamic analysis is performed considering the generators with and without the OELs representation. During the dynamic analysis, the summed type OEL and the takeover type OEL with ESS scheme are considered.

The OELs are modeled in the excitation system of generators G5, G6 and G10. In the initial operation point, G5 and G6 are overexcited, while the field current at G10 is equal to the nominal field current (2.095 p.u.), as shown in Table 2.

The dynamic analysis considers the most severe contingency, which is a three-phase short-circuit at the transmission line that connects buses #16 and #17. The fault is cleared after 200 ms by the faulty line disconnection. The OEL activation is taken into account from the beginning of the simulation, limiting the field current to 105% of its nominal value.

4.2.1. Summed type OEL

The first dynamic analysis consists on the comparison between the security regions with and without the summed type OEL representation in generators G5, G6 and G10. The obtained nomogram (Group 2 x Group 3) is presented in Fig. 12. The complementary projections (Group 1 x Group 2 and Group 1 x Group 3) have similar information and are not shown.

The OEL activation at the beginning of the simulation does not modify the dynamic security region boundaries. This behavior is expected, since the summed OEL acts indirectly, influenced by others AVR control signals. Fig. 12 illustrates the distance from the initial operation point and the security boundary for a certain direction. Beyond this point, the system become transiently unstable.

Table 2
Generation groups.

Generator	*Ifd [p.u.]*	*Ifd [p.u. of Ifdnominal]*
G5	2.26	1.08
G6	2.26	1.08
G10	2.09	1.00

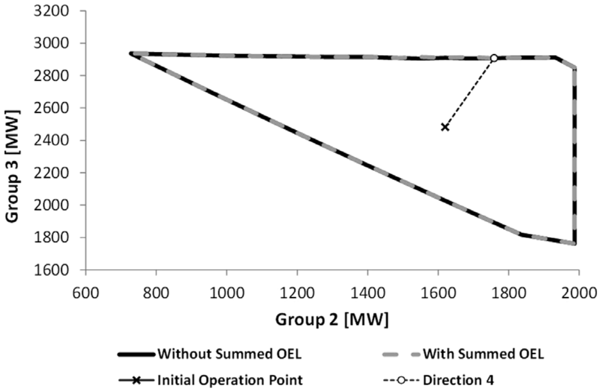

Fig. 12. Dynamic security nomogram: summed type OEL.

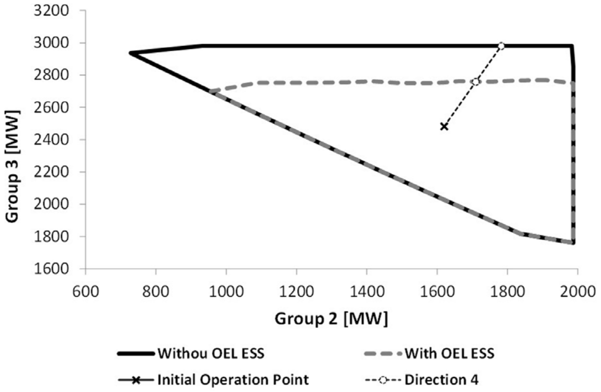

Fig. 13. Dynamic security nomogram: takeover type OEL (ESS).

4.2.2. Takeover type OEL – ESS scheme

The dynamic security region is now calculated considering the generators G5, G6 and G10 with and without the takeover OEL model representation with the ESS scheme. The result is presented in Fig. 13. As one can see, the takeover OEL activation results in a considerable reduction in the dynamic security region boundaries. This reduction occurs in the redispatch directions in which generators G5 and G6 remain overexcited, activating their OELs at the beginning of the simulation at each operation point. In order to preserve the system security, the redispatch in those directions is limited, reducing the safety area. Fig. 13 also illustrates the distance from the initial operation point and the security boundary for a certain direction (direction #4). Beyond this point, the system become transiently unstable, but this instability is not observed when the active OELs are not modeled.

Table 3 presents a comparative analysis of Group 3 generation limit with and without the OEL modelling. The comparison is shown for the

Table 3
Impact of OEL modeling in dynamic limit: Group 3.

Redispatch direction	*Dynamic limit without ESS [MW]*	*Dynamic limit with ESS [MW]*	*Reduction [MW]*
2	2980.8	2766.4	214.4
3	2980.8	2758.8	222.0
4	2980.8	2758.0	222.8
5	2980.8	2761.6	219.2
6	2980.8	2753.6	227.2
7	2980.8	2750,3	230.5
8	2980.8	2750,3	230.5
9	2980.8	2751.9	228.9
10	2980.8	2760.9	219.9
11	2980.8	2755.3	225.5
12	2980.8	2752.2	228.6
13	2936.5	2752.3	184.2

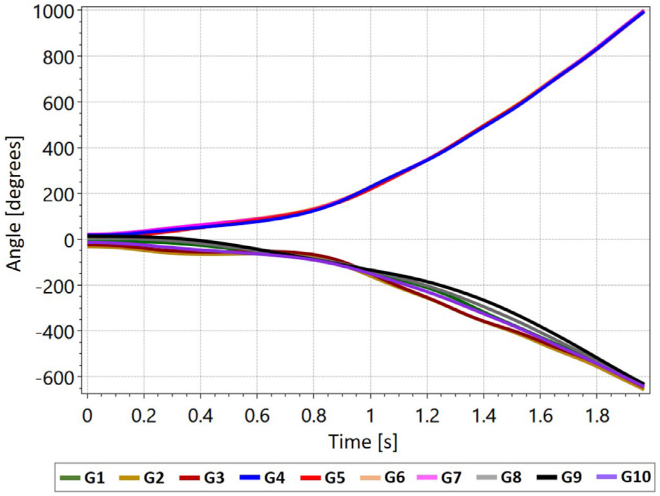

Fig. 14. Stability analysis with OEL ESS: unsafe limit.

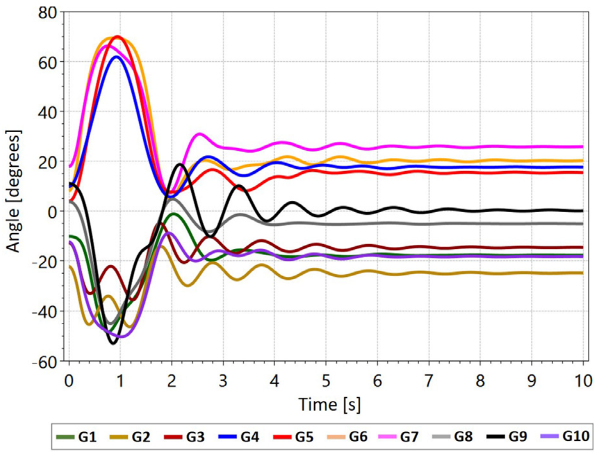

Fig. 15. Stability analysis with OEL ESS: safe limit.

redispatch directions that have resulted in transient instability (#2 to #13). The fourth column of Table 3 shows the reduction in the generation limit at Group 3 due to the OEL representation. Taking direction #4 as an example, not modelling the OEL leads to a 2980.8 MW generation limit, while the OEL representation reduces it in 222.8 MW (7.5%). In order to illustrate how the absence of the OEL model may impact the dynamic analysis, a transient stability evaluation has been performed in these two limiting conditions obtained in direction #4. However, the OEL has also been included for simulating the limiting condition calculated without the OEL representation. Figs. 14 and 15 present the rotor angles dynamic behavior with the OEL, considering, respectively, the limiting operation point obtained without (2980.8 MW) and with (2758.0 MW) the OEL representation. These graphs corroborate the results, showing that the limiting condition calculated without OEL modeling is actually not safe.

4.2.3. *Comparative analysis*

Fig. 16 compares the dynamic security regions obtained in the previous studies, considering the summed and the takeover OEL (ESS). The security region without the summed OEL does not match the one without the takeover OEL due to the AVR modeling difference. The comparative nomogram (Group 2 x Group 3) is presented in Fig. 17.

The comparative results demonstrate the impact of active overexcitation limiters on the dynamic security assessment. Depending on the OEL representation and the operating scenario, inaccurate security regions can be obtained, providing wrong security margins to the operator.

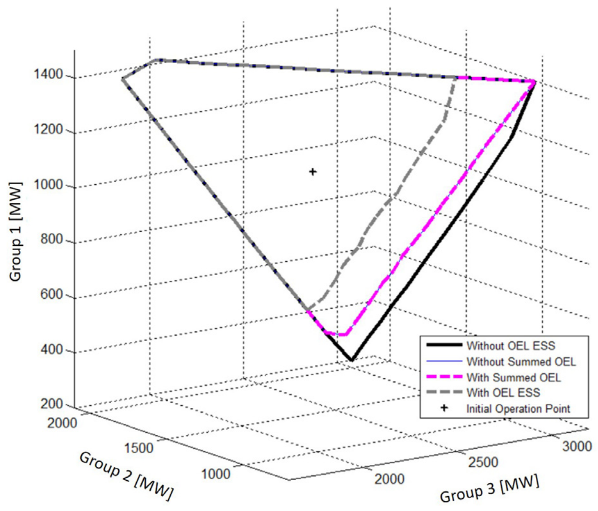

Fig. 16. Comparative dynamic security region.

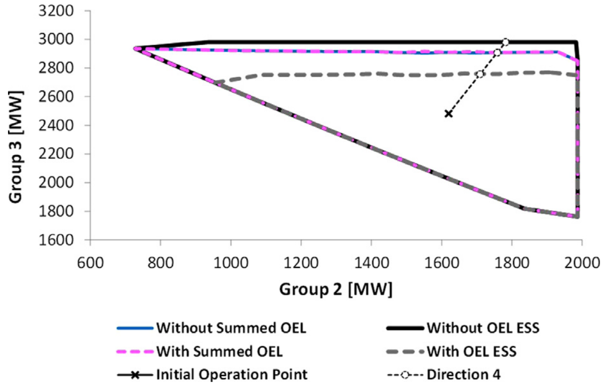

Fig. 17. Comparative dynamic security nomogram: Group 2 x Group 3.

5. Conclusions

Overexcitation Limiters (OELs) are fundamental devices to ensure the safety operation of synchronous machines. Due to their timed characteristic, these limiters are commonly represented in long term stability studies. However, operating the system with active overexcitation limiters can also influence the short-term dynamic security assessment.

This work has presented a study about the impact of active overexcitation limiters on the power system dynamic security assessment. This impact has been illustrated through analysis in the Brazilian Interconnected Power System and by the development of comparative dynamic security regions in the New England system.

The results demonstrate that the representation of active overexcitation limiters may become relevant in transient stability analysis, mainly when the overexcitation occurs in takeover OEL type. Depending on the operating scenario, inaccurate security regions can be obtained, providing wrong security margins to the operator. It is also important to notice that, modeling the OEL time delay higher than the simulation time may lead to the false conclusion that the system is stable if the field current limit is already being violated at the initial operation point.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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