Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Quantifying the risk of a blackout using PSA/Eurostag platform software

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***Abstract*-- This paper is treating the problem of quantifying the risk of a blackout in a power system when realizing off-line simulations for dedicated power system analysis. The issue consists in the computation of the *stability limit* for a power system, the concept of *steady-state stability reserve* being reviewed. Even in off-line simulation the stability reserve of a power system is not a straight forward analysis. The difficulties appear when trying to solve the stability reserve aspect for a large power system. For this kind of electrical network the common well known analysis techniques are not available mainly due to computational burdens. Present paper is proposing an original methodology to find out the stability reserve of a power system. The main theme of this paper is particularly relevant in the light of the blackouts that affected utilities all around the world recently. For preventing blackouts first step consists in analyzing and studying the reasons and the mechanism of the registered blackouts. The second step is to understand how to prevent the blackouts. Present paper is focusing of the second step in preventing blackouts by finding out a methodology to assess the stability reserve for a power system or a specific area from a power system beyond that a blackout might appear.**

***Index Terms*—steady-state stability, eigenvalue, time domain analysis, stability limits.**

I. Introduction

THIS document is focusing on the specific aspects related with the stability reserve on modern power systems. In general, stability describes the tendency of an alternating current (a.c.) power system to maintain a synchronous and balanced operating state. Most often, the term *stability* refers to angle stability, which means that all the system's components remain locked "in step" at a given frequency.

Stability analysis is concerned with these differences in phase and their implications for keeping the system locked in step. This "locking" phenomenon is based on the electrical interaction among generators.

We distinguish steady-state and transient or dynamic stability. In the steady state, we evaluate a system's stability under some fixed set of operating conditions, including constant generator outputs and loads. A crucial factor here, is the length of transmission lines in relation to the amount of power they transmit.

Modern engine tools used to analyze the behavior of a power system from all points of view, present both advantages and disadvantages. The major advantage of present software tools consists in the ability of modeling very large power systems both in terms of load flow and dynamics. On the other hand one of the greatest disadvantage consists in the need of a huge amount of information that have to be implemented as input data, another big problem being the computational burdens especially in the dynamic simulations. These computational burdens are caused by the large number of differential equations created as a result of having a detailed dynamic model of the analyzed power system which includes all the automatic controllers of the generating units.

The PSA/Eurostag software platform is not a part of above mentioned aspects. This software tool is composed of several software packages integrated through a common data model. The computation area is including: load flows, short-circuit, optimal power flow, single line diagram representation, security analysis tool. All the dynamic behavior is modeled and analyzed using the Eurostag software tool [1].

With the present release of PSA/Eurostag we face computational burdens when trying to perform steady-state stability analysis on large power system. The problem was the impossibility to linearize the power system equations around an operating point due to the large number of the differential variable. Without the steady-state matrix of the system, no eigenvalues are available and no assessment may be done about a specific operating point: stable or unstable when speaking about steady-state stability.

II. Blackout - Stability Limits Connection

A blackout represents a large failure in electricity supply that causes enormous loss in the economy and society. This kind of phenomena occurs with some regularity throughout the world power systems. If the very large scale blackouts are rare not the same thing may be said about the small scale blackouts which are often happing in the world.

The well known stability limits of a power system are the *Transient*, *Voltage* and *Steady-State* limit.

When speaking about *transient stability*, it has to be mentioned that a lot of work was done to develop specific "transient stability indices" in order to assess the "degree of stability" [2]. The different methods developed in this field present a common pattern [3]:

Paper presented at the "Cascading Events" Panel, IEEE Power Tech Conference 2009 (IEEE BPT2009), Bucharest, June 28 - July 2, 2009

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978-1-4244-2235-7/09/$25.00 ©2009 IEEE

- Start with a base case and a postulated major contingency
- Derive a “severity index” for this contingency
- Compute new power flows
- Repeat the process until an unstable case has been obtained

The *stability limit* thus identified qualifies as a limit only for the particular disturbance that was evaluated. In a real power system many disturbances are possible, for this reason a true “system-wide transient stability limit” for a given state vector would require that a huge set of possible disturbances should be examined.

Voltage stability tools, on the other hand, determine the point of voltage collapse at individual buses by making certain assumptions about the nature of the load. The process needs to be repeated to evaluate all the load buses or, at least, a minimum set of load buses known to be critical.

A practice of assessing voltage stability consists in running successively increased load levels and stopping when the load flow diverged. A disadvantage of this method is that it does not detect voltage instabilities associated with synchronous machines [4].

The *Steady-State Stability Limit* (SSSL) of a power system is “a steady-state operating condition for which the power system is steady-state stable but for which an arbitrary small change in any of the operating quantities in an unfavorable direction causes the power system to loose stability” [5].

Approaching the search for a “stability limit” from this perspective presents following advantages [3]:

- SSSL is mathematically definable and
- it represents an operating limit, which is local - depends both upon the current state vector and the assumptions made to “worsen” the case - and unsafe - operating states immediately below this limit may quickly become unstable-.
- SSSL can be quantified.

Incidentally, this limit is also connected to the state where voltage instability might occur [6], [7].

A metric can be identified on bases of SSSL known as *steady-state stability reserve*.

This metric is at the core of the *stability envelope* concept developed in [3].

It is possible to find a “safe” MW system loading, referred to as *security margin*, such that, for any system state with a steady-state stability reserve smaller than this value, no contingency, no matter how severe, would cause transient instability and blackout.

A *security margin* can be expressed as a percentage of the SSSL. Paul Dimo used to recommend, for the power system of Romania in the 1960s and 1970s, a 20% security margin, thus implying that for system loadings below 80% from the SSSL there was no risk of transient instability [8].

The security margin represents a “safe system MW loading limit” that can be interpreted as a stability envelope. The graphic representation of the *stability envelope* concept was developed in [3] and it is illustrated in Figure 1 where we find out the answer of the question: *How far from blackout ?*

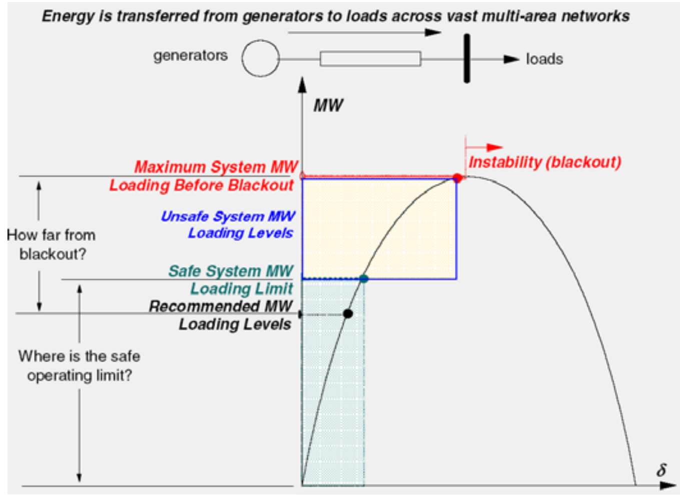

Fig. 1. The “Stability envelope”

The computation of a *stability envelope* may be performed as follows [3]:

- Starting from a state estimate or solved load-flow, determine the steady-state stability reserve, i.e., the distance to SSSL
- For a given x% value of the security margin, determine the corresponding safe system MW loading below the SSSL

This can be accomplished both by detailed analysis, which is well suited for off-line studies, and by fast approximate methods, the latter approach being appropriate for real-time and quick off-line decision making.

III. Identifying The Steady-State Stability Limit

Several different techniques are known when speaking about steady-state stability analysis. Hereunder two already known approaches and a new one are going to be presented.

A. *Paul Dimo's Simplified Steady-State Stability Approach*

Dimo’s method, is a very well known approach in steady-state stability assessment being first published in France in 1961. Main computational steps of a typical steady-state stability analysis by using this method are [9]:

- Expand the network with the transient reactances of generators and synchronous condensers
- Replace the load-buses with constant admittances, add the Zero Power Balance Network and apply the REI reduction to form a single-load REI equivalent that retains the internal buses of generators and synchronous condensers
- Extract the REI net
- Computation of the steady-state stability index dQ/dV to determine whether the current state is stable
- Increase the system load and, accordingly, the generation until instability occurs, then measure the “distance” between the original state and the unstable one.

The last step of the method is referred to as case worsening and represents a unique ability of the REI-Dimo methodology to simulate a system state without having to re-compute a series of new load-flow cases. Case worsening simply means identifying, under given operating conditions, the limits of steady-state stability corresponding to a certain deterioration process.

Further details, including the mathematical formulation of Dimo's approach, can be found in [8].

B. Steady-state matrix analysis

Steady-state matrix analysis is starting from the following relation:

$$\frac{d}{dt}\underline{x}(t) = A * \underline{x}(t) + B * \underline{u}(t) + \Gamma * \underline{p}(t) \qquad (1)$$

where A, B, Γ represent the state, control and perturbation matrix and the vectors $\underline{x}(t), \underline{u}(t), \underline{p}(t)$ are the state, control and perturbation vectors.

The state matrix A from equation (1) depends on system parameters and on operation conditions when in the mean time the perturbation matrix Γ and control matrix B depend only on system parameters.

Therefore for certain operation conditions and system parameters, the eigenvalues of the system are obtained by solving the system characteristic equation.

System stability depends on the eigenvalues of the steady-state matrix as follows:

- A real eigenvalue corresponds to a no-oscillations mode. A negative real eigenvalue do represent a stable system and in the mean time a positive real eigenvalue represents an unstable system.
- A pair of complex eigenvalues corresponds to an oscillation mode. The real part of the eigenvalue gives the damping and the imaginary part gives the oscillation frequency. A negative real part of the eigenvalue represents a damped oscillation and a positive real part of the eigenvalue represents an un-damped oscillation.

C. Time domain analysis

This paper is proposing a new approach in analyzing the steady-state stability of a critical area in a power system. Mainly the new proposed approach consists in a time domain simulation.

The authors have developed an algorithm which can be implemented in the PSA/Eurostag software to find out the static stability limit for a specific critical area in a power system:

- Obtaining an operating point of the analyzed power system
- Applying a "worsening" procedure by accentuating the power excess/deficit of the analyzed area
- The last accepted and the first refused steady-state points are saved for the steady-state analysis
- The behavior of the analyzed power system (for both operating points) facing a small load variation is visualized using the PSA/Eurostag tool.

The results of the simulations are presented for both cases stable and unstable.

A block scheme was also developed and it is illustrated in Figure 2.

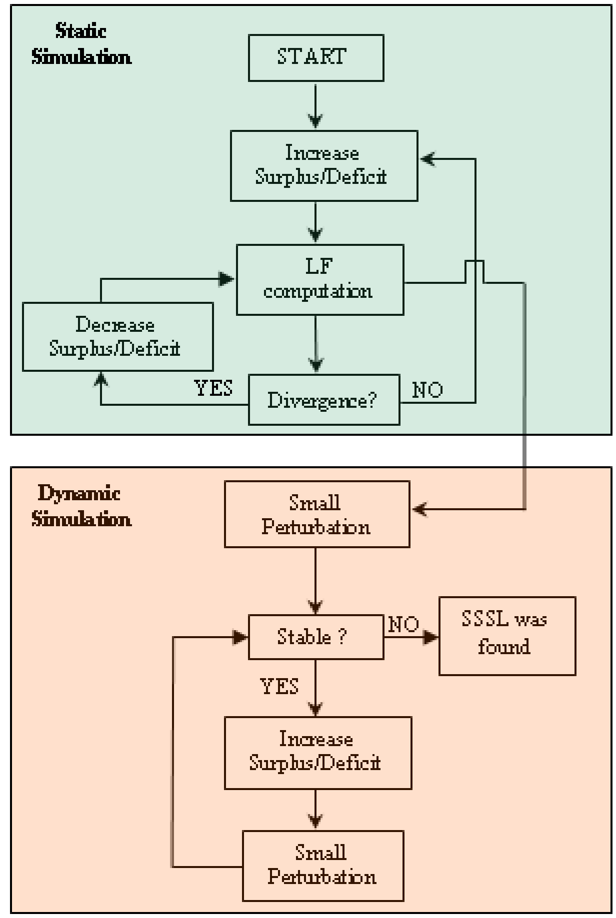

Fig. 2. Steady-state stability – time domain analysis

IV. Case Studies

Case study analysis is divided in two parts: testing the validity of the time domain analysis for steady-state stability on a test network, and an example of the utility of the developed methodology on a real power system.

A. Test network

The *Test Network* analyzed here is a simple two area system similar with the one used in reference [10]. This test network is widely used when trying to highlight the steady-state stability inter-area oscillation modes.

The dynamic model consists in 4 identical machines of 900 MVA each. The AVR system and the speed governor were modeled as simple as possible: constant E_{fd}, constant mechanical power P_m.

According to the methodology described in section III, C the power flow from Zone A to Zone B was increased in the static simulation part up to 506 MW before the divergence.

In Figure 3 the *limit load flow* on the analyzed network are presented. The active and reactive power flow on branches is represented in MW and MVAr respectively, the buses being described by their names and voltage levels in kV.

No steady-state instability was detected on the limit load flow. For this reason the active power excess from Zone A had to be increased in the dynamic simulation part.

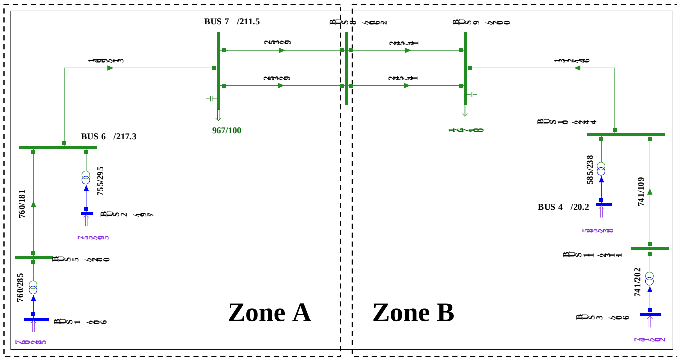

Fig. 3. Last accepted load flow on *Test Network*

The last stable and the first unstable case were kept for steady-state stability analysis. The eigenvalues computation results are indicated in Table 1.

TABLE I
STEADY-STATE MATRIX EIGENVALUES – CASE STUDY 1

Eigenvalues				
No.	Stable case		Unstable case	
	real	Imaginary	real	imaginary
1	-3.84E+01	-	-3.84E+01	-
2	-3.73E+01	-	-3.73E+01	-
3	-3.53E+01	-	-3.54E+01	-
4	-3.36E+01	-	-3.35E+01	-
5	-3.27E+01	-	-3.27E+01	-
6	-3.17E+01	-	-3.18E+01	-
7	-2.45E+01	-	-2.46E+01	-
8	-2.35E+01	-	-2.34E+01	-
9	-5.82E-01	5.82E+00	-6.02E-01	5.82E+00
10	-5.82E-01	-5.82E+00	-6.02E-01	-5.82E+00
11	-5.36E-01	5.37E+00	-5.17E-01	5.25E+00
12	-5.36E-01	-5.37E+00	-5.17E-01	-5.25E+00
13	-6.15E+00	-	-6.13E+00	-
14	-6.08E+00	-	-6.11E+00	-
15	-4.78E+00	-	-4.79E+00	-
16	-4.26E+00	-	-4.24E+00	-
17	-7.33E-02	1.33E+00	4.23E-02	1.00E+00
18	-7.33E-02	-1.33E+00	4.23E-02	-1.00E+00
19	-2.41E-01	2.45E-01	-3.52E-01	3.20E-01
20	-2.41E-01	-2.45E-01	-3.52E-01	-3.20E-01
21	-3.51E-01	-	-3.67E-01	-
22	-2.73E-01	-	-2.74E-01	-
23	-7.48E-02	-	-7.17E-02	-
24	-1.29E-10	-	-1.42E-12	-

The power flow from Zone A to Zone B was increased up to 800 MW, in the dynamic simulation part, before reaching the steady-state stability limit, Figure 4. The key aspect of the simulations performed on the Test Network is that the steady-state instability seen by visualizing the power flows on the tie lines between Zone A and Zone B is confirmed by the eigenvalues of the steady-state matrix.

These simulations confirm that the assessment of the steady-state stability limit for a specific area in a power system may be approximated by avoiding algebraic and differential system linearization and eigenvalues computation.

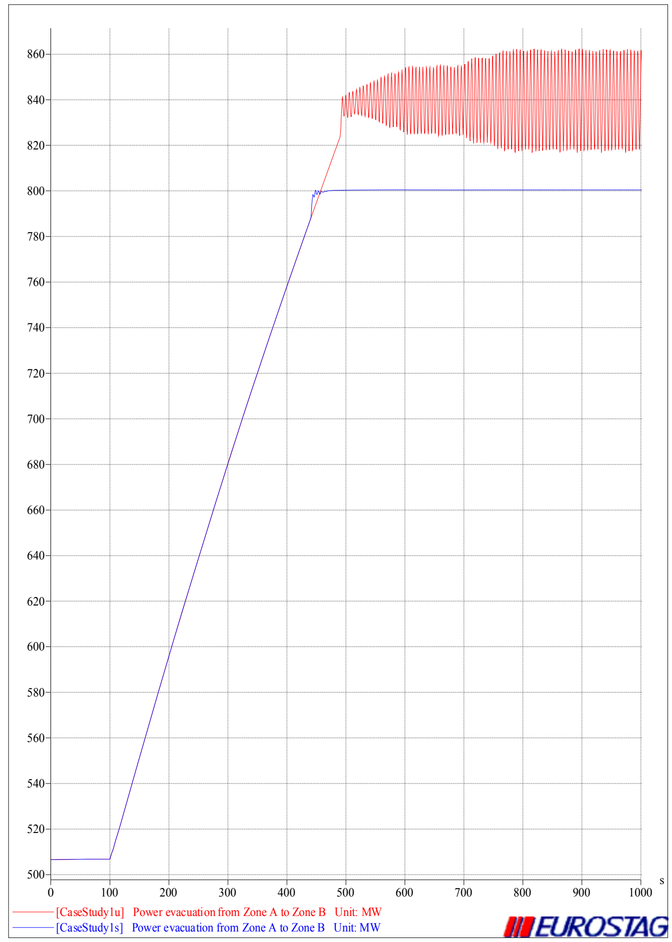

Fig. 4. Steady-state stability limit - Case Study 1

B. Romanian Power System

The Romanian transmission system is in the center of the Southeastern European interconnection and sustains MW transfers between parties situated beyond its geographical borders. A further complication comes from the fact that the network consists of electrical areas interconnected through stability constrained transmission paths. The system operation is quite complex and the dispatchers must meet conflicting requirements in order to maximize the use of the transmission system while avoiding the risk of blackout [11].

The populated areas and the industrial zones of Romania are aggregated in concentric areas divided by the Carpathian mountain chain. The center area is surrounded by mountains and encompasses a dense 110 kV network sustained by 220 kV – 400 kV network. Around it there is an outer ring of major power plants that inject power into a strong 220-400 kV transmission system. The power flows between the outer ring and center area being transferred primarily from south-southwest towards the center, from south-southeast towards the northeastern part of the outer ring, and from the northern part of the central area towards the northeastern part of the outer ring. Due to this particular pattern of the MW transfers across the network several stability constrained links exist in the network. One of these stability constrained links is treated in this paper: the *southeastern area* of the Romanian grid.

The performed analysis considered 5 OHL of 400 kV and 1 OHL of 220 kV as tie lines between the *southeastern area* and the rest of the Romanian electrical grid.

The case study was implemented on the whole Romanian power system which consisted in: 1097 nodes, 1321 lines, 232 transformers, 679 loads, 15 capacitor banks, and 227 generating units.

Due to system complexity the number of the differential equations (about 1200) didn't allowed us to perform a steady-state analysis based on the steady-state matrix. For this reason the proposed *time domain simulation* was tested.

Analyzed area is an area with a power excess for this reason we have identified the maximum amount of power that can be generated inside this area before instability to occur.

Applying the methodology described in section III, C, we were able to compute the stability reserve beyond that a zonal or total blackout might occur.

The total amount of power excess from analyzed area could be increased up to a surplus of about 4350 MW, value for which instability occurred (Fig. 6).

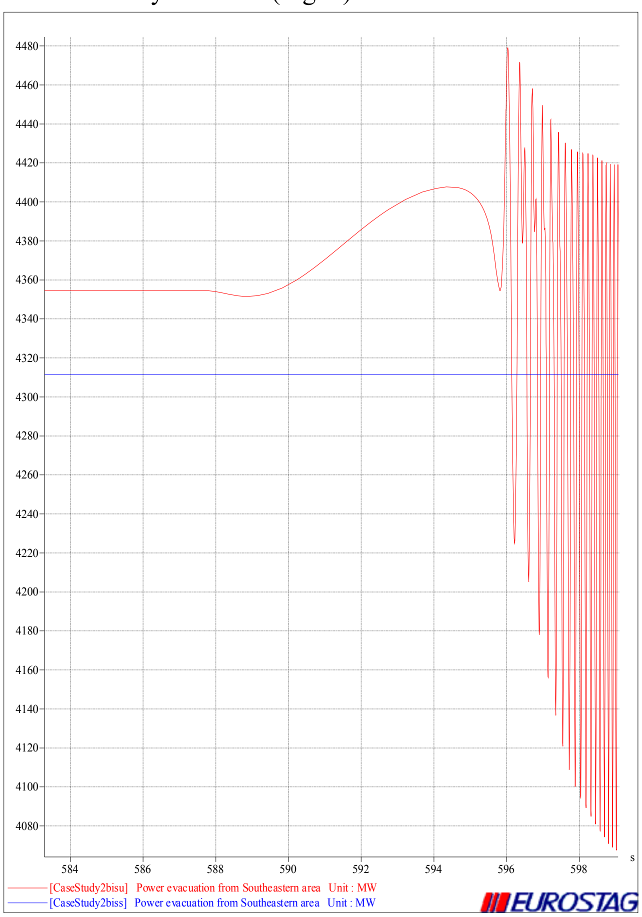

Fig. 6. Steady-state stability limit – Case Study 2a

By successive load flows computations we have reached the instability limit that could be seen in the dynamic simulation.

It can be seen that introducing the *limit load flow* into dynamic simulation lead to sustained oscillations on the interface links between *southeastern area* and the rest of the Romanian grid.

The instability is initiated by the over-excitation limiters of the generating units included in the dynamic model of the analyzed power system.

The results obtained in Fig. 6 are corresponding to a constant impedance dynamic load model. Due to the fact that the instability is initiated by the variation of the reactive power control of the generating units, the limit of the power evacuation from a specific stability constrained area may vary a lot when having a voltage/frequency dependent load model.

For this reason a supplementary test was performed considering the following coefficients for the dynamic load model:

$$K_{P=f(V)} = 1 \quad (2)$$

$$K_{P=f(\omega)} = 0.85 \quad (3)$$

$$K_{Q=f(V)} = 2 \quad (4)$$

$$K_{Q=f(\omega)} = -0.6 \quad (5)$$

As we expected the power excess from analyzed area resulted as limited at 4177 MW value for which instability occurred (Fig. 7).

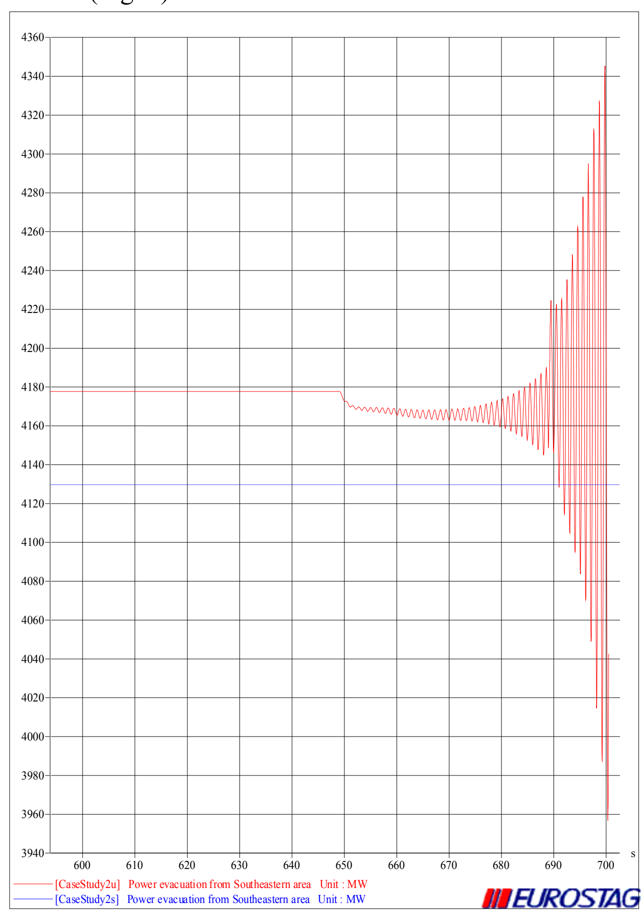

Fig. 7. Steady-state stability limit – Case Study 2b

As can be seen from presented curves, the dynamic load model of the analyzed power system is very important when trying to find out the stability reserve.

Another important aspect consists in the dynamic model of the generating units included in the analyzed operating point, the Automatic Voltage Regulator (AVR) systems being determinant in the assessment of the stability reserve.

For the analyzed constrained area we concluded as having a 4177 MW limit power excess.

V. Conclusions

Present paper is illustrating a new approach for stability reserve assessment in the modern large power systems that may be successfully applied PSA/Eurostag software tool.

The proposed methodology consist in an alternative solution for the classical methods used to assess the steady-state stability limits: Paul Dimo's simplified steady-state approach, or steady-state matrix eigenvalues computation.

The simulations performed on the Test Network confirmed that the assessment of the steady-state stability limit for a specific area in a power system may be approximated by looking on the dynamic behavior of the power system on the limit load flow, avoiding algebraic and differential equations system linearization and eigenvalues computation.

A case study on the Romanian electrical grid was also performed by identifying the maximum power transfer from the southeastern area to the rest of the analyzed power system, loading limit beyond that the instability occurs.

Testing proposed methodology both on a test network and on a real network revealed a direct link between steady-state instability and voltage instability. Nevertheless different stability reserve might be obtained when using proposed methodology against classical steady-state eigenvalues computation approach. In the present we are studying the second approach in the PSA/Eurostag software. At the present we are trying to obtain a validation of the sustained oscillations with positive steady-state matrix eigenvalues (steady-state instability) on the Romanian grid as it was exemplified in present paper for the test network analyzed.

In any case, even the limit power excess of a specific constrained area is a voltage instability defined limit or a steady-state instability defined limit, the obtained reserve is the *stability reserve* of analyzed area. Once we have the stability reserve it means that we have the answer of the following question: *How far from blackout ?*

When using the voltage/frequency dynamic load model a more restrictive stability reserve was obtained in the case of a voltage/frequency dependent load model. For this reason we are in the phase of developing a detailed dynamic load model for the whole Romanian Grid with different characteristics for the different geographical regions which will allow us to obtain more accurate stability reserves.

The proposed methodology might be successfully applied on any large electrical network. The most interesting aspect of all is that proposed approach is giving the stability reserve of a power system by analyzing a very detailed model of the electrical network.

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VII. Biographies

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