Skoltech
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Thesis Changes Log

Name of Candidate: Mazhar Ali

PhD Program: Engineering Systems

Title of Thesis: Voltage Feasibility Boundaries

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Chair of PhD defense Jury: Prof. Keith Stevenson ***Email***: *K.Stevenson@skoltech.ru*

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The thesis document includes the following changes in answer to the external review process.

Comments

1. *In 2.3 Q is a positive injection. It would be more reasonable to assume inequality Q<QMax instead of the opposite. This will result in a bounded feasibility space.*

We agree with the reviewer, that it is more reasonable to assume the following inequality Q<QMax instead of the opposite.

2. *In 3.1 equation (3.3b) g=0 can correspond to a limit enforcement, e.g. V=Vmin.*

It corresponds to a disappearance of the power flow solution due to the singularity of Jacobian or violation of any technological constraints.

3. *In 3.3 equation (3.30) requires a complementarity condition: t must be positive for lower Q limit, and negative for upper Q limit.*

Thank you for the comment. The numerical results also indicated that *t* must be positive for a lower limit on Q, *and negative for upper Q limit.*

4. *t is better to extend the notion of the slack bus to the so-called "distributed slack" where all generators participate in slack power-sharing.*

In the updated version of the thesis, the notion of the slack bus is extended to "distributed slack" representing a group of generators corresponding to slack power-sharing.

5. *It is well known that for a simple zero eigenvalue (and singular value), the eigenvectors and singular vectors are equal (ref [29], p. 248). Thus a better explanation of section 6.1.1. is required.*

Although, for the zero eigenvalue and singular value, the corresponding eigenvectors and singular vectors are equal. But, enforcing the transversality condition (i.e., g(x) = 0) through (6.4) has following benefits over (6.2), i) small computational burden as the dimension of system variables is increased only by 1, ii) does not require any guess for initialization in comparison to g_{eig}, iii) and the singular values are less sensitive to numerical perturbations. iv) And better scalability as this condition requires computing SVD only for the lowest singular value, which can be computed with an exceptionally fast speed for sparse structured matrices just like Jacobian matrix J.

6. Reference [24] is the same as [11], with the editors' names listed as authors, obviously by mistake.

Thank you for pointing out such a mistake. In the updated version of the thesis, following the reference list is corrected.

The following list of references is also added in the updated version of the thesis.

1. M. E Karystianos, N. G. Maratos, C. D. Vournas, "Maximizing Power-System Loadability in the Presence of Multiple Binding Complementarity Constraints", IEEE Trans. on Circuits and Systems I, Vol. 54, pp. 1775 – 1787, Aug. 2007.

2. N. G. Sakellaridis, M. E. Karystianos, C. D. Vournas, "Local and global bifurcations in a small power system", International Journal of Electrical Power and Energy Systems, Vol. 33, No. 7, Sept. 2011, pp. 1336-1347.

3. C. D. Vournas, M. Karystianos, N. G. Maratos, "Bifurcation Points and Loadability Limits as Solutions of Constrained Optimization Problems", IEEE/PES Summer Meeting, Seattle, July 2000.

4. S. C. Savulescu (ed.), "Real-Time Stability in Power Systems", Springer, 2014.
5. Ch. 10: "On-Line Voltage Security Assessment", by C. Vournas and T. Van Cutsem.

Minor Comments:

As the TENR algorithm may not be scalable for a large-scale system, the author to comment on the possibility of making the approach tractable. Would estimation be deployed here to this end?

TENR algorithm might not be scalable to a different type of transversality choices, namely, i) determinant and ii) eigenvector transversality conditions. But, the proposed transversality choices based on SVD and QR shows better convergence and scalability for a large-scale system.

The concept of Transfer Capability in Section 5.3 can be generalized to Available Transfer Capability (ATC). An ATC then relates to the critical gain λ[illegible].

We agree with the reviewer that generalization of the Transfer Capability can be made for Available Transfer Capability (ATC) as well.

Figure 5-9 illustrates the convergence of the TENR algorithm applied to the IEEE 14-bus system. It is not clear to justify how more constraints cause more iteration steps.

We apologize for this misunderstanding. For global convergence, the Newton step size was selected small enough. It is not the case that adding more constraints will result in more iteration steps.

Even though the overall complexity of TENR depends on the network structure, the reviewer would like to recommend to provide more insights and give some estimation of the cost of computation as well as the involved complexity.

From numerical studies, It was observed that the overall complexity of the TENR depends on the network topology mainly, when it comes to scalability. It was observed that the proposed scalar transversality choices work well in comparison to alternatives from literature.

The reviewer can spot several typos and grammar errors throughout the thesis as below. It is highly recommended to proofread the thesis.

–Page 2: delete "abstract-text", change "this thesis address" to "this thesis addresses".
–Page 17: change "DER's" to "DERs".
–Page 18: change "the power system security analysis not" to "the power system security analysis is not";
"Figure.1-3", "Fig.1-3" need space.
–Page 29: change "as follows," to "as follows."
–Page 33: delete "from" in Section 2.2.1
–Page 54, equation (3.17) should beS=V(YbusV)?.
–Page 63: change "parametrized the solution" to "parametrize the solution".
–Page 69: too much space before the last paragraph.
–Page 70: change "P and Q denotes" to "PandQdenote"

Thank you for pointing out all these mistakes. The revised version of the thesis has been proofread to eliminate grammatical errors and typos.

Major comments

Unlike boundary construction methods based on CPF, this work leverages the singular conditions and combine those with power flow relations and feasibility conditions to constitute a compact and convenient approach to find the boundary. This approach opens up a new research direction which helps to study the boundary directly.

Also, the author proposes a method to trace the boundary of the cross-section of the security set relying on sphere continuation. This technique helps trace part of the boundary continuously and adaptively

We appreciate this comment and thank the reviewer for allowing us the opportunity to address the comments and concerns.

The proposed TENR approach features the extended Jacobian that is not degenerate towards the boundary if the incremental loading direction is not tangential to the boundary of solvability. Then it is interesting to investigate and compare the extended Jacobian shown in (4.9) and its version presented in (5.4) to that of the well-known CPF approach.

In comparison to the standard extended Jacobian presented in (4.9), the formulation from (5.4) allows us to converge to a solution in the vicinity with positive λ. Applying the (5.4) formulation to the well known CPF approach will allow us to trace the curve with $\lambda > 0$.

The extended Jacobian in (5.4) seems to be better than that in (4.9) as the last diagonal entry is nonzero. The author may comment on this observation.

It means even if the extended Jacobian (4.9) is degenerate, the formulation of the extended Jacobian from (5.4) may not be degenerate.

The stability index presented in (4.47) might be useful to indicate how close to the boundary the solution is. Should the power factor or reversal power flow play a role here?

This will allow finding effective ways to keep the distribution network stable

The author states that the TENR algorithm may not perform well if the boundary is non-convex. How could one further improve the algorithm for non-convex security sets? Another interesting question is whether the TENR algorithm can help quantify the nonconvexity of the concerned boundary.

The proposed TENR may not work well if the boundary is non-convex. One way to overcome this is to as follows,

i) First for each discretize direction a bound on the number of the real solutions should be defined.
ii) Secondly, to find each solution will require a good initial guess.

Thus, one can use a polynomial homotopy approach along with the TENR framework to quantify a non-convex boundary at the expense of computational speed.

As for feasibility conditions, the author proposes to use slack variables to convert inequalities to equalities. Such slack variables will introduce new and larger Jacobian matrices. How can one assess the effect of slack variables on the Jacobian?

Thank you for this comment. Through our numerical experimentation, It was observed that adding inequality constraints through slack variables did not have any significant effect on the extended Jacobian as the sparsity structure was intact, and the computation complexity was not compromised either. But overall convergence of the TENR depends upon the good initial guess, thus for global convergence, a reasonable estimate for the corresponding slack variables was necessary.

The proposed spherical continuation approach uses hyperspheres or spheres as correctors. The adaptive sphere strategy adjusts the variables, for example, based on the radius of curvature. In connection to this, it is worth referring to recent work by Wolter [1]. The reviewer would like to suggest to deploy spherical continuation to trace other curves such as PV curves.

It is most certainly a good idea to extend the notion of spherical continuation for tracing other curves such as PV curves. It is part of the plan for this work.

In Figure 5-4 for IEEE 30-bus, the stability index corresponding to QR, SVD, and Eig approaches fluctuates over Newton iterations. It is then recommended to select another index which decreases monotonically over iteration steps. This new index may help improve and keep track of the convergence of the iteration procedure.

It was observed that choosing an appropriate value of Newton step size results in a more monotonical behavior of the stability index over the course of Newton iterations.

On top of this major and minor changes, the thesis has been proofread and a number of grammatical mistakes corrected, but not marked explicitly