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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Ali Mazhar

PhD Program: Engineering Systems

Title of Thesis: Voltage Feasibility Boundaries

Supervisor: Prof. Janusz Bialek

Date of Thesis Defense: 09 December 2019

Name of the Reviewer: Assistant professor Hung Dinh Nguyen

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Signature:** **Date: 28-11-2019**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense. *If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.*
Reviewer's Report
Reviewers report should contain the following items: • Brief evaluation of the thesis quality and overall structure of the dissertation. • The relevance of the topic of dissertation work to its actual content • The relevance of the methods used in the dissertation • The scientific significance of the results obtained and their compliance with the international level and current state of the art • The relevance of the obtained results to applications (if applicable) • The quality of publications The summary of issues to be addressed before/during the thesis defense

1. Evaluation of the thesis quality and overall structure of the dissertation

In this thesis, the author addresses the computational issues in characterizing the security boundary. This thesis represents a substantial amount of work with well-presented results. The candidate expertise in the field of power system security can be well-recognized in the community. The research is original and meets Ph.D. criteria. Overall, this thesis is ready to be defended.

The thesis consists of 8 chapters. Chapter 1 introduces the background and the problem of power system stability along with contributions. In Chapter 2, the author presents the power flow solution spaces wherein the power flow problem is solvable. Chapter 3 focuses on the mathematical formulation of the security boundary problem. Chapter 4 introduces the feasible space with various transversality conditions and the associated form with the Newton-Raphson approach. Chapter 5 presents numerical simulations for the developed results in Chapter 4. Chapter 6 focuses on the computational method and homotopy continuation with spherical continuation. Chapter 7 presents more simulation results with various IEEE test cases as well as Russian systems. Chapter 8 concludes the thesis.

2. The relevance of the topic of dissertation work to its actual content

The introduction of intermittent renewable resources and the inherent non-linearity of power systems make the problem of characterizing security limits difficult. The computational issue then becomes the bottleneck. This thesis focuses on the computational aspect of constructing the solvability and feasibility boundaries of the power system. In this work, Mazhar Ali proposed several algorithms for characterizing the security boundaries that are robust and less computationally intensive and allow fast convergence.

3. The relevance of the methods used in the dissertation

Unlike boundary construction methods based on CPF, this work leverages the singular conditions and combines 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.

4. The scientific significance of the results obtained and their compliance with the international level and current state of the art

The work concentrates on the nonlinearity of power systems which manifests itself through AC power flow equations. The work proposes a set of new approaches for characterizing the solvability and feasibility boundaries which indicate to what extent the solution exists and is compliant with operational requirements.

The novel contributions of the work includes i) the development of a mathematical formulation of technological inequality constraints with slack variables and preserving the sparsity structure of the power flow model; ii) the development of a novel algorithm for calculating points on the boundary of power flow solution space as well as feasibility space using computationally efficient algorithms based on ``Transversality Enforced Newton-Raphson'', and iii) calculating the power flow feasible space in multi-dimensional parametric space using continuation based on a Euler-Homotopy approach using a predictor-corrector path tracking procedure.

5. The relevance of the obtained results to applications

Using TENR approaches, critical points on the solvability boundary can be computed efficiently without conventional continuation power techniques. Also, power flow feasible space was explored in multi-dimensional spaces. Such boundaries help system operators identify the safe margins under a wide range of operations. This information is particularly crucial and timely as the system is gradually reaching its limitations due to the load growth, not to mention that it works under a high-level penetration of intermittent renewable resources.

6. The quality of publications

The author has published one IET paper and a number of high-quality conference papers at major venues in the field.

7. Major Comments

a. 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.
b. 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.
c. 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?
d. 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.
e. 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?
f. The proposed spherical continuation approach uses hyperspheres or spheres as correctors. The adaptive sphere strategy adjusts the variable r, 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 deploying spherical continuation to trace other curves such as PV curves.
g. 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.

8. Minor Comments

a. 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?
b. 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^*.
c. 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.

d. Even though the overall complexity of TENR depends on the network structure, the reviewer would like to recommend providing more insights and give some estimation of the cost of computation as well as the involved complexity.
e. The reviewer can spot several typos and grammar errors throughout the thesis as below. It is highly recommended to proofread the thesis.

Provisional Recommendation

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*

☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*