Skoltech
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Thesis Changes Log

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PhD Program: Engineering systems

Title of Thesis: Optimization of Frequency Control in Power Systems

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

Answers to Assistant Professor Elena Gryazina:

0. Typos mentioned before the items are fixed.
1. Nonlinear DC power flows stands for nonlinear Direct Current power flows (equation 9.32).
2. There was a typo. t^m must be used instead of t^g that were mentioned in the equation (12.20).
3. Typo. Should be kappa instead.
4. Typo is fixed. Figure of the system is present in every example for the convenience purpose.

Answers to Assistant Professor Federico Martin Ibanez:

1. Reference to Karush-Kuhn-Tucker (KKT) conditions is added.
2. Primal-dual approach is a method for control derivation and not a control. Thus it is not possible to provide a diagram for a general primal dual approach. However it is described in [42-44] and referenced to on the page 23 item 1 of the 3 item, list.
3. The three main groups do not include all the considered papers. Some of them have unique approaches. The presented order is used to give the more general description first.
4. Names of each problem are long and consequent problems contain names of the previous ones. E.g. "Distributed frequency control and congestion management" and "Distributed frequency control, congestion management and inter-area flows control". Moreover, the names repeat information given in the last 4 columns of the problem. Therefore table contains numbers and description is moved to the corresponding paragraph.
5. Symbol $^\circ$ is used only for the disturbance approximation defined in the section 11, formula (11.8). Other symbols are used only for the purposes of mathematical derivation. Their only purpose is to avoid usage of the same symbols for different variables.
5. Trip of a line (4-5) is added to the numerical experiments. This allows to see control working with N-2 contingency that includes disturbance and change of the system topology.
6. Labels and captions are improved.
7. Signed is fixed. It was a typo that did not affect the proof.
8. Correction is made. Lyapunov function (12.8) and other Lyapunov functions have summand corresponding to power balance constraint with "-" sign.

9. In the section 3.2 we separate disturbance approximation from the control equations. Then in the section 11 we show that it is only possible to approximate integral of the disturbance and not the disturbance itself. The mathematical derivation is given in details in equations (11.4-11.11)

Answers to Assistant Professor David Pozo:

a. Incorrect number is removed.
b,c. Typos are fixed.
d. "workability" is replaced with "working capacity".
e. Typo is fixed.
f. Equation (7.10f) contains multiplication by α_i^k. Therefore addition of α_i^k to (7.10h) is possible but unnecessary.
g. x is replaced with N-x
h. Typo is fixed.

Answers to Assistant Professor Simon Tindemans:

1. a. Typos are fixed.
   b. Signs in formulas are fixed. Proof of the the theorem 12.3 is updated.
   c. Definitions of function ν^n and ψ^n are added before the first use.
   d. Control gains k^I and k^{II} dimensions are added.
   e. Description of the example 7.1 is expanded.
   f. Equations (10.2). Inequality constraints are included in X. X is defined above(10.2): "In addition we introduce three sets of linear inequality and equality constraints: control limits, line limits and inter-area limits. For simplicity, within this chapter we define a convex set determined by this constraints by *X*."
   g. Formula (12.63) . Introduction of r^{new} is needed only for the explanation. This parameter is not used further. If we somehow know that for some $\Psi = [t_1, t_2]$ and for some i $u_i(t) = \overline{u_i}$ then, during this period, we can consider control $u_i(t)$ to be a disturbance and bus i as a bus with no control.

2. Equation (9.23) is removed as it is unnecessary for the proof.
3. The numerical example contained an error in the coding of power flow direction on the line (1-3). The example is completely redone. In addition to the previous set of events line trip is added.
4. Figures quality is improved.
5. Variable corresponding to consumption on p64 is changed from r_i to z_i. Definition on p75 is updated. The word "disturbance" is used due to the following 2 reasons: 1) The size of r is not predefined and control is applicable even when it is small. Therefore term "disturbance" is used a more general notation. 2) The major part of the thesis is mathematical derivations in the area of algebraic integral equations stability. Word "disturbance" remains applicable even if without power systems background because r is the inhomogeneity vector.

Answers to Professor Yong Tae Yoon:

1. Paragraph 3 in section 7 is added in order to address variety of ancillary services for frequency regulation. The control operates in the timescale of primary and secondary frequency control and also performs congestion management, which is normally a part of tertiary control.
2. Typos and mathematical formulas are corrected.
3. As the numerical experiments show, the presented method is beneficial in terms of congestion management and frequency dynamics even when applied to generators only. Additionally all power systems have load shedding procedures. Therefore controllability of the loads is present in power systems to some extent. Therefore, load-side control does not introduce completely new mechanics, but only modifies the existing one.