KTH Electrical Engineering

Optimal Railroad Power Supply System Operation and Design

Detailed system studies, and aggregated investment models

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Abstract

Railway power supply systems (RPSSs) differ mainly from public power systems from that the loads are moving. These moving loads are motoring trains. Trains can also be regenerating when braking and are then power sources. These loads consume comparatively much power, causing substantial voltage drops, not rarely so big that the loads are reduced. By practical reasons most RPSSs are single-phase AC or DC. Three-phase public grid power is either converted into single-phase for feeding the railway or the RPSS is compartmentalized into separate sections fed individually from alternating phase-pairs of the public grid. The latter is done in order not to overload any public grid phase unnecessarily much.

This thesis summarizes various ways of optimally operating or designing the railway power supply system. The thesis focuses on converter-fed railways for the reasons that they are more controllable, and also has a higher potential for the future. This is also motivated in a literature-reviewing based paper arguing for the converter usage potential. Moreover, converters of some kind have to be used when the RPSS uses DC or different AC frequency than the public grid.

The optimal operation part of this thesis is mainly about the optimal power flow controls and unit commitments of railway converter stations in HVDC-fed RPSSs. The models are easily generalized to different feeding, and they cope with regenerative braking. This part considers MINLP (mixed integer nonlinear programming) problems, and the main part of the problem is non-convex nonlinear. The concept is presented in one paper. The subject of how to model the problem formulations have been treated fully in one paper.

The thesis also includes a conference article and a manuscript for an idea including the entire electric train driving strategy in an optimization problem considering power system and mechanical couplings over time. The latter concept is a generalized TPSS (Train Power Systems Simulator), aiming for more detailed studies, whereas TPSS is mainly for dimensioning studies. The above optimal power flow models may be implemented in the entire electric train driving strategy model.

The optimal design part of this thesis includes two aggregation models for describing reduction in train traffic performance. The first one presented in a journal, and the second one, adapted more useful with different simulation results was presented at a conference. It also includes an early model for optimal railway power converter placements.

The conclusions to be made are that the potential for energy savings by better operation of the railway power system is great. Another conclusion is that investment planning models for railway power systems have a high development potential. RPSS planning models are computationally more attractive, when aggregating power system and train traffic details.

Sammanfattning

Banmatningssystem skiljer sig huvudsakligen från allmänna elsystem genom att lasterna rör på sig. Dessa rörliga laster är pådragande tåg. Tåg kan också återmata vid inbromsning och agerar då som energikällor. Dessa rörliga laster konsumerar förhållandevis stora mängder effekt, vilket resulterar i substantiella spänningsfall, inte sällan så stora att lastuttaget begränsas. Av praktiska skäl matas järnvägen vanligen med enfasig växelström eller likström. Effekt från trefasiga allmänna nät omvandlas antingen till enfas för att mata järnvägen, eller så delas banmatningssystemet upp i mindre sektioner som matas individuellt från omväxlande fas-par i det allmänna nätet. Det senare görs för att inte snedbelasta faserna i det allmänna nätet i onödan.

Denna avhandling behandlar olika sätt att optimalt driva eller utforma banmatningssystem. Avhandlingen fokuserar på omriktarmatade järnvägar eftersom de är styrbarare och besitter en större framtidspotential. Omriktaranvändning motiveras ytterligare i en litteraturstudiebaserad artikel som visar på fördelarna med omriktaranvändning. För övrigt så måste omriktare av något slag användas för att mata järnvägar med likström eller växelström i annan frekvens än det publika nätets.

Den optimala drift-delen av denna avhandling behandlar huvudsakligen optimal effektstyrning och påslagning/avslagning av järnvägsomriktarstationer i HVDC-matade banmatningssystem. Modellerna är generaliserbara till olika typer av matning, och de hanterar återmatning. Denna del behandlar MINLP-problem (blandade heltals och ickelinjära programmeringsproblem), och den huvudsakliga delen av problemet är icke-konvex och ickelinjär. Konceptet precenteras i en artikel. Frågan hur problemets modeller skall formuleras har i detalj behandlats i en artikel.

Avhandlingen innehåller också en konferensartikel och ett artikelutkast för modeller som inkluderar den fullständiga tågkörstrategin i ett enda optimeringsproblem som modellerar elsystemet såväl som de mekaniska tidsmässiga sambanden. Denna modell är en generaliserad TPSS (Tågelsystemssimulator), avsedd att tillämpas på detaljrikare studier, medan TPSS huvudsakligen är utvecklat för dimensioneringsstudier. Ovan nämnda optimala effektflödesmodeller kan implementeras i den fullständiga el- och tågkörstrategimodellen.

Den optimala utformningsdelen av avhandlingen innehåller två aggregeringsmodeller för att beskriva reducerad tågframförandeprestanda. Den första modellen är presenterad i en tidsskrift, medan den andra är anpassad för att vara mer användbar med andra simuleringsresultat presenterades på en konferens. Delen innehåller också en tidig modell för optimal järnvägsomriktarplacering.

Slutsaterna som dras är att potentialen för energibesparingar genom bättre drift av banmatningssystemet är stor. Visade konstateras att investeringsplaneringsmodeller för banmatningssystem har en hög utvecklingspotential. Banmatningssystemsplaneringsmodeller är beräkningsmässigt mer attraktiva när elsystems- och tågtrafiksmodeller aggregeras.

Acknowledgement

I would like to thank Lennart Söder for having accepted me, employing me and supervising me as a doctoral candidate at EPS. I would also like to thank Thorsten Schütte for fruitful research and general life-related discussions through these years. Also a big thank to Stefan Östlund for the last year of tighter research discussions and cooperation.

I also would like to thank Joseph Kallrath for the opportunity to attend his courses in GAMS programming and sharing his great experience.

I would also like to thank Anders Bülund at Trafikverket and the people at Elforsk for financial support.

I would also like to thank all my national SULF and local Saco-S KTH labor union comrades for great cooperation over the years. An especial thank to the extreme work horse, great motivator and inspirer, and yet ideologically stringent Rikard Lingström for the time working together in the labor union locally and nationally. I have learned a lot, not only about universities and unions, but also about myself and people.

I would also like to thank my family just for being there. And, last but not least I would like to thank all my colleagues for nice chats and discussions during coffee and lunch brakes.

Dissertation

This part of the thesis mentions the publications in the same order as the abstract does. So it is not the chronological order of publication.

Paper I
Lars Abrahamsson, Thorsten Schütte, and Stefan Östlund, "Use of Converters for Feeding of AC Railways for All Frequencies", *Elsevier Energy for Sustainable Development*, vol. 16, pp. 368–378, Sept. 2012, DOI 10.1016/j.esd.2012.05.003.

Paper II
Lars Abrahamsson, Tommy Kjellqvist, and Stefan Östlund, "HVDC Feeder Solution for Electric Railways", *IET Power Electronics*, Accepted for publication. 2012.

Paper III
Lars Abrahamsson, Stefan Östlund, and Lennart Söder, "Optimal Power Flow (OPF) Model with Unified AC-DC Load Flow and Optimal Commitment for an AC-catenary Railway Power Supply System (RPSS) fed by a High Voltage DC (HVDC) transmission line", submitted 2012.

Paper IV
Lars Abrahamsson and Lennart Söder, "An SOS2-based moving trains, fixed nodes, railway power system simulator", presented at *COMPRAIL 2012*, New Forest, UK, September 11-13, 2012. To appear in the *COMPRAIL 2014* proceedings.

Paper V
Lars Abrahamsson, Stefan Östlund, Thorsten Schütte, and Lennart Söder, "An electromechanical moving load fixed node position and fixed node number railway power supply systems optimization model", submitted 2012.

Paper VI
Lars Abrahamsson and Lennart Söder, "Fast Estimation of Relations between Aggregated Train Power System Data and Traffic Performance", *IEEE Transactions on Vehicular Technology*, p. 16–29, Vol. 60, Issue 1, January 2011.

Paper VII
Lars Abrahamsson and Lennart Söder, "Traction Power System Capacity Limitations at Various Traffic Levels", *WCRR 2011; the 9th World Congress on Railway Research*, Lille, France, May 22-26, 2011.

Paper VIII Lars Abrahamsson and Lennart Söder, "Railway Power Supply Investment Decisions Considering the Voltage Drops - Assuming the Future Traffic to Be Known", *15th International Conference on Intelligent System Applications to Power Systems, 2009. ISAP '09*, Curitiba, Brazil, November 8-12, 2009.

In addition to the above references [1–8], the following publications have also been authored or supervised (only the railway-related and relevant ones) by Lars Abrahamsson during the time as a doctoral candidate at KTH:

Conference Articles References [9,10] leading to the Train Power Systems Simulator (TPSS) model presented in the Licentiate Thesis [11] and in the Masters' Theses [12, 13].

Conference Articles References [14–16] leading, together with the Train Power Systems Approximator (TPSA) model presented in the Licentiate Thesis [11] to the journal article [6], the improved approximator model [7], and the optimal design model [8].

Licentiate Thesis Reference [11], which contains a general Railway Power Supply System (RPSS) model, a thorough presentation of TPSS, and the then most recent version of TPSA. The TPSS moving load models in the Licentiate Thesis inspired the RPSS models used in the Masters' Theses [17, 18].

Book Chapter The conference article [16] was selected to be included as a chapter [19] in a book containing selected RPSS articles from the COMPRAIL (Computer System Design and Operation in Railways and other Transit Systems) conference series.

Conference Article As a spin-off of the TPSA model presented in [11], a TPSA model proposal considering peak power consumption and time-window energy consumption was presented in [20]. This side-track is still to be further excavated in order to obtain a completer optimal design model of the RPSS.

Journal Article Some of the articles at the AUPEC 2008 conference were picked to be part of a special number of the Australian Journal of Electrical & Electronics Engineering, which [21] is the result of. The original article is [20].

Magazine Article The results of the Masters' Thesis [17] resulted in the Elektrische Bahnen (in English: Electric Railways) article [22], which was coauthored.

Journal Article During a 2009 late-summer visit at KTH (Royal Institute of Technology) by the fellow RPSS researcher Eduardo Pilo then working for Institute for Research in Technology at University Pontificia Comillas in Madrid, Spain, some discussions and reference suggestions resulted in the co-authored article [23], based on [24]. Eduardo is for the moment mainly working for EP Rail Research and Consulting.

Conference Article As a result of the Masters' Thesis [18] and the related supervision, the conference article [25] was co-authored.

Conference Article In order to promote the ideas presented in [2,3,18,25], some of the results obtained was also presented in [26].

Masters Thesis #1 In the thesis [27], supervised at Rejlers in Västerås by Thorsten Schütte, and at KTH by Lars Abrahamsson, the possibilities of controlling the voltage phase angles on the public-grid-sides of rotary converters were studied. The proposed solution involved the connection and disconnection of inductors and capacitors on the public-grid side.

Masters Theses #2 The thesis [12] was about improving and debugging the then-present TPSS version and the project was completely supervised by Lars Abrahamsson. Some alternative models were also presented and suggested.

Masters Theses #3 The thesis [13] was about comparing TPSS accuracy and performance with the commercial RPSS simulation software TracFeed Simulation [28, 29]. The project was examined at Uppsala University, mainly supervised by Lars Abrahamsson, and the TracFeed Simulation support was given by Peter Deutschmann at Trafikverket, i.e. the Traffic Authority (Peters affiliation was Banverket, i.e. the Railway Authority, when the project was done).

Masters Thesis #4 In [17], the possibilities of direct generation of $16\frac{2}{3}$ Hz AC power to the Swedish RPSS were discussed and investigated. A case study was made for a directly generating hydro power plant in Älvkarleby, and more general discussions were made regarding wind power. The thesis was initially supervised at Rejlers in Västerås by Thorsten Schütte, whereas it was finished at KTH under supervision by Lars Abrahamsson.

Masters Thesis #5 In [30], an auxiliary power system for the railway with two different low-voltage levels was proposed and studied. The thesis was written and supervised at Sweco in Luleå, and co-supervised by Lars Abrahamsson at KTH.

Masters Thesis #6 In [18], an optimal power flow and optimal commitment model is applied on a unified AC/DC model of a VSC-HVDC-fed AC-railway. Thorough comparisons are made between various RPSS configurations, load types, and converter losses functions. The project was a result of the ideas presented in [2], and also resulted in a conference article [25] on its own.

Division of work between authors

Paper I

Lars Abrahamsson and Thorsten Schütte formulated the idea, and added academic references to justify the claims jointly. The idea was however based upon discussions with Uwe Behmann and Kurt Rieckhoff. Stefan Östlund commented upon technical discussions, language and report layout. Lars wrote the article.

Paper II

Initially Tommy Kjellqvist and Stefan Östlund came up with the idea of employing the concept of medium frequency lightweight converters for feeding railways through HVDC (High Voltage Direct Current) feeders. The illustrative case study examples was found out by Tommy Kjellqvist as well as the accompanying drawings. The mathematical modeling of the MINLP (Mixed Integer NonLinear Problem) problems for optimal operation and commitment of the HVDC converters in the railway power system was performed by Lars Abrahamsson with discussions about converter losses modeling with Stefan Östlund, and some modeling and programming issues with Masters Thesis student John Laury.

Paper III

This paper mainly focuses on describing the exact mathematical modeling of the problem in "Paper II". The model was designed by Lars Abrahamsson, technical as well as paper layout ideas were exchanged with Stefan Östlund. Figures were borrowed from "Paper II". Lennart Söder was the supervisor.

Papers IV–VIII

These papers are written by Lars Abrahamsson. The supervisor was Lennart Söder.

Contents

Part I

Introductory part of thesis

Chapter 1

Introduction

This chapter provides a background to railway power supply systems in general, and optimal railway power system operation and design in particular. This chapter also defines the aim and the main contributions of this work.

1.1 Background

Railway power supply systems need to be expanded and operated more efficiently due to increased transport demands on rail and increased energy economy awareness.

In this section, differences between the public grid and the railway grid are presented. Moreover, the relations between the two grids are mentioned. Finally, the challenges in present-day railway power system operation and design are mentioned briefly.

Differences between public electricity grids and railway power system grids

Generally speaking, an electric railway power supply system (RPSS) differs from a public transmission or distribution system in many ways. Briefly, the loads of RPSSs, i.e. the trains, are moving, and the size of the loads varies with time and location. Power consumption increases with speed, weight, acceleration, inclination (gradients) and horizontal curvature, etc. Trains can also regenerate, when braking electrically, then the RPSS also has moving distributed generation sources.

Moreover, it is not uncommon that the loads of the trains are so high that voltage drops in the contact line system are much larger than what is allowed in public power grids. The contact line system is often referred to as the catenary system and the two terms are in this thesis used synonymously. Even though trains are more resilient to voltage drops than traditional electricity customers, their performance is reduced for low catenary voltage levels, resulting in trains slowing down. This is a great difference compared to public grids where a voltage drop of comparable size would make the grid stop functioning. Voltage drops are naturally also bad because of the losses they cause, in public as well as in railway grids.

Short outages, orders of a number of seconds, also affect the public grid much more severely than the railway electric grid. A very brief power outage will not affect train running times significantly if not security systems force them to brake due to safety reasons.

The railway grid structures vary, but since they follow a railway line, it is not uncommon that the grid is considered radial if interconnected. In that sense RPSSs have more in common with distribution grids than with transmission grids. On the other hand, some RPSSs have additional transmission lines feeding the railway. These may be meshed. Railways in urban areas also have higher likeliness to be meshed.

The relation between the railway power system and the public grid

Railways using the same frequency as the public grid are typically not fed by an interconnected railway power system. Such an RPSS is rather built up by a number of single-phase public-grid loads constituted by sections of the contact line system.

Railway power supplies using DC or different frequencies than the public grid have, if fed by the public grid, to be fed through converters. There are many technical benefits of feeding the railway through converters anyway, but it is maybe not always economically the best solution. DC grids can also be fed through simpler rectifiers.

In this thesis, a *feeding point* means a point where the railway grid is connected to the public grid. For various railway topologies that definition might have to be altered. In for example the German system the converter stations and power plants are big and sparsely distributed indirectly feeding the trains through a high voltage transmission grid connected to the catenary by transformers. In such a system the transformers connecting catenary to transmission grid would be the natural *feeding point*s.

All railway grids may be fed by direct generation, so there may very well exist RPSSs that have no connections to any public grid.

Challenges in present-day railway power system operation and design

An RPSS can typically be under-dimensioned in two ways. Firstly, the transmission system (including catenaries) can be too weak for the loads, such that the voltages drop too much. That is typically common in rural areas where the loads may be high, but the feeding points are sparsely distributed and the railway grid is radial.

Secondly if the locally available installed power is less than the local power demand of the trains. That is more common in urban areas during rush hours.

The load variations cannot be smeared out over time, even if that would be the best for the power system. Passenger trains, especially the ones for commuters, have to be correlated to when working days normally begin and end. Freight trains, on the other hand, are considered more efficient if they can be few and heavy, which increases the peak loads without guaranteeing power system utilization the remaining time.

Traditionally railway power supply grids have, like the public electricity grids, been controlled passively. Due to the reduced willingness of the public to pay for unnecessarily costly infrastructure investments, an opportunity has opened for ideas of utilizing existing infrastructure as efficient as possible and in planning for infrastructure investments such that the investment costs and the costs related to over/under capacities are balanced.

One way of utilizing the existing infrastructure optimally is to by optimal operation and commitment[1] of converters minimize the system losses for given load sizes and positions. With the cheaper power electronics technology of today this is not only theoretically and technically possible, but also economically realizable. Another way of utilizing the existing infrastructure optimally can be to create traffic plans that the existing power system can cope with. With the ever-increasing computer capacities, these kind of studies become more and more attractive.

In order to make efficient and redundant long-term investment plans of the intrinsically complex railway power supply system, its models need to be heavily simplified due to problem complexities and computation times. Simplifications can be made by still studying the power flows and train movements, but with stripped models. But simplifications can also be made by first making detailed studies of the railway power system, and then simplifying the problem setup and the results as well as the relations between them. No matter how, when these simplifications are done, the costs for changing the infrastructure and the costs of operating it has to be modeled. And these models have to be computable for available algorithms.

Generally, it should be stated that dedicated railway lines like e.g. MRT (Mass Rapid Transit) systems and dedicated high-speed railways are easier to model and study in simplified manners compared to railway main lines and their mixed traffic. For dedicated railway lines, load sizes and load locations are far more predictable. These systems contain a few train types, and the headways are clearly defined, and a traffic increase simply means a decreased headway.

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[1] To determine when it is best to switch something on or off with respect to something. In this case when to switch catenary-feeding converters on or off with respect to the idling losses of the converters and how they contribute to the total losses of the system. The objective is to minimize total system active power losses.

1.2 Thesis objectives

The overall original objective of the doctoral project behind this thesis was to develop investment planning models for railway power supply systems and to make these models resilient to uncertainties in e.g. future prices and traffic levels.

In order to do this, a satisfactory knowledge of railway power supply systems and the consequences of different combinations of power system designs and traffic intensities is needed. Moreover, one has to determine how to easily model and detect situations that cause negative consequences for an under-dimensioned railway power system.

It was at a comparatively early stage in the doctoral project clear that railway power systems differ too much from public ones in order to be able to apply existing investment planning models for public grids. Due to the scarce supply of existing models in the field, the work focus had to be redistributed, and in the end more focus than was initially expected has been set on understanding and modeling the interaction of train traffic and operating various RPSS configurations. That in turn resulted in no yet published studies regarding optimal distribution of installed power, optimal investments over time, or parameter uncertainties.

The final overall objective can be subdivided into the following sub-objectives. To look upon existing published work, to look at alternative ways of operating and designing the RPSS, to look at alternative ways of modeling moving loads in a power system, and finally, to use simplified models in finding the optimal location of converter stations with regard to train running times.

In all these four sub-fields more questions could be addressed and answered, but those questions are not in the scope of this thesis, c.f. Chapter 8.

Determine what already is done

The first sub-objective, in the thesis particularly treated in Chapter 2, is to determine what already has been done regarding modeling of, operation of, and changes in the design of an RPSS.

Look at alternative ways of operating and designing the RPSS

The second sub-objective was to look at alternative ways of operating and designing the RPSS, compared to the existing solutions.

In Chapter 3, the technical benefits of feeding the RPSS through converters instead of through substation transformers, and the potential in smarter converter usage, are discussed in the context of reduced costs for power electronics.

In Chapter 4, the technical and practical benefits of strengthening the RPSS by HVDC transmission lines instead of AC transmission lines or denser located connections to the public grid are treated. The main reasons for using HVDC feeding are reduced land use and power flow controllability.

Look at alternative ways of modeling moving electrical loads

The third sub-objective was to seek for ways of modeling moving loads in fixed-size power supply systems over time. A proposal with a fixed number of power system nodes, and still moving electrical loads, has been presented in Chapter 5. The proposed model is mainly suited for detailed studies regarding time-optimal operation of trains or controllable power equipment.

Moving load models that have been used in this thesis, but are not presented here, are the TPSS models presented in [11, 12]. Those models are mainly developed for RPSS dimensioning purposes when train operation and power equipment operation are assumed to be of the more traditional kind.

Modeling RPSS design impacts on train traffic

The fourth sub-objective was to develop models for optimal locations of converters for given traffic intensities (i.e. load situations) and RPSS types. This is done in Chapter 7.

General methods of developing approximators describing the relation between train loads and RPSS configuration in a simplified manner have been presented, together with particular neural-networks-based approximators describing the average train velocities and running times. The presented approximators can be generalized, but in Chapter 6 they assume one type of trains, starting and stopping at the same locations. One of these approximator models is applied in an optimal placement problem in Chapter 7, where the train delays are considered in different alternative cost functions.

This optimal design part is based upon using simulation results to create and define simplified models that can be used for optimal RPSS investments. The sub-objective has been narrowed to focus on treating the voltage drop issues, and the installed power issues has been left out for future work.

1.3 Why this thesis?

In a future with reduced fossil emissions, scarcer energy resources, and maintained possibilities to travel, railway expansion is inevitable. How to operate and design the future railway power supplies without wasting energy or infrastructure are key issues to solve in the future. It is of great importance to determine the possibilities and weaknesses of different RPSS designs, how to robustly but efficiently operate the system once it is built.

Question Formulation

The questions that were desired to be answered with this doctoral thesis were:

- Are there any existing models for the operation of an RPSS?

- Are there any existing models regarding the design of an RPSS?
- Could there exist future alternative ways of operating or designing the RPSS that could be compared to existing methods and equipment?
- How can the RPSS interacting with the train traffic be modeled and described?
- How can energy be saved or train traffic performance be improved?
  - How can feeding operation of the RPSS be improved?
  - What are the consequences on the state of the RPSS and on the train traffic of a change in the railway power supply system infrastructure?
- How to formulate the optimal design problem in closed form in order to be able to formulate a classical optimization problem?

Challenges related to the Questions

There are a few challenges related to the above mentioned optimal design questions:

- What is the right level of modeling the RPSS? There is an intrinsic conflict between details, computability and ability to generalize.
- It is not clear what is the most suitable way of measuring traffic levels or energy demands.
- What kind of simplifications should be made?
  - Keeping the power system – but simplify its models. Common approach, c.f. [31, 32].
  - Keep the power system – very detailed simulations, but approximative metaheuristic optimization algorithms, and not having models on closed form [33–36].
  - Or like in this thesis – only implicitly considering the power system in the closed-form approximation.

1.4 Main Scientific Contributions

The main contributions of this thesis are:

- A comparatively broad literature review for energy, electricity, and optimization in railways in general. This is presented in Chapter 2.
- The technical benefits of using converters as connecting equipment (feeding points) also in public-grid-frequency AC railway power systems have been summarized from literature studies and logical arguing. This is further discussed and presented in Chapter 3 and in [1].

- Optimal power flow and converter commitment models for railway power supply systems have been developed. This is treated in Chapter 4 and in [2,3].
- A moving load model, embracing power system details as well as mechanical details over time. This model has a fixed number of catenary nodes, regardless of number of trains in traffic in the sections studied. The user chooses the desired detail of the catenary nodal modeling. The model is contained within one single MINLP. This is discussed and explained further in Chapter 5 and in [4, 5].
- The development and presentation of one more general, and one more specific, neural-networks-based approximator. These approximator models calculate rapidly and in an aggregated manner the train traveling times and/or average train speeds for various combinations of power system configuration and railway traffic intensity. This is treated in Chapter 6 and in [6, 7].
- A model for the optimal locations of RPSS connecting equipment (feeding points) has been developed and presented. Further details are presented in Chapter 7 and [8].

1.5 Other Contributions

Besides the scientific contributions of the doctoral thesis, it has resulted in industrial contacts with Rejlers, EP Rail Research and Consulting, and Atkins. The supervised Master's theses have resulted in placing railway-specialized engineers on places like Swedish Neutral, Uppsala University, Areva, Vectura, and Sweco.

The explicit results of these Master's theses are:

- Cost-efficient measures of making rotary converters possible to coexist with more modern static converters controlled to adjust for the voltage angle fluctuations in the public grid [27]
- Improved railway power system simulation models [12]
- Verified railway power system simulation models [13]
- Concrete results of the impact of possible direct generation of hydro power into the Swedish 132 kV railway-transmission line system [17]
- An alternative auxiliary railway power grid configuration was proposed for the cases when the poles carrying the catenary system become mechanically overloaded, and the auxiliary power grid needs to be relocated from these poles elsewhere [30]
- The technical superiority of an HVDC-fed AC-railway using optimal power flow and optimal commitment over the present-day existing feeding solutions was shown [18]

- The optimal power flow and optimal commitment solution sensitivities to converter losses, power system configuration, and locomotive power factors were determined in [18]

1.6 Outline of the thesis

The chapters of the thesis are organized as follows:

Chapter 2 provides a literature review of publications in the railway field focusing on models and studies of railway electric power supplies, optimal operation, optimal configuration, energy management, traffic, etc. In that priority order.

Chapter 3 summarizes why converter feeding of railways is to prefer above mainly transformer substation feeding. The original detailed argumentation is presented in Paper I [1] and some complementary arguments and additional clarifying references are presented in Chapter 3.

Chapter 4 regards static load optimal commitment and optimal power flow models and studies of the RPSS. These models are developed for studies and model development of HVDC transmission-line-fed AC railways. The mixed nonlinear and integer optimization is done with respect to the overall system active power losses. The chapter treats the three papers

- Paper II [2] which presents opportunities, simulative results, and discussions regarding the optimal operation of HVDC-fed AC railways.
- Paper III [3] which presents development and detailed presentation of the models used in [2].

The in Chapter 4 obtained and presented results give lower bounds on the total railway power system losses. In real-life operation of the system, one will aim at coming as close to this ideal operation as possible, using smart control laws. The models developed and presented in Chapter 4 could besides being used for losses minimization, also, for example, be used for optimizing the voltage levels at the pantographs.

Chapter 5 presents and motivates the complete moving load fixed node model. The attached papers include detailed moving load studies. The presented fixed node model for moving loads embraces power system details, mechanical details, their interaction over time, and is formulated as one single MINLP.

- Paper IV [4] presents the idea and some promising simulative results.
- Paper V [5] contains a detailed presentation and motivation of the developed model. The model is applied to some numerical examples to clarify its usage, and to show on computational performance regarding accuracy and time usage.

Moving load studies describe how the RPSS and the traffic interact. Physical traffic limitations may be determined, the momentary need for power for different feeding systems and driving strategies can also be studied.

Chapter 6 presents and discusses the aggregated approximator models. In Chapter 6 it is explained and motivated why to aggregate the changes in RPSS traffic behavior caused by voltage drops. It is explained how it is done in the attached papers. The aggregated models are based upon relationships found while studying simulation results. These findings, that allow simpler investment models, indicate that voltage-drop-caused train-delays mainly depend on the loading of the system, and the impedances of the power section trafficked by the studied train. The loading of the system is described by the number of trains in traffic on-average in the power system section within the time frame studied, whereas the impedance is described by power system technology used and the distance between the connecting equipment (feeding points) right in-front of and right behind the trains.

- The original idea of how to approximate average maximal train speeds is presented in Paper VI [6].
- An improved and simplified model is motivated and presented in Paper VII [7]. This one also approximates train traveling times, for which cost figures exist.

Chapter 6 also contains discussions about possible future improved and new approximator models and improved application of them.

Chapter 7 presents and describes models of the optimal design of an RPSS. Models where to optimally locate RPSS connecting equipment (feeding points) are presented. The numerical examples regard converters for the Swedish RPSS.

- A working DNLP (nonlinear programming with discontinuous derivatives) model of optimal connecting equipment (feeding point) placement is presented and applied on a test case for two alternative objective functions in Paper VIII [8].

Chapter 8 highlights the key conclusions of the thesis and summarizes ideas for future work in a final discussion.

Chapter 2

Review over broadly related work

This chapter provides a literature review to broadly related work regarding railways, railway electrification, railway traffic optimization, and power supply optimization.

The scarce supplies of RPSS (railway power supply system) literature motivated a deep and broad search for publications in the field. In the RPSS field of research it may be troublesome to define a specific gap where more work is needed to be done, because the number of publications is not large enough to create such an overview. Some interesting work has been presented, and many interesting issues are treated. Detailed presentations of models and methods used are however in general lacking.

It is not only scarceness of publications that makes finding articles challenging, the terminology used is not uniform, and therefore no universal index terms exist. Terms like electrified railways, mass transit, ground transport, traction systems, trolley systems, railway power supply, railroad electrification, train power supply, and many others exist in parallel.

The main intention with this chapter is to provide orientational material for researchers new to the field of RPSSs. The purpose is also to put the presented thesis into a context.

2.1 Modeling of Railway Power Systems and Components

Generally

Most of the existing RPSS standards used in the world are described and compared in [37,38]. Electromagnetic compatibility [39] and electromagnetic interference [40] are topics not treated in detail in this thesis. A historical review of RPSS can be found in [41] together with examples of modern real-life power-electronics products for the railway.

A review of simulation models for railway systems is presented in [42]. More particular, an overview for the calculation of train performance in electric railway systems is presented in [43]. In that overview a very deep description is included,

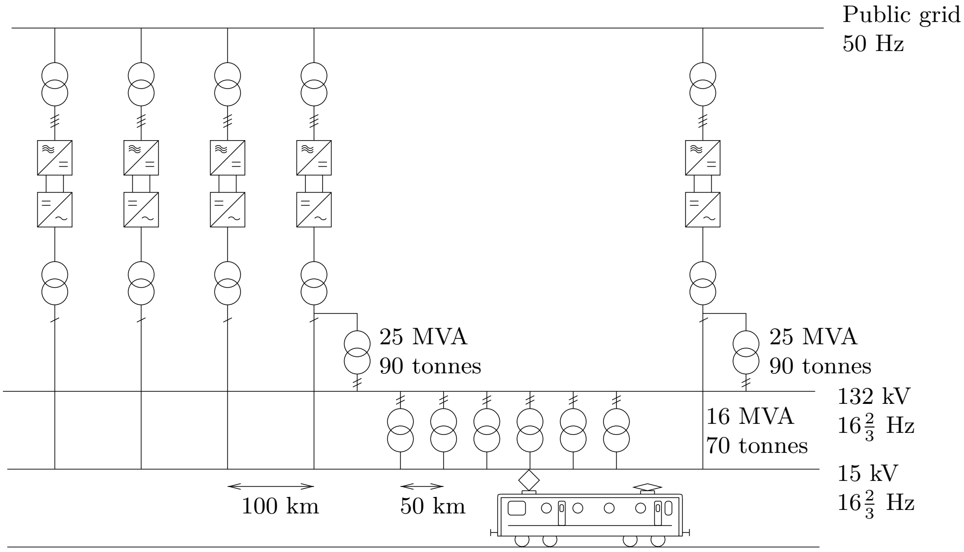

Figure 2.1: Illustration of the current Swedish railway power supply system solution. Both the decentralized and the centralized solutions are visualized.

considering technical, economical, and historical explanations. Various supply system standards are listed, catenary system types, motor types, converters, interferences of the railway, train tractive forces, traveling times, small trains contra big trains, etc. are treated.

In [44] the main differences between public power systems and railway power supply systems are extensively discussed and explained. Typically, the loads are neither fixed power or fixed current, and they vary heavily. This is also one of the earliest publications where the problem with moving nodes connected to the railway power supply is ventilated. It was proposed to replace loads along the section with loads at each substation. The number of nodes was successively increased, but kept fixed to the number and their locations in each study.

Besides that keeping the number of and the location of the nodes fixed simplifies the systematic bookkeeping of simulation results [44, 45], also the admittances of the system become more of the same orders of magnitude not hazarding admittances close to zero or infinity, which the solution to the moving load problem in [45] rather amplifies than alleviates. In [44] the different algorithmic methods are discussed. Also the challenge of finding good starting iteration points for the load flow equations calculations is discussed in [44].

In [46] it is confirmed that the coupling between train movements and the states of the electric power system is important. What to expect from a traction simulator is also listed.

Voltage levels can be kept up not only by converters, transformer substations, or SVCs, but also by super-capacitors and flywheels. Super-capacitors are used in Germany, and flywheels are used in the London and New York urban DC networks [47]. These solutions are more attractive to DC system than to AC systems since the SVC option does not exist for DC.

Various factors that ease or aggravate regenerative braking are studied in detail in [48].

Sometimes very particular details of the railway power supply system are studied, e.g. in [49] where the nonlinear frequency dependencies of rail impedances are studied. In [50, 51] the impedances, time constants, and transients of a trolley system are studied. Methods for induced voltage computations can be found in [52].

The Swedish railway power supply system is described in [53]. The Swedish RPSS is graphically illustrated in Figure 2.1. The solution with feeding the trains only via the catenaries is often denoted *the decentralized solution*, whereas the solution of feeding the trains also via the HVAC (High Voltage Alternating Current) transmission line is often denoted *the centralized solution.* Simplistic modelings and studies of the RPSS can be found in [54].

In [55] it is explained that DC-motored trains in AC railways very well can regenerate, depending on the interface between AC contact line and DC motor.

Different iterative techniques for solving DC-railway load flows with regenerating trains are discussed in [56]. It is unclear if and how the model includes moving loads or not.

In [57] it is suggested that power flow computations should be sped up by modeling the trains as current injectors. That allows the power flow equations to be written in linear form. This is done sequentially by using the known power consumption and last iterations voltage levels to compute the injected current in the present iteration step.

A unified AC-DC power flow model for AC-fed DC railways is presented in [58]. In [45], a literature review of railway AC-DC power flow is presented.

Catenary System Models and Technical Properties

Well-explaining illustrations of rail return conductor systems, separate return conductor systems, BT systems using rail as return conductor, BT systems using a separate return conductor, and AT catenary systems are present in [59, pp. 7–9]. Illustrations of many possible AT-BT combination are presented in [60].

The Simplest Catenary System Types

Catenary systems can be designed in various ways [59], where the basic design is a conductor supplying the trains with current which flows back to the source through the ground and the rail. The second simplest option is to connect return conductors to the rail [59].

There are also typical transformer-based catenary system designs treated separately below, designed for improved voltage quality and/or keeping track of the return currents.

Booster Transformers

In countries or areas where earth resistivity is high, booster transformers (BT) are used to make sure that the same current level that passes through the contact line also goes back through the return conductor [11, 37, 59]. This is done in order to reduce the rail potential and disturbances to telecommunication systems and other electrical equipment [60]. In some parts of the world, BT are not needed.

The main drawback with BT systems is the comparatively high impedance, partly depending on that the current has to pass through each BT transformer along the contact line. It should however be noted, that this is due to the purpose with the BT technology, namely to avoid ground currents. The ground cannot be used as return path for the current in BT-systems, wherefore of course also the total circuit impedance increases.

The same impact that the usage of BTs has can also be achieved using power electronics to actively taking care of the return currents. Model and case study is presented for AC railways in [61], and a patent application treating both DC and AC is presented in [62]. A booster circuit for DC has also been presented in [63].

BTs are used in catenary systems in at least Sweden, Korea, India, and England [64]. BTs are also used in many other countries such as Denmark and Norway.

Auto Transformers

The main benefit of using auto transformers (AT) is that the feeding catenary voltage can be raised substantially without the trains taking any notice. To put it more technically; with AT systems, the voltage between contact line and rail remains the same as in a non-AT system, whereas there is a higher voltage between the contact line and an additional conductor, the so-called negative feeder.

The classical overhead contact line is as a consequence denoted the positive feeder and an auto transformer is connecting the positive feeder to the negative feeder. At the same time, the AT is grounded in the rail in order to receive return currents.

The negative feeder voltage is normally a 180° phase-shifted version of the positive feeder voltage. This results in a doubled feeding voltage, but the train experiences still the standard voltage. In some RPSS the AT solution has a different number of windings for the positive and the negative sides of the transformer, resulting in even higher voltages for the negative feeder [23, 37], reducing losses and voltage drops even further. AT systems are described further in [11, 23, 37, 65, 66]. The main drawback with AT contra BT is that stray currents in the ground are not reduced as efficiently.

To study every detail exactly is rarely of relevance for general dimensioning purposes. If for example studying voltage levels and power consumption without caring about individual auto transformers (AT) loading, a useful and yet comparatively detailed approximation can be found in [23, 24, 67].

Commonly, AT-based catenaries are modeled one point-like impedance and one distance-dependent impedance. The latter model is even simpler. When using that model and studying many interconnected power sections with many trains it is important to put the point-like impedance at the train load, in order to make sure that this point load leaves the section when the train does. In the [23, 24] model, trains positioned under the same pair of ATs share a common point impedance. It is implementable in RPSS simulations but one needs to specify the exact locations of each AT then. Descriptive illustrations are present in [23].

Sectioning the particular contact wire but not the positive AT feeder creates a solution reducing return rail currents without having to introduce BTs [68].

ATs are for example used in Norway [68], Sweden [53], Spain [23,24], Japan and in both the 60 Hz and 25 Hz US systems [64]. The dimensioning of the Hungarian AT system with respect to reduced telecommunication interferences was presented in [69]. The Hungarian ATs are remotely controlled.

A detailed AT study is presented in [70]. Voltage levels of rail and catenary are studied between AT pairs.

There are concepts similar to AT also for DC lines. One example is the feasibility study [71] on some feeding arrangements for improving the 1.5 kV DC-system by a negative feeder on −1.5 kV and/or a positive feeder on +3 kV.

Combining Booster and Auto Transformers

The combination of AT and BT transformers have been suggested and studied in [60, 72]. With that solution one can combine low impedances with reduced rail potentials and electromagnetic disturbances. For the same investment costs as for a pure AT system however, the AT transformers have to be placed somewhat sparser resulting in increased impedances of the catenary system.

Several different configurations are discussed and presented in [60]; BTs that are located between positive and negative feeder, three-coiled BTs with a connection also to the earthed rail, three-coiled BTs connected to a return conductor wire instead of the earthed rail, 2-coiled BT pairs connecting negative feeder to return conductor and positive feeder to return conductor respectively, additional positive feeders connected to the negative feeder also between the ATs by other BTs whereas the standard BTs still connect positive feeder to either return conductor or the earthed rail, this additional positive feeder can also be run at a higher voltage by extra ATs, and finally a solution where each BT between a pair of ATs is sectioned so that current only has to flow through one BT regardless of train position.

In [72] one of the suggested combined AT+BT solutions are verified experimentally in a field study.

The numerical study in [60] was done on a two-coil BT pair system connecting return conductor to positive and negative feeders respectively. Three systems were compared: one that had two ATs and seven BT pairs, one with three ATs, and one with seven BTs, and the railway is about 40 km in section length.

In the later, experimental study [72], four systems are studied; the case added contains three ATs and seven BT pairs.

RPSS Transmission Lines

In low-frequency AC railway systems, it is common to use railway-dedicated transmission lines. Amtrak uses 138 kV transmission lines to their 12 kV AC system in 25 Hz on the US east coast [73]. In Sweden (132 kV) [11] and Norway (55 kV) [22] the HVAC transmission lines are used as a supporting backbone to and connected in parallel with some of the existing catenary lines. Power is in Scandinavia converted to the catenary system, and thereafter transformed up into the transmission line. In (most parts of) Germany [74] the (110 kV) transmission line system is meshed and fed by large-size converters. In the German system, the catenary is fed indirectly through this transmission line, where present. The Swedish system is illustrated in Figure 2.1.

In [2] it is suggested to use DC transmission lines instead of AC, and case studies are made on AC railways. The models used are presented in [3]. DC transmission lines for DC railways are suggested in [75].

High Voltage Catenary Systems

High voltage catenary systems are catenary systems using voltages higher than the standardized ones. This means voltages above 3 kV for DC railways, and above 25 kV for AC railways.

Railway power supplies with extra high catenary voltages have been studied in [76]. Typical designs for HVDC contact lines and various levels of traffic are treated in [77], whereas migration strategies from AC to DC are treated in [78]. The usage of HVDC catenaries was also suggested in [79]. It is in [80] concluded that high voltage catenaries are particularly attractive if the supplying strong public grid is sparsely present along the railway line and the line is not electrified since before. One should then bear in mind that there are alternatives, like small-scale converter feeding also from weak public grids [1], or feeding the railway from HVDC-cables with small or medium-size converters along the line [2, 3].

Through the years, many people have suggested high voltage railways, and some have in fact been realized. For example, the SishenŰSaldanha 50 kV AC railway in South Africa [76], the Tumbler Ridge 50 kV AC railway in Canada [81], and the Black Mesa and Lake Powell Railroad 50 kV AC railway in Arizona, USA, [82].

As early as in the 1930s, 15 kV DC systems were suggested [83]. Parts of the development was made at KTH [83]. In the late 1970s 6 kV DC and 50 kV AC railways were discussed [84]. It is in [85] claimed that 3 kV DC systems are to prefer over 25 kV AC systems with regard to energy and economy. Therefore [85] claims that the next logical steps would be to introduce 6 kV and 12 kV DC systems. Once again in mid 00s, 12 kV DC was suggested [86].

Detailed Moving Load Studies

Railway power systems with moving loads are studied in many publications. There are typically two kinds of moving load models.

The first kind of moving load model repeatedly computes train movements and active power demands. Then these moving loads are put into the RPSS and the power flow is computed according to the pre-computed load sized and locations. This kind of approximation works comparatively well for power systems strong enough to keep catenary voltages about nominal for all expected loads. The benefit with this first kind is of course reduced computational times.

The second kind, solves a combined electrical and mechanical problem. Doing so increases the accuracy of computations, especially for weak grids. It does however demand more computer time.

In [87], the loads are precalculated in size and thus independent of power system voltage drops. A created probabilistic load flow approach is where the probability distribution of train locations are based upon their time being spent at each place according to non-electric moving train pre-computations.

In [59] an extensive study has been made in order to develop criteria for harmful catenary voltage levels, more useful than the ones in [88]. In all the studies, TracFeed Simulation [28] were used. It was shown to be a low correlation between low "U-mean-useful" (the voltage level the standard wants catenary voltage levels to be classified according to) values and train delays. The main reasons therefore was that train running resistance and weight, track topography, number of train stops, locomotive type(s) are not considered in [88]. Moreover, in [88], high voltages makes the values of "U-mean-useful" increase whereas voltage values above 1 p.u. for most present train types cannot compensate for previous voltage drops. For many trains, the tractive performance is reduced for voltage levels about

$$\frac{14.5 \text{ kV}}{15 \text{ kV}} \approx 0.967\text{p.u.} \tag{2.1}$$

and lower [59], but the trains will not run faster for nominal voltages or overvoltages. It is concluded in [59] that passenger trains often are more sensitive to voltage drops than freight trains. That is explained with higher top-speeds and different gear ratios than for freight trains.

Closely related to the above [59], in [89] studies of different tractive force curve regulations with respect to voltage levels are studied. The impact on energy efficiency of variations in that regulation is studied. The importance of which regulation was used increased, logically, with grid weakness. A smart regulation scheme may be a protection against too great voltage drops in the grid.

In [90] the impact of varying the no-load voltage levels on the catenary sides of converters feeding DC-railways are treated. It shows that the issue is complicated, and further studies are suggested. Trip travel times and energy consumption are both desired to be low, a contradictive goal. Besides that high no-load voltages reduce losses and increase train speeds, raising the voltage operating point also reduces the ability to absorb regenerated power.

There are also Simulink-based RPSS simulators [91], where however the modeling is not described in detail, and the voltage dependence of the tractive force seems to be neglected.

A detailed controllable inverter model for DC railways is presented in [92].

For DC-systems, the electric modeling is simpler, and the number of iterations can be reduced to never exceed the number of nodes in the system using the ICCG method [93]. For the proposed method to work, the conduction matrix have to be symmetric and positive definite. Physically that means that all self-conductances has to be positive.

In [94], as with many moving load simulators, the loads are determined purely mechanically, whereafter they are put into the power system as predefined constant loads changing in position and size over time. Therefore, voltage-drop-induced train delays cannot be studied as can be done in e.g. TPSS [11, 12] or TracFeed Simulation [28]. The imbalances caused in the public grid due to direct transformer feeding are considered in [94].

The harmonics in DC railways are studied in [95], where is is suggested that mean values and standard deviations of harmonics should be considered.

Moving load DC mass rapid transit systems are studied in [96], whereas the model is not presented in detail. Similarly for [97].

A comparatively early published and detailed DC rapid-transit simulator is presented in [98]. Sparsity of railway power supply systems, and the technique of diakoptics (i.e. the Method of Tearing, which involves breaking a (usually physical) problem down into subproblems which can be solved independently before being joined back together to obtain a solution to the whole problem) are treated in [99] for more efficient computations. The latter is useful when the grid is subdivided into infrequently connected parts. More about exploiting sparsity for computing DC railway power systems in [100].

A DC railway moving load simulator, applied on a subway system is presented in [101]. There the feeding AC grid is included in the model, and sequential AC-DC load flow is performed. The train models are somewhat simpler modeled than in TPSS [11, 12], whereas the rail impedance and voltages are modeled in more detail in [101]. The train traffic and its power demand is precalculated in a purely mechanical simulator.

A moving load study is made for the purpose of power system dimensioning in [64]. Voltage levels are studies so that they do not fall below levels that reduce tractive force too much or cause protection systems to trigger. Extreme traffic is supposed to be studied. Only one train per catenary section seems to be studied, extensions to multiple trains per section are discussed.

The commercial but not-for-sale RPSS operation simulation software from Siemens, SIDYTRAC is presented in [102]. The software is used internally within Siemens for dimensioning equipment and consultancy tasks. No modeling details regarding SIDYTRAC are known for the author.

According to [103], regeneration may save up to 40 % of in-fed power, and 20 % will be re-consumed by neighboring trains when the traffic is dense and feeding back to public grid is forbidden. A moving load model for super-capacitor energy storage is presented, where it is concluded that energy storage is of more use if traffic is sparse, because energy passing through storage if not necessary will induce extra losses. Different control strategies of the storage equipment are suggested and tried out for both on-vehicle and rail-side storage. Simulink is used as simulating software. The control strategies for rail-side capacitors are more elaborate. It is claimed that super-capacitors are superior to batteries for railway energy storage purposes. The paper treats DC-fed light-rail[1] vehicles.

Moving loads and optimal design and operation of super-capacitors for DC-fed light-rail systems are studied in [104]. The objective function is a linear combination of squared substation output currents, squared pantograph voltage drops, and the maximal internal losses of the super-capacitor. The first should be regarded as a capacity minimization of installed substation power, whereas the second should be regarded as a measure of the voltage quality, and the third as a capacity minimization of the super-capacitor. The optimization model and setup is not explained in full detail, but comprehensible. Converters are used to control when to charge or discharge the capacitor. The converters are modeled as lossless since they are set to work close to their rated values where losses are small. Substations are modeled as voltage sources, and trains are modeled as current generators. Simulation time step is set to 1 second.

In [105], onboard super-capacitors for DC-fed light-rail vehicles are modeled and simulated numerically as well as electromechanically. A control strategy for the capacitors is proposed, integrated with motor drive control. The control strategy proved good also for not predefined speed cycles. The model that seems to be made for one vehicle and one power supply is for moving loads, and the power supplies are modeled as Thévenin equivalent sources, the trains consume variable amounts of DC current. Capacitors are modeled to have an affinely voltage-dependent capacitance, and they are assumed to keep their voltages above half the maximal. The capacitor stack also has an internal resistance. It is in [105] claimed that inverting substations are not paying for metropolitan railways, and since they also change the substation layouts, energy storage is preferable. On-vehicle storage should bear many charges and discharges as well having a high power-weight density, and

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[1] Light rail, light railway, or light rail transit (LRT) is a form of urban rail public transportation that generally has a lower capacity and lower speed than heavy rail and metro systems, but higher capacity and higher speed than traditional street-running tram systems. Light rails are supposed to be more traffic-separated than traditional trams/streetcars/trolleys, but less than metros/subways. Under Swedish conditions, the local railways of Gothenburg are considered to be *trams*, whereas Tvärbanan in Stockholm is considered as *light-rail*

flywheels are physically not wise to accelerate with, so only super-capacitors are left [105]. It is suggested to charge the super-capacitor when braking, discharge it when accelerating, and do nothing when cruising. A similar article is [106].

Simplified Modeling

In [107] simplified models assuming homogeneous traffic determines the minimal allowed headways for a given power supply configuration and train speed.

Vehicles

The running resistances of trains, traction loads, and also a description of traction drives using DC machines can be found in [108], whereas traction drives with inverter-fed three-phase induction motors are described in [109].

Power System Dynamics

Also dynamic studies of the American 25 Hz railway power system have been performed [73], whereas in [110, 111] the low-frequency interactions between vehicles and converters have been studied.

In [111] a stability criterion is proposed and tested for a small test system. The model used is based upon an ideal AC voltage source, an impedance representing the network, and another impedance representing the vehicle. The proposed stability criterion is derived around the idling point of operation.

2.2 Optimal Electrical Railway System Operation

The operation of the RPSS can be optimized in many ways. Converter control, energy storage control, train reactive compensatory control, and the like. Publications in that field are reviewed here. In this section, no detailed review of public grid OPF (Optimal Power Flow) will be made. One such can however be found in [3]. Driving strategies, are treated in Section 2.4.

DC railway losses as well as energy cost have been minimized in [112], where the voltage levels of converter stations are controlled. In the energy cost minimization the different prices for different public grid operators are considered. The tractive forces are modeled as independent of voltage levels, and some parts of modeling are unclear.

Optimal power flow in a public grid integrated electric traction system is made in [113], where the focus is on algorithm development. Today there are commercial algorithms doing what they have in their planned future work.

Another early approximative railway grid optimal power flow model [114] linearizes rotary converter railside voltage angle as a function of active power conversion only. One of the rotary converters is uncontrolled and acts like a slack bus [114]. For the converters that are controlled, catenary-side voltage level and active power converted into the railway are controlled. The OPF is solved approximately and successively, by first sequential linear optimization where the maximal changes in converter voltage is 0.5 kV and in converter active power is 25 % of its rating. For each successive OPF problem solved, these maximal changes are halved until convergence appears. Min and max values are assigned but not specified to node voltages, converter current loadings, line and transformer currents.

An early railway optimal commitment study [115] treats the classically controlled rotary converter stations as slack buses, separating the system into power sections, allowing a fast power-flow calculation. Train power consumption is precalculated in beforehand for loaded and unloaded ore trains at fixed speed. The loads within a power section are summed, and divided on a location-proportional basis on the feeding converter stations. The number of converters being committed, determines the capacity of the station for the moment. That capacity has to exceed the computed loads. The discrepancies from exact power flows can however reach up to 40 %, so a more detailed model like [3] can definitely be motivated using the computers of today. In reality, the number of converters committed to a station impacts the power output from neighboring stations. The converters can be either on, off, or connected only to the public grid for reducing idling losses and avoiding start-up costs.

Energy management of substations so that the electricity bill is minimized is done in [116], the main focus is on keeping the peak loads on the individual substations low and spread the system peak loads on as many substations as possible. No modeling details are presented.

HVDC supplied DC light rail power flow is optimized with respect to catenary losses in [75], and these are compared with a unclearly described standard power flow control scheme. Moving loads are studied.

How to optimally control the reactive power generation on the catenary sides of the on-train converters is treated in [117]. The case study is made on an Southeast Asian commuter train line with 5 minutes headway, 25 km feeding sections, direct transformer feeding, and 50 km/h maximal train speed. The tractive force voltage dependency is neglected. The suggested control is centralized. It is shown that the minimized losses are almost as small for 50 % controllable trains as for 100 % of the train population having the reactive power control possibility. Regenerating trains are not studied in [117].

In [118], which is a further development of [119], the pantograph voltage levels are controlled by reactive power production/consumption of the train-converter. In [118], the desired voltage levels are not subject to optimization, but the controller, that makes sure the voltage levels lie in the desired accepted range, is. The two-norm error between the actual and the desired open-loop transfer functions are minimized for different train positions, with respect to stability constraints. The optimization problem is convexified by smaller approximations. The controller works for both doubly and singly fed catenaries, and both generating and regenerating trains.

In [119], PI regulators are used, identifying the system by using a high frequency signal. If more than one train is in use at the same time, with the [119] model, one has to make sure each train use different identifying frequencies.

Reactive power control of trains is also treated in [120].

Locomotives have in real-life been used as movable but stationary SVCs [121].

A bi-criterion optimization of DC railway substation firing angles are studied in [122]. The two objectives are load-sharing between substations, and high regeneration capabilities. Genetic algorithms are used, the load sizes and positions are predefined in a purely mechanical simulation. The weighting between the two objectives have been varied. The model description is not detailed.

The optimal switching of DC MRT systems are in [123] studied with regard to the loading of transformers in the feeding AC-system. Peak and off-peak traffic is considered. This results in loss reductions and the loading factors of main transformers are improved. The exact modeling is unclearly described. A similar study is made in [124] but then respect is also taken to the installed amount of power in transformers. Similarly, but now studying investments over time, the commitment of transformers is studied in order to minimize losses and investment costs in [35]. Somehow the study is based upon detailed simulations and some dynamic programming optimization.

2.3 Optimal Dimensioning and Design

This literature review contains the most known publications about optimal RPSS dimensioning and design.

In [125], the voltage drops are minimized for investment in catenaries of greater cross-section areas or adding auto transformers to the catenary.

The optimal location of inverters in a DC railway is studied in [126], using an immune algorithm – a relative to the genetic algorithms. The allowed locations of inverters are where there already are rectifiers present. The denser the traffic is, the lesser the need for inverters, because the likeliness of a fellow train to be able to consume the regenerated power of the braking train increase then. The need for inverters are greater on the end of lines, for that reason. The problem is not presented in detail, but conceptually. The future train headways are the measure of the future train traffic. The costs for inverter investments are weighed against the benefit of energy restoration. The paper [126] also has a predecessor in [127].

An early publication regarding DC railways, and the optimal location of inverters, when the rectifier stations are already present is [128]. That paper seems not to use any algorithms, but rather an extensive search for finding the best solution. The objective is to minimize energy consumption. These studies consider the reduced maximal tractive effort due to voltage drops. The results in [128] are based upon detailed simulative studies. One logical but important result in [128] is that the rectifier peak loads increase with increased number of inverters. That is because trains now to consume locally rectified power rather than power regenerated far away.

A simple method for determining substation spacing for DC and AC railways is presented in [66], whose simple models are presented nomographs. The hands-on graphical solutions are not general and systematic but innovative for the time. It is in [66] assumed that train currents are known and fixed, and fixed load problems representing time snap-shots are studied.

One of the earliest publications regarding optimal railway power supply system design is [129], where the appropriate feeder distances are computed and plotted for various traffic performance for both AT catenaries and non-AT catenaries. Similar discussions follow in [130], where comparisons for four 50 Hz and $16\frac{2}{3}$ Hz railways with different catenary feeding types are compared. It seems in [130] that the definition of transmission capacity over catenaries is the amount of power that can be transmitted without causing voltage levels not allowed by the regulations.

In [131] a variational calculus model is presented for the sizing and localization of a super-capacitor in a small-scale light-rail system. The case study considers two trains, one rectifier station, and the super-capacitor station. The authors admit that for larger systems, optimization models must be used. The presented study considers in detail the impact of different time tables and their impact on optimal investments, an important issue to discuss, since in reality time tablers and power suppliers do not always communicate enough. The particular super-capacitor models are detailed in [131]. The capacitor stack is connected to the catenary via a converter controlling the charge/discharge of the stack. The trains on the other hand are simply modeled, current consumption is predetermined with respect to ideal voltage levels. The problem is multi-objective, considering pantograph voltage deviations from nominal, rectifier currents, and super-capacitor currents. The first one regards traffic performance, the second one electricity bills, whereas the third regards capital costs regarding capacitor sizing. It is in [131] concluded that the chosen weights of the multi-objective functional heavily affects the solutions.

In order to speed up the computation times, in [32], genetic algorithms were used to find the optimal number of and location of transformer substations, as well as number, type, and location of catenaries. A maximum voltage drop is defined for the catenaries, and the substation rating may not be exceeded for the static-load situations studied. Electric modeling is simplified. The proposed algorithm is approximative and may result in solutions slightly infeasible to the original problem. Substation prices varies with geographical location due to e.g. various distances to public grid. Paper [32] lacks the mathematical formulation that can be found in [31]. There the electric model simplification is specified as a DC-like model, linearizing the problem, different operational scenarios of loading are studied. The problem is formulated as an MILP.

In [34], the optimal rectifier station locations and their optimal fire angles were determined for a DC railway. This was done using tabu search algorithms, a heuristic optimization method which is approximative and fast. There is a finite set of predefined possible locations for the rectifier stations, the optimization is integrated with a railway power system simulator. Heuristic methods allow constraints that are numerical rather in closed form.

The optimal sizes and locations of harmonic filters for mass rapid transit systems are determined in [132].

An example of optimal planning of traction substations for an MRT system with DC catenaries is presented in [133]. The exact modeling is not exactly presented. Train traffic and its load is precalculated separately in mechanical software. Thereafter voltage levels on catenaries are considered in the way that they should stay within some limits. A worst-case traffic is studied. The headways between trains are the same in each study. The objective is to minimize investment costs without violating ratings of substations or voltage level limits. N-1 criterion is considered for reliability. Substations may only be placed at train stations.

Pareto-optimal railway power system configurations are determined in [33]. Lots of things are optimized: traveling times for every train that possibly can depart, investments in vehicles, conductors, transformer stations, peak power demand, passengers per train seat. The report [33] concludes that faster trains consume more energy and results in reduced vehicle investments since less vehicles will be in traffic for a given headway. Not too much is said about modeling details, but genetic algorithms are used, probably because they do not require closed form expressions of all the constraints and allow simulation software to be used as black-box optimization problem constraints. A subway system is considered. The study considers many details like station platform lengths, maximal train loads as constraints, and the optimization variables seem to include choice of nominal voltage and railway power supply system type, even system frequency is an option, single or doubly fed catenaries, interconnected or separate catenaries for multiple-track lines, overhead contact lines or feeding through rails on the sides, different transformer station types, etc. Some variables are not variable over time, and can only be chosen once and for all like choice of system frequency. Results are plotted in 3D-graphs considering traveling time, energy consumption and investment costs. The studies made are deterministic. In order to reduce the number of pareto-optimal alternatives, additional constraints have been added in the report.

The articles [134, 135] present a novel method of locating PRT (Personal Rapid Transit) power supplies. The load power density in power per length unit of the PRT system is assumed to be known, and thus indirectly assumed to be independent of voltage levels. This allows the system to be divided in sections where the demanded power is equal, making the sections virtually isolated electrically. This can be compared to the sectioning of this thesis, where each supply (feeding point) constitutes a section divider. The objective is to minimize losses. It is necessary to beforehand determine how many supplies are needed. It is shown graphically that the total losses is a convex function of the location of the first supply. The algorithms starts by locating the first of the supplies. Then the placement of the others follows by the definition of equal consumption per supply. After placing all the supplies, the power flows can be calculated, and thereafter the power densities can be updated and now also voltage drops are considered. Then the other supplies can be relocated to the current centroids of each new equal-power section, to start a new iteration step. That iteration continues until also the location of the first supply is optimal with respect to losses. The loads are shared evenly among the supplies.

The main drawback with the [134, 135] solution is that it is not obvious how to generalize the model to a system where supply locations are forbidden or location pricing varies. Moreover, it is not clear how an already existing system should be expanded.

2.4 Optimal Time Tabling & Optimal Train Operation

The term time tabling is here used when the focus is on when a train leaves a place, when it stops at possible stations along the way, and when it arrives. The term train operation is used when the studies focus on how the train acts in every moment when to accelerate, how much, when to cruise, when to coast, etc.

Time Tabling

Generally time tabling is out of the scope of the field of electrical engineering. If however, implementing power-system-induced velocity constraints in problems like the ones in [136–138], or adding costs or constraints representing energy usage they would be interesting also from the power system point-of-view.

A time tabling model that implicitly considers the power system by trying to schedule train departures (implicitly accelerations) to occur simultaneously as train stops (implicitly regenerative brakes) is presented in [139]. Evening out load peaks and regeneration peaks is good for the power supply. Something similar, but less described is done in [140].

There are already commercial software trying to do the above-mentioned connection between time tabling and power system [141–143].

Train Operation

In [36], a differential evolution algorithm is studying multi-objective train operation considering running times, energy consumption, and train jerkiness. Instead of using closed-form models, the problem uses a simulator as a constraint during the iterative process. It is unclear if the power supply is modeled at all.

In [144] train position rather than time is the independent variable. An optimization model for determining the non-inferior surfaces for traveling time against mechanical energy consumption is presented. Train trajectories are determined for individual trains traveling from one point to another. There are some numerical and computational benefits using position as the independent variable. For systems with more than one train however if one wants to incorporate the power system into the model, time has to be independent variable since it has to be known not only where each train consumes power, but also when. This in turn motivates the existence and the development of [4, 5]. If power is consumed from two trains at the same time, the system is far more constrained than if they do it when the other train coasts or brakes regeneratively. So this model functions best for single-train systems as long as the power system will be considered, i.e. losses in lines or reduced tractive effort due to voltage drops. It would however be possible incorporating power system modeling into [144] for single-train situations.

Optimal train movements are studied in [145], where trains can either motor, coast, or brake to stop. Some other models also include cruising. The focus is on energy consumption, punctuality, and comfort. Genetic algorithms are used, the and these are intended to be used in real-time, not considering any preset time plan. Voltage levels are only considered in the way that they cannot be to high in order to allow regeneration. No detailed models are presented.

In [146], and its predecessors [147,148] the traveling times and energy consumptions are minimized by finding the optimal speeds of coasting for a mass rapid transit (MRT) line.

A good motivation why artificial neural networks may be to prefer instead of simulator software when optimizing things can be found in [149]. That paper determined the optimal point for coasting the trains considering the power system. A neural network is trained by simulation outcomes and used as a closed form constraint. Also in [150] neural networks are using simulation data for training. They are later used to estimate voltage levels with respect to control of train speeds and accelerations. The paper is presented more conceptual than accurately.

Chapter 3

Converter usage potential in the railway field

This chapter briefly introduces and summarizes Paper I, an article analyzing the potential in converter usage in AC railway power systems. As the economical drawbacks are reduced in parallel with the prices of semiconductors, the technical benefits become clearer with increased traffic and rural railway electrification.

3.1 Introduction and Background

Paper I is more a literature review than a publication of model development or experimental results. The main conclusions are that there is a potential in using converters more actively in the DC systems and low frequency AC systems that use them today, and that for un-electrified railway systems and public grid frequency systems, the use of converters at all would be beneficial. Railway converter feeding means symmetric loading on the public grid, reduction of peak loads of at least half, reduced catenary voltage drops owing to double-sided feeding, possibilities to feed railways also from weak supplying grids, etcetera.

In order to quantify the exact benefits using converters instead of substation transformers, detailed simulations are needed. Some numerical studies have been made in [151, 152].

Other publications that discusses potential in using controllable converters rather than passive direct transformers or passive converters are [153, 154]. When actively controlling the converters, the dependence on good IT systems has to be considered. is The particular potential in China is treated in [155, 156]. The technical drawbacks with direct transformer feeding are discussed as early as in 1934 [130], and converters were the main mean of feeding railways until after the second world war.

In the postwar era financial resources were often scarce and rectifiers suited for use in traction units were under development [1]. That combined with stronger public grids, made many new-electrified railways use the more economical way of feeding railways through substation transformers.

3.2 Conclusions

From the paper, one can conclude that:

- Converters guarantee symmetrical loads on the public grid
- Converters make possible the feeding of railways from public grids normally too weak for railway power supply, an opportunity for un-electrified railways with great transport demands but where the nearby public grid is weak, e.g. in rural areas
- Converters ease the interconnection and meshing of catenaries, trains are normally fed from two converter substations in converter-fed railways
- Converters can be controlled such that the public-grid loads can be limited comparatively unrelated to the actual catenary section peak loads
- Converters are controllable in ways to minimize losses, improve voltage profiles, etc.
- It is optional if the regenerated power should be fed back to the public grid or not using static converters, whereas regenerated power is unstoppable in transformer-fed railways, and impossible to feed back for DC-railways fed by simple rectifiers.
- Substation transformer have higher reliability than substation converters.

Many of the conclusions are in line with the independently developed paper [157]. One technical benefit with substation transformer usage compared to substation converter usage is that the substation losses are smaller for both no-load, and loading conditions.

3.3 Paper Followup, Additional Comments

The problems related to unbalanced three-phase loads on public grids from single-phase railway grids are documented in [158, 159]. Unbalances in the public grid due to railway feeding always occurs to some extent in substation transformer-fed railways. Such railways are always using the same AC frequency as the public, feeding grid.

Briefly, there are special-transformer solutions [1] that takes the three public grid phases and transform them into two railway phases, feeding two different parts of the railway. These two railway phases need to be separated by neutral sections since they are not in phase with each other. The two railway phases are mathematically linear combinations of the three public grid phases. These two railway phased are feeding two separate but similar catenary sections. The linear weighting of public grid phases are made such that if these two railway sections are equally loaded, the public-grid loading will be perfectly symmetrical. If not, it will still be more symmetrical than feeding each catenary section with altering pairs of public-grid phases.

In East Asia it has been suggested [160] to use the so-called SPC (Static Power Conditioner) to not unbalance the public grid at all, by equaling the two previously mentioned railway phases. SPC can also reduce harmonics and compensate reactively in each of the two catenary sections. The load-equalling is done by DC-connecting two converters back-to-back to each catenary section. Naturally, there is still no guarantee that railway phases from two different transformer substations will be in-phase, so they still need to be separated by a neutral zone. Thus, SPC-fed catenaries will not solve the problem of separated catenaries discussed in [1]. For other types of special transformers feeding the railway, there are other but similar SPC solutions [161].

The catenary interconnection issue is solved together with the symmetrization issue in [157, 162–164], where the transformer and converter topologies are slightly altered compared to the [160] SPC solution and to each other. When making the two catenary sections in phase and possible to interlink, the term *co-phase* is used [157, 163, 164]. Co-phase systems reduce the need for neutral sectioning equipment [163]. In co-phase systems the converter-pair inject active and reactive power between the two railway-grid phases in order to symmetrize the load of the public grid, and at the same time creating catenaries fed from different transformer substations that are in-phase with each other.

The advantage with the co-phase solution compared to real converters are economical since the converters needed are of comparatively low rating, whereas the main drawback is that the substation terminal voltages on the catenary side will not be freely controllable since a substantial share of the power flowing from public grid to railway grid will flow over the substation transformer.

The most technical obvious drawback with separated catenaries are that all the feeding current goes to the load from one source (instead of from two sources), resulting in higher currents, and thereby losses, than in interconnected catenaries. A consequence of interconnected feeding, instead of separated feeding, is that the load variations acting on the feeding public grid will on each load point be smoothed out and its peaks be slightly reduced. Interconnected catenaries also alleviates the use of regenerated energy from braking trains of nearby[1] motoring trains. The number of dead sections are naturally also higher in a separated catenary system, than in an interconnected one.

One drawback of separated catenaries not mentioned in [1] is that eco-driving strategies have to consider the dead sections. Many eco-driving models of today

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[1] geographically near, but far enough to risk being on the wrong side of the dead section separating the two catenary phases

assume perfect catenary voltages so the models will not be valid for electric trains without on-vehicle storage.

In the discussions about the potential of converter usage in China [155,156], and in [1], is it discussed that the interconnection of catenaries may make regenerating trains possible even when the supplying public grid owners ban any regeneration. This does however not mean there cannot exist cases where regeneration to the public grid is desired and useful. In the extreme case of the Ofot railway (the Norwegian part of the Swedish Ore Railway) heavy loaded ore trains are braking regeneratively on their way down to the harbour of Narvik, regenerating significant amounts of power to the local public grid [165] on the 132 kV level.

It should also be noted, that static converters converting 3-phase public-grid-frequency AC to single-phase public-grid-frequency AC already exists – in Japan [166], where the Shinkansen railways use 60 Hz AC traction regardless if the railway is in the 50 Hz part or the 60 Hz part of the country. Thus, in the 50 Hz part of the country, converters have to be used, and in the 60 Hz part of the country transformer feeding is the present solution.

Part II

Railway power systems operations part of the thesis

Chapter 4

Static load models and studies of the RPSS

This chapter discusses the backgrounds for, purposes with, and conclusions of the papers. The topic of Paper II is to propose and study the feasibility and attractiveness of small-scale VSC-HVDC feeding of railways. The topic of Paper III is the exact mathematical and numerical modeling of optimal commitment and power flow of an HVDC-fed RPSS used in Paper II.

Paper II presents the concept with some numerical examples, whereas Paper III presents a simulation tool for static loads.

4.1 Assumptions

A few assumptions have been made in the HVDC-fed static load studies of this thesis.

- The feeding public grid is assumed to be strong enough
- Everything is reliable, equipment always work
- Thermal restrictions in lines and rotary converters are neglected
- Only fundamental frequencies are studied
- Frequencies are maintained constant

4.2 Background and Purpose

Within the doctoral project [167] small-scale converters to be used in locomotives and multiple-unit trains were developed. An idea emerged however that these converters could be used for the RPSS feeding as well. The DC-link between the catenary-to-DC and the DC-to-three-phase converters on the trains will then be

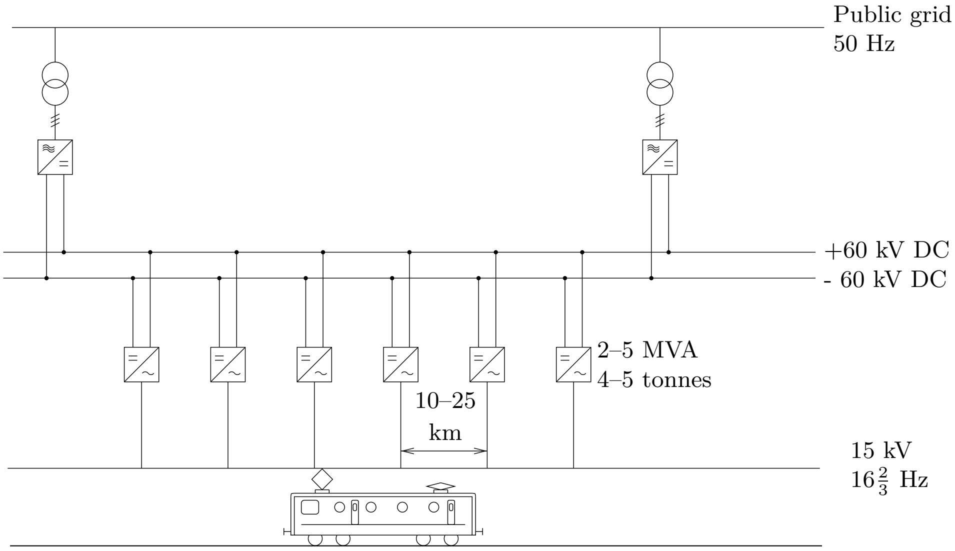

Figure 4.1: Visualization of the proposed solution comprising an HVDC feeder line.

replaced by an HVDC feeding system. This proposed solution is illustrated graphically in Figure 4.1, which can be compared to the existing railway feeding solution in Sweden illustrated graphically in Figure 2.1. The catenary-to-DC converter will then be used for feeding the catenary from that DC system, thus replacing existing rotary or static converters converting three-phase AC into single-phase AC. The last part of the on-train converter, the one converting DC to three-phase-AC for feeding the tractive motor, will then be used for feeding the HVDC grid with power from the public grid. The latter kind of converters are expected to be scaled up and fewer in number compared to the HVDC-to-catenary converters.

What, besides the increased controllability, makes HVDC transmission lines attractive, is that overhead lines claims more land usage. It is difficult to get building permissions for new overhead power lines that require approximately 32 m broad transmission line clearing [168]. That makes transmission line cables attractive. The use of AC in cables might however cause over-voltages due to the reactive power being produced by the capacitances in cables, especially when the power flows are small. When using DC in the cables, the capacitances cause less problems during operation.

In Paper II the concept is presented, and a numerical comparison is made between optimal commitment and power flow of the proposed HVDC system and classical converter feeding of the railway. This is done for four different test systems – of which two comprises regenerating trains combined with motoring ones, and of which two comprises HVAC (High Voltage Alternating Current) feeding transmission lines in the classical converter cases and denser located but less powerful converters in the HVDC cases. The converters station commitment is being done in order to avoid idling losses in the converters, the converter optimal power flow is made in order to minimize transmission and conversion losses. The optimization is made in a unified model where the overall active power losses of the system are minimized. It is implicitly assumed that everything is known about the state of the power system, since the losses minimization does not consider specific measurements or IT system limitations.

Paper III focuses on presenting and explaining the unified optimal commitment and power flow model comprising a unified AC-DC-load-flow as well. Model descriptions are detailed.

The unified AC-DC-load-flow models consider that converter loss functions are different when rectifying compared to when inverting. Also idling losses are considered, wherefore the optimal commitment of catenary-feeding converters is relevant to study in combination with the power flows. All these studies are for static load problems, but can be generalized to moving load problems.

4.3 Conclusions

One can for:

- Paper II conclude that; VSC HVDC feeding of railways using optimal commitment and optimal power flows causes a significant loss reduction compared to existing feeding solutions, especially when:
  - A HVAC (centralized) system does not already exist or is impossible to invest in due to land[1] prices or public opinion
  - Trains are regenerating power
  - The feeding catenary system is weak compared to the system loading
  - The loads and sources are heavy, few, and far from each other – then long distance power transport is taken place in the HVDC line.
- and for Paper III conclude that when; modeling the optimal commitment and unified AC-DC-load-flow, it is important to introduce appropriate variable bounds, initial values, and choices of solver. No model for unified AC-DC power flow combined with unified optimal power flow and optimal commitment of converters have been presented for railway applications before. This was completely new.

The proposed solution is typically beneficial for AC-catenary railways of any kind of frequency (i.e. $16\frac{2}{3}$ Hz, 25 Hz, 50 Hz, or 60 Hz), but would also work for DC railways with buck-converters.

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[1] Cables need less used land than overhead lines.

4.4 Discussion

In the papers presented in this thesis, unit commitment of converters is considered, enforcing the use of binary variable models and thus MINLP formulations.

If already knowing which converters that should be turned on or off, a pure NLP problem would be possible to formulate. Having pure NLP problems for optimal power flow, semi-definite programming models are possible [169]. This in turn would allow the usage of conic models in GAMS [170].

Possible challenges that are subject for future investigations are how the optimal commitment and power flows should be realized in practice. What have to be measured, how to handle disturbed data transfers, and stability issues are yet unsolved.

Chapter 5

Moving load models and studies of the RPSS

This chapter motivates and presents the needs for and benefits with moving-load studies with an all-embracing fixed-node model as presented in Papers IV and V. Detailed moving load studies and models in general are treated in Chapter 2.

5.1 Assumptions

A few assumptions have been made in the moving load RPSS models and studies of this thesis.

- The feeding public grid is assumed to be strong enough
- Everything is reliable, equipment always works
- No transients, but only the slowly changing dynamics naturally caused by train movements are considered. These are modeled as time-dependent and time-consecutive static load flow problems.
- Thermal restrictions in lines and rotary converters are unconsidered
- Only fundamental frequencies are studied
- Frequencies are maintained constant
- Auxiliary power consumption in trains is disregarded

5.2 Motivation and Purpose

There are some well-known problems associated with power system modeling of moving electrical loads for load flow studies in power systems. One of the first to ventilate these was [44]. In [44] also the main differences between public power systems and railway power supply systems are extensively discussed and explained. Typically, the loads are neither fixed power, fixed current, or even fixed location, they vary heavily.

If each moving load is represented by an electric node in the power system, the ordering and numbering of nodes and loads (in this case train vehicles) will soon need detailed bookkeeping algorithms [11,45]. Such bookkeeping will involve: train numbers, train locations, node numbers, which trains are in traffic or not, which nodes coincide and should be merged or not, etc.

In order to keep the admittance matrix element values within reasonable limits, electrical nodes cannot be located too close to one another. If two trains are very close to each other, or if a train is right under a catenary junction or substation of any kind, the admittances might tend to infinity. This can be overcome with an additional bookkeeping, that merges nodes if they come too electrically close to each other [11, 44]. Another option is to introduce minimally allowed impedance values [45]. This bookkeeping obstructs a straight-forward modeling. It should however be noted, that from a strict computational point-of-view, the bookkeeping and updating of matrices between each time step is not a severe problem [44].

Besides the bookkeeping issues for the merging of nodes, the number of nodes in the power system varies also when trains start or stop and run in and out of the studied part of the system. If the number of nodes change between a pair of consecutive time steps, it is untrivial to optimize train operation or power system operation over time. That is because optimization problems cannot change in size during computation, and migrating the book-keeping algorithms into an optimization program without introducing a multitude of binary variables is not doable. Such a model cannot be rejected without investigation, but is however out of the scope of the papers treated in this chapter.

5.3 The Main Idea

The proposed modeling solutions use a fixed number of stationary nodes to represent the RPSS electrically. This alleviates temporal optimization. The idea is to shop up the catenary in discrete segments in order to create a power system with a fixed number of stationary nodes. That idea was first introduced in [44], which model moved the electrical load of each train from its actual position to the most adjacent node.

The core of the here proposed solution is to make the above described bookkeeping unnecessary. The bookkeeping issues are with the proposed solution treated internally and automatically in the optimization model. The models presented in [4, 5] use a linear weighting distribution of the train load to the pair of nodes most adjacent to the train. In turn, the train voltage is computed as the weighted average of the voltages in the two most adjacent nodes to the train.

Another solution to the bookkeeping problem has been proposed in [45], using incidence matrices and graphs. Drawbacks with that proposal are that trains never leave the power system, trains not connected to the system are instead assigned extremely high numerical values on impedances. This results in an undesired wide spread range of impedance magnitudes [44], and might cause computational problems in studies where there are many trains not in service for the moment combined with trains close to each other or to a fixed node. The sizes and locations of the loads are in [45] determined in an external program, and therefore the load flows are (and have to be) solved separately for each time step.

The fixed-node models treated in this chapter and presented in [4, 5] embraces the time dimension, the electrical power system, the mechanics, the tractive load, and the driver strategic part. The main benefits with an all-embracing model are that:

- all electrical nodes are geographically stationary and keep their node numbers all through a simulation
- an all-embracing model can easier be ported to different programming languages or solved as it is put into supercomputers for large-system studies
- including the time dimension into the optimization allows driving optimization and studies of optimal energy storage strategies.

The moving load power supply system problem does also become more synoptical for the developer/user when having everything in one problem instead of many subproblems with node numbers changing from one time to another.

The main idea behind the models is to alleviate the possibility to optimize train movements and converter power flow operation in the time dimension for railway power supply systems with moving loads. Optimization can be done in order to minimize a variety of things. Typical objective function can represent train running times, power system losses, peak power consumption of individual converters, etcetera.

Optimization over time is made possible because of the introduction of a fixed number of, a and fixed location of the electrical nodes in the system. The real train positions are kept track of in a specific variable. The modeling has been facilitated by the application of the special-type variable SOS2 (special ordered sets of type 2) available in the GAMS [171] software package. The power flow equations are nonlinear. The different train traffic states *driving*, *braking*, and *standstill* introduces binary variable usage.

5.4 Discussion

The drawback with the model developed compared to time-consecutive load flow problem with updated power system configurations each time is mainly computation time. Computation times are primarily increased because of another introduced dimension, namely the time.

When not desiring to optimize train or RPSS operation over time, the models can be decomposed into separate static load flow problems. Keeping the fixed-node structure would however still make the bookkeeping simplified, and the models and results surveyable.

Another reason the computation times are increased is that the number of power system nodes grows (and therefore also the number of variables and equations) when the predefined electrical nodes are large to their number, and densely distributed.

Part III

The approximator part of the thesis

Chapter 6

Approximators

The approximators presented in this thesis can be used both for fast calculations of train running times in a railway power supply system and as constraints in optimization problems determining the optimal railway power supply system design. Therefore, they get their own part of the thesis.

This chapter treats Papers VI and VII by introducing them, putting them into context and presenting their motivation of existence. The assumptions being done are also listed.

The denotation Connecting Equipment (CE) is like *feeding point* used as a general name for a component that is supplying the catenary with power.

6.1 Assumptions

A few assumptions have been made in the approximator models and studies of this thesis.

- It is assumed that when studying voltage drop impact on a larger scale, and under normal non-faulty conditions, the power system design and loading on one side of a CE does not significantly affect the voltage levels on the other side of it. This means that the RPSS can be cut up in sections of the same length and size as the distances between each pair of CE.

- Based upon simulation results presented in [11], the installed power of the RPSS plays an insignificant role for the train running times as long as there is no lack of power. Therefore, in this chapter, and in the accompanying papers [6, 7] it is assumed that for studies regarding voltage-drop-related reductions in train running times, the size of the CE can be disregarded and the focus be set on their locations.

- It is assumed that these RPSS sections, independent of each other with respect to design, loading, and voltage-drop-caused lowered tractive performance, can be described well with information of used power system technology and the aggregated figures inter-CE-distance, number of train loads, their speed limits, and aggregated values of the track topography.

6.2 Purpose and Motivation

The main purposes of the approximators treated in this chapter are to aggregate important and relevant information of, and relations between train traffic levels, and the power system capacity. The approximators enables the use of closed-form nonlinear constraints in optimal RPSS design problems. These constraints can, in turn, be further approximated into piecewise linear constraints. For weaker electric railway grids, the maximal average speed as a function of traffic density have a more nonlinear behaviour [6, 7]. Compared to the average train speeds, the running times functions have more linear behaviour [7] which from a future optimal design model point of view is attractive. The main differences between [6] and [7] are that the former is presented in a more general way, and that the latter is based upon more relevant simulations. Moreover, the latter is kept specific enough to suite for small-scale models [8].

In most other RPSS investment problems, a closed-form description model of the connections between operational costs and RPSS configuration is lacking [33–35, 126, 127]. Without closed-form descriptions, classical optimization models cannot be used, and one has to confide to metaheuristic methods.

The models presented in [6, 7] are designed to make a good compromise between accuracy, robustness and computability. The benefits with using aggregated models are that they become less sensitive to disturbances and changes in details that anyway are difficult to predict and of small interest for long-term RPSS dimensioning studies. For instance, disturbances like trains being lumped together and others being left behind or leaving the others behind, within their time frames are not unusual.

The approximators were modeled as artificial neural networks. There was no explicit reason for using that particular type of nonlinear function approximator besides that they are famous for being robust and still flexible if undertrained and having a small enough number of degrees of freedom. They have in [8] proved to be functional for their purpose.

The choice of studying train running times or train velocities instead of catenary voltages are justified by the results in [59], where it was shown to be a low correlation between low "U-mean-useful"[1] values and train delays. The studies in [59] confirm that the problem is too complex for simply using the voltage levels to measure the qualifications for the train traffic. Other influencing factors are for example train running resistance, train weight, track topography, number of train stops, locomotive type(s). The main ideas of [6, 7, 11] are thus confirmed.

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[1] "U-mean-useful" is the the averaged voltage level the standard [88] wants catenary voltage levels to be classified according to.

In [59], some ideas of how to develop better evaluation criteria than "U-mean-useful" [88] for catenary voltage levels are presented. All those ideas are based on detailed RPSS simulations. The articles [6, 7] summarized in this chapter of the thesis instead present approximator models supposed to relieve the user of the from future detailed iterative system studies. The approximator models are based upon simulations done in beforehand. In the articles [6, 7] included in this thesis, the voltage levels are only considered indirectly by the study of traffic levels combined with RPSS design. The articles [6,7] included in this thesis aim to present models that are not stretch-specific, but generalizable to RPSS designs and traffic combinations not studied in detail before.

Railway operators are not interested in voltage levels as such [59], they simply want to know how long time a certain journey will take for a given combination of train sets and a given power system design.

6.3 Discussion

The models could be further verified by randomizing train headways and study how well the approximator works for a given number of trains in the power section compared with with equal train headways cases.

Possible future extensions of approximator models could include a larger number of inputs describing the system such as train masses, train running resistance parameters "A, B, and C" [11, 28, 29, 172], velocity breaking point for the tractive force curve, maximal train tractive force, maximal train tractive power, voltage breaking point in p.u. for reduced tractive effort, possible voltage braking-point for zeroed tractive effort, conductor area instead of only catenary type, number of train accelerations, maximal allowed train speed. All these parameters relate to RPSS power consumption and/or shortest possible train traveling times.

Part IV

The optimal design part of the thesis

Chapter 7

Planning and Investments

In this chapter, paper VIII is treated. This is done by briefly mentioning the modeling assumptions made, motivating the importance and purpose of the paper, and finally a discussion about the model used, numerical and algorithmic impacts as well as a hands-on modeling presentation. Details are available in the paper, this chapter constitutes as a teaser.

7.1 Assumptions

A few assumptions have been made in the studies of the optimal placement of converter models of this thesis. It is assumed:

- that the railway power system can be separated into sections that are not too dependent of each other

- that based upon simulation results presented in [11], the installed power of the RPSS plays an insignificant role for the train running times as long as there is no lack of power. Therefore, in this chapter, and in the accompanying paper [8] it is assumed that for studies regarding voltage-drop-related reductions in train running times, the size of the CE can be disregarded and the focus be set on the CE locations.

- that the most important parameters describing the loading of a given system section are its configuration, length, the number of trains (of given type(s)), and the maximal allowed speed on the section

7.2 Aim of Paper

In [6–8] the focus has been set on finding the best location of RPSS CE considering train running times. In the numerical examples of [8], the CE represent converter stations, and if they had been representing substation transformers, the modeling had to be slightly altered.

The model in Paper VIII, [8], shows the basic idea of the problem and finds for a given number of converter stations and a given train traffic situation, the optimal locations of the CE. The CE sizes do not have to be determined in this problem. The computations are comparatively fast, despite that the problem is formulated as a DNLP which is considered to be a problem type ill-treating the algorithms.

Paper VIII [8] uses the velocity approximator presented [6] is a constraint. Train velocities, in turn, constitutes the major part of the cost functions representing operation costs of the RPSS. The lower the train speeds, the higher the operation costs.

7.3 Modeling Discussion

Some work has been done on DNLP-to-MINLP-conversions of [8], however not yet published. This conversion is an important issue since MINLP models are considered neater and are also accepted for a greater variety of optimization algorithms. Integers will be needed for the future model development, and theoretically MINLP models should always outperform DNLP models if the model is wisely formulated. Such a model will use the velocity approximator of [7].

The model in [8] multiplies the train speed variable with the variable indicating the number of trains in a catenary section for one of the proposed cost functions. This introduces variable bilinearities strongly related to the neural network approximator into the cost function. Instead of using this typically hard bilinear formulation, there are alternatives more attractive from a computational point-of-view. The aggregated results used for approximator development can be re-sampled to create a new approximator incorporating the bilinear variable representing total traveling times in a section as a new variable.

Part V

Conclusion of the Thesis

Chapter 8

Conclusions and Discussion & Future Work

This chapter treats the overall thesis conclusions, general discussions, some model specific and paper specific discussions, as well as future work suggestions.

8.1 Conclusions

There exist a number of publications regarding the RPSS operation, but models and methods used are generally presented very briefly.

In the literature, there are some publications treating the optimal RPSS design. A few of the models are presented in a comprehensible manner. Like in this thesis, the focus is not set on when to make an investment, but rather on where to do the investments.

It is concluded that there is a potential in expanded converter usage and active control of converters in all kinds of railway power supply systems.

In particular, active control of HVDC-fed AC railways has been proposed and studied. The proposed solution resulted in lower losses and improved voltage profiles compared to present-day feeding solutions.

This thesis shows that it is possible to modeling the RPSS in details in operation with moving loads in one single optimization problem with a fixed number of power system nodes.

There are national and international standards about voltage levels in the RPSS [88]. It has however been clearly shown in [59] that these standards are not always followed in practice, and that they are not always the most relevant descriptions of RPSS limitations. Therefore, the approximators presented in this thesis model the train traveling times or speeds, which are interesting for the train operators, rather than the voltage levels which are of less interest.

Closed-form approximations of the relations between train traffic intensities and the design of the RPSS have been determined. These simplified relations have been applied for determining the optimal placement of converters with regard to train running times.

8.2 Discussions & Future Work

Optimal Operation of Converters

The solutions obtained by complete knowledge of the entire system in [3] cannot be directly applied in practice. Current work is being carried out developing static load-flow control rules for the converters voltage and power outputs that approximates the optimal solution. These models will be verified in moving load studies. These rules are based upon inputs from measurable entities.

In future studies, not only power supplying converters could be controlled, but also the on-train converters.

Converter Usage Benefits

Regarding converter usage, numerical simulative experiments are needed to further show on potentials for usage in public-grid-frequency railway power supply systems. It is anticipated that installed power over investments can be reduced, an increased number of connections points will be possible, and a symmetrized public grid will be the results. Moreover, the catenary voltage levels can be controlled in a more elaborate manner using converters. The exact impact should however be concretized numerically.

Approximator discussions and improvement suggestions

The nonlinear approximator used in the planning problem could be replaced with a piecewise multidimensional linear function, either made out of the sampled original function or right from the simulation data. This could be expected to reduce the computational demands of the model without severely reducing the reliability of the results. By using the expected strict monotonicity of the approximative functions, it can be expected that usage of SOS2 variables would speed up the process. Possibly a MILP problem would be designable. It is in [7] visualized why completely linear approximators would not suite generally, and especially not for weak power supplies.

If the approximator functions are not completely monotonous, whereas the original simulations are known to be of that nature, monotonicity constraints could possibly be added to the approximator function when being created.

The artificial neural-networks-based approximators could possibly also be interchanged with for example Chebyshev polynomials, known to be the polynomial approximators that minimize the overshoots and undershoots of the estimation [173].

One drawback with the approximator model presented is that it is based upon the assumption of the independence of power system sections. The validity of that assumption is naturally dependent on the stiffness of the voltage control of the terminal points of the CE. The approximation would theoretically be problematic for some system designs, for example with high loads, quite active converter control and small-scale local converters. The approximation is however expected to hold generally. On the other hand, strong converters controlled actively would reasonably result in power sections which voltage levels would affect each other barely at all.

Future approximators considering the energy demands and peak power loads will probably somehow have to accept power to be consumed not only locally in the catenary section studied, especially for railway grids fed with small and densely distributed converters. On an aggregated level, it would be of interest to be able to predict the limitations in power transports over the catenary.

One additional value with using the approximators is that they give a visual explanation of complicated relations. Such illustrations are manifestable also for non-technical decision makers.

It should also be mentioned that there are not only benefits with choosing not to model voltage levels explicitly. The benefits are obvious, simpler computation, abstracted models, and getting rid of the problem of rating impact of a particular voltage drop. Drawbacks are that voltage levels are concrete and communicable to everyone and that needed assumptions like power section independence will not be needed.

To use an approximator, instead of, like [31,32] study voltage levels in simplified grids have two main benefits and two main drawbacks.

- Benefits
    - It is hard assign a utility or a cost to a certain voltage level [59], without making a complete exhaustive study of traveling times
    - Even with singly fed grids and DC-models for AC grids, the voltage level studies demands burdensome computations
- Drawbacks
    - Concrete measured values, could be expected to easier get acceptance by people working in the field
    - It does not matter if the grid is meshed or not, or if it is strong or not, since the sectioning assumption is no longer needed.

The inclination average values of [6] could be weighted with a value above 1 when far from a feeding point, and oppositely, below 1 close to a feeding point. For power consumption, the location of the slopes matters probably less.

Investment model discussions and improvements

Investment costs in converter stations would preferably in the future be modeled to differ with location. This is due to various ground conditions, but also due to different costs of connecting converters to supplying public grid depending on distances and possible nature preservation areas.

When studying the amounts of installed apparent power capacities in the converter stations, the model needs to consider the economies of scale for building a big station, or expanding an existing one.

Future models should include more investment alternatives:

- Different contact line types and standards
- Different feeding lines – HVAC and HVDC
- In case of HVAC, transformer investments
- SVC instead of converter if connection to public grid is too expensive? In DC grids SVC will not be possible, then some kind of energy storage might be attractive.
- Retirements; moving, interchanging, or selling existing equipment.

General optimization issues

A general issue regards accuracy. It is normally not motivated to theoretically enforce global optimums. But sometimes solutions may be produced that are not bad, but still obviously not the global optimum. Should one be satisfied with something that probably is close to, but not the real optimum?

Sometimes, even though the numerical precision of the computers of today are comparatively high, the scaling of numerical problems have an impact on accuracy and convergency rates. Future studies could contain the impact of scaling the jacobians and hessians [174,175] of the optimizations problems by scaling variables and equations. Scaling can however be further generalized [176, 177], and for example consider translation of variables so that they fluctuate around unity rather around a very big positive or negative number. Scaling can improve computational times as well as the ability of the algorithms to find the right optimum.

Uncertainties

Future models could consider uncertainties in future prices and budgets, as well as future traffic levels. Even the future sensitivities to voltage drops are not completely known, but can be expected to increase due to stricter regulations.

In the further horizon, also investment-induced uncertainties might be of interest. An improved power system might make a denser traffic more attractive and likely. It must however be made sure that the optimal solution not strives for weak power systems just not to have to bear with increased traffic energy costs.

Ventured Idea

It would be interesting to implement the approximators developed as non-constant speed limits for time tabling problems. It is however unclear how complicated that would be from an algorithmic point of view.

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Part VI

The publications part of the Thesis

Paper I

Use of Converters for Feeding of AC Railways for All Frequencies

Paper II

HVDC Feeder Solution for Electric Railways

Paper III

Optimal Power Flow (OPF) Model with Unified AC-DC Load Flow and Optimal Commitment for an AC-catenary Railway Power Supply System (RPSS) fed by a High Voltage DC (HVDC) transmission line

Paper IV

An SOS2-based moving trains, fixed nodes, railway power system simulator

Paper V

An electromechanical moving load fixed node position and fixed node number railway power supply systems optimization model

Paper VI

Fast Estimation of Relations between Aggregated Train Power System Data and Traffic Performance

Paper VII

Traction Power System Capacity Limitations at Various Traffic Levels

Paper VIII

Railway Power Supply Investment Decisions Considering the Voltage Drops - Assuming the Future Traffic to Be Known