Coordinated Control of HVDC Links in Transmission Systems

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Abstract

Dynamic security limits the power transfer capacity between regions and therefore has an economic impact. The power modulation control of high-voltage direct current (HVDC) links can improve the dynamic security of the power system. Having several HVDC links in a system creates the opportunity to coordinate such control, and coordination also ensures that negative interactions do not occur among the controllable devices.

This thesis aims to increase dynamic security by coordinating HVDC links, as an alternative to decreasing the transfer capacity. This thesis contributes four control approaches for increasing the dynamic stability, based on feedforward control, adaptive control, optimal control, and exact-feedback linearization control. Depending on the available measurements, dynamic system model, and system topology, one of the developed methods can be applied. The wide-area measurement system provides the central controller with real-time data and sends control signals to the HVDC links.

The feedforward controller applies rapid power dispatch, and the strategy used here is to link the N-1 criterion between two systems. The adaptive controller uses the modal analysis approach; based on forecasted load paths, the controller gains are adaptively adjusted to maximize the damping in the system. The optimal controller is designed based on an estimated reduced-order model; system identification develops the model based on the system response. The exact-feedback linearization approach uses a pre-feedback loop to cancel the nonlinearities; a stabilizing controller is designed for the remaining linear system.

The conclusion is that coordinating the HVDC links improves the dynamic stability, which makes it possible to increase the transfer capacity. This conclusion is also supported by simulations of each control approach.

Keywords: Coordinated control, dynamic security, exact-feedback linearization, feedforward control, HVDC power modulation, LCC HVDC, LQG control, power oscillation damping, power system stability, small-signal stability, system identification, transient stability, VSC HVDC.
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Dissertation

Paper I

Paper II
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Paper VI

Paper VII

In addition to this the following publications have also been published [1–7].
Division of work between authors

Paper I
D. Van Hertem and R. Eriksson formulated the outline and jointly wrote the article. D. Van Hertem focused on the phase-shifting transformer and R. Eriksson on the HVDC link. L. Söder and M. Ghandhari contributed discussions on the content.

Paper II
M. Perninge and R. Eriksson formulated the outline and jointly wrote the article under the supervision of L. Söder. M. Perninge contributed a model for forecasting load paths and R. Eriksson contributed the HVDC modulation control. The problem formulation and its solution were jointly and equally performed by M. Perninge and R. Eriksson.

Papers III, IV, V, and VII
R. Eriksson formulated the outlines, and researched and wrote these papers under the supervision of L. Söder.

Paper VI
R. Eriksson formulated the outline, and researched and wrote this paper under the supervision of V. Knazkins and L. Söder.
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Chapter 1

Introduction

This chapter provides a concise background to the topics covered in this thesis, and defines the aim and main contributions of this work.

1.1 Background

The number of controllable devices in today’s power systems is increasing rapidly. Controllable devices, such as high-voltage direct current (HVDC) links and flexible AC transmission system (FACTS) devices, have been recognized as being of key importance for satisfactory operation of future power systems [8]. The main function of HVDC links is bulk power transfer over long distances. Besides being efficient at this main function, i.e., bulk power transmission, HVDC links possess controllability that can be used to make various stability enhancements [9-11]. FACTS devices can also be used to enhance system stability [12].

As of February 2011, seven HVDC links are in operation between Scandinavia (Nordel) and continental Europe, as shown in Figure 1.1. These form a meshed system of HVDC links between these zones. Having full power flow controllability, these links determine the power exchange between the synchronous zones [13] and are the places in the grid where this power is exchanged. As HVDC link installations usually directly connect two zones, their operation is dependent on the two zones.

Coordination between controllable devices exists to only a limited extent today [14], especially between devices located in different zones and controlled by different operators. As more devices are installed, coordinated strategies must be incorporated into the controller design [15]. If the controllable devices are not coordinated, then negative interactions may occur among the steady-state and electromechanical damping controllers [15].

One question, then, is how a possible stability problem in one of the AC systems can be dealt with when the HVDC links of this system are used to help another AC system. It is unacceptable to prevent instability in one system if the consequence
Figure 1.1: Installed HVDC links between Scandinavia and continental Europe.

is instability in the other.

Power system stability must be maintained even when the system is subject to severe, low-probability disturbances, so that the electricity can be supplied to consumers with a high reliability. Power system stability includes transient and small-signal stability and limits its transfer capacity. An obvious way to improve the stability margin is to transfer less power through the corridors. However, a more constructive way to improve system stability is to take advantage of the controllability provided by the controllable devices [16]. Power systems are subject to highly nonlinear dynamics and operate in a constantly changing environment, so controlling the system is challenging.

The allowed power transfer capacity is often based on a security criterion, such as the N-1 criterion. Transmission limits in meshed AC transmission systems are set so that dimensioning faults do not lead to cascading failures elsewhere in the system. If a contingency occurs, is it possible to control the controllable devices in such a way that two main objectives can be achieved? These objectives are that the system remain stable after the contingency, and the transients induced by the fault be quickly damped, bringing the system to a new acceptable equilibrium point.

1.2 Aim of the work

This thesis research was performed as part of the Swedish research program Center of Excellence in Electrical Power Engineering (EKC²) within the Controllable Power Systems research group. The project is entitled “Security-centered coordinated control for efficient use of AC-DC controllable transmission systems.” The main aim of this project was to look at the possibilities and benefits offered by
1.3 MAIN CONTRIBUTIONS

coordinated control of the HVDC links, to handle stability problems as an alternative to decreasing the transfer capacity. The main focus is on controlling the active power of the HVDC links. Transfer capacity is directly related to stability, so enhancing the rotor angle stability is emphasized. The stability issues examined here concern convergence to a stable and acceptable equilibrium point, to keep generators synchronized.

A system’s transfer capacity is limited by the transmission line thermal limit, voltage stability limit, and rotor angle stability limit (i.e., transient and small-signal stability).

1.3 Main contributions

The main contributions of this thesis are in model development, coordinated control of multiple HVDC links, and demonstrating the advantages of the developed methods. Specifically, the main contributions are as follows:

- Control strategies for HVDC links are reviewed.
  - This thesis reviews the control strategies for controllable components with a focus on line-commutated converter (LCC) HVDC technology.
    
    Presented in Chapter 2.

- The advantages of developing basic HVDC link control coordination are demonstrated.
  - Feedforward control combined with feedback lead-lag compensation are developed for power oscillation damping and transient stability assessment.
  - An adaptive coordinated linear controller is developed based on forecasted load paths to increase transfer capacity.

    Presented in Chapter 3 and Papers I and II.

- Wide-area measurement system coordinated control based on system identification.
  - Reduced-order linear multiple-input multiple-output (MIMO) models are developed based on system identification using wide-area measurement system signals.
  - An optimal power oscillation damping controller is developed for multiple HVDC links.
  - The influence of time delay and measurement noise on the control effect is investigated; the robustness of system changes is also investigated.
  - Significant damping improvement and advantages compared with local signal control are demonstrated.

    Presented in Chapter 4 and Papers III, IV, and V.
CHAPTER 1. INTRODUCTION

- Nonlinear control: exact-feedback linearizing coordinated control.
  - A nonlinear exact-feedback linearizing coordinated controller is developed for multiple HVDC links.
  - The robustness of the controller is investigated in the face of system parameter deviations.

  Presented in Chapter 5 and Papers VI and VII.

- The developed coordinated control strategies are applied to different test power systems. It is demonstrated that by using coordinated control
  - the dynamic security can be improved

  Presented in Papers I, II, III, V, VI, and VII.

  - the transfer capacity can be increased

  Presented in Papers I, II, V, VI, and VII.

1.4 Rationale for coordinated control

Control of HVDC links in power systems offers the opportunity to improve system properties; coordination of control yields still further improvement.

1.4.1 Main objectives

In this thesis, improvements of system properties refer to the following main objectives:

Increased transfer capacity

Improved dynamic security

These main objectives exert an important economic impact on the electricity market. The transfer capacity may be limited by the dynamic security. In a liberalized electricity market, transfer capacity represents economic value. One would prefer to allow the system operator to use cheaper production units as much as possible to keep the electricity price low.

This thesis mainly looks at rotor angle stability, i.e., small-signal and transient stability, since it is directly related to the main objectives.

1.4.2 Available information

Designing a controller calls for information about the system in the form of a dynamic system model and measurement signals. Depending on this input, one may then consider appropriate control methods.
1.4. RATIONALE FOR COORDINATED CONTROL

1.4.3 Basic power systems

Figure 1.2 shows two general power systems. System A consists of two asynchronous systems interconnected by HVDC links. System B consists of one synchronized system including installed HVDC links. The focus of this thesis is on the controller design for the HVDC links in these types of systems.

The control signals are the active power or DC current setpoints of the HVDC links. In the case of voltage source converter (VSC) HVDC, the reactive power may also serve as a control signal.

![Diagram of interconnected asynchronous systems, System A vs synchronous system, System B]

Figure 1.2: Two types of general power systems with HVDC links installations.

1.4.4 Assumptions for the developed controllers

The present research develops four controllers, namely, feedforward, adaptive, optimal, and exact-feedback linearization controllers. Depending on the control approach, various assumptions are made as to the availability of the dynamic system model and measurement signals.

Feedforward control is used in combination with feedback control. The following information is assumed to be available:

- Knowledge of system behavior if a line is tripped
- System data for the lead–lag block design
• Frequency measurements at the HVDC connecting buses
• Information from the relays on whether a line is tripped

This controller focuses on increasing the transfer capacity by linking the N-1 criterion between two systems using rapid power dispatch. The controller is developed for interconnected asynchronous systems (System A shown in Figure 1.2). The system improves both the small-signal and transient stability.

Adaptive control is used to enhance the transfer capacity by adaptively changing the controller gains. The following information is assumed to be available:

• Linear model of the power system
• Load paths
• Frequency measurements at some buses

This controller adaptively changes the controller gains to maximize the damping in the system based on forecasted load paths. This controller is designed for synchronous systems and improves the small-signal stability.

Optimal damping control is designed based on the estimated linear model. The model is estimated from the measured signals provided by the wide-area measurement system. The following information is assumed to be available:

• Speed measurements from selected generators

This controller improves the small-signal stability. This controller is designed for synchronous systems.

Exact-feedback linearization uses the nonlinear model description and algebraically cancels the nonlinearities using a pre-feedback loop. The following information is assumed to be available:

• Measurements or estimates of the state variables
• All system data

This controller is applicable to synchronous and interconnected asynchronous systems. This controller can improve both the small-signal and transient stability.

1.4.5 Reasoning favoring different control methods

The feedforward-based controller shows that coordinating the HVDC links is of value.

The adaptive controller improves the system damping. The system parameters must be known to be able use this control method; when using the model identification, no system parameter values are needed. However, when using a linear model
of the system, as in the two latter control methods, it is impossible to ensure transient stability. Using exact-feedback linearization improves both the small-signal and transient stability; the drawback is that more system data, parameters, and measurements/estimates are needed.

1.5 Outline of the thesis

The chapters of the thesis are organized as follows:

Chapter 2 provides background information on power system stability and security; existing strategies for HVDC link control are reviewed.

Chapter 3 discusses basic coordinated control and demonstrates that coordination is of value.

Chapter 4 describes the use of system identification to model the power system using a reduced-order model. The development of a central controller based on this model is also examined.

Chapter 5 describes a coordinated nonlinear exact-feedback linearization controller. This controller can stabilize the system in the face of both small and large disturbances, under various operating conditions.

Chapter 6 highlights the key conclusions of the thesis and summarizes ideas for future research work.
Chapter 2

Background

This chapter provides background information on power system stability, security, and modeling; in addition, HVDC control strategies are reviewed.

2.1 Why HVDC?

HVDC transmission is generally used for economic reasons. Some advantages are as follows:

- It can be cheaper to build HVDC overhead lines than AC lines per length for the same transmission capacity. However, the converter stations at the ends of HVDC lines are more costly than the substations of AC transmission lines. There is a breakeven distance at which the costs of HVDC and AC transmission converge. The breakeven distance is typically approximately 600-800 km for overhead lines and is much shorter for submarine cables, typically approximately 50 km [17,18].

- HVDC transmission has other advantages over AC, such as lower environmental impact and other types of electric and magnetic fields compared to AC.

- A back-to-back station is a plant in which both inverters and rectifiers are located in the same area, usually in the same building. A back-to-back station interconnects systems of different frequencies or systems of the same nominal frequency but no fixed-phase relationship (asynchronous systems).

- High controllability is another reason why HVDC is chosen instead of AC transmission.

Line-commutated converter (LCC) HVDC links can quickly control the active power passing through them. Voltage source converter (VSC) HVDC links can also control the reactive power at the connected buses, independently of each other and...
of active power. In the LCC HVDC link, the reactive power is not fully controllable. The converters consume reactive power nearly proportionally to the active power [19]. The high consumption of reactive power and the harmonic filter requirement are two disadvantages of LCC HVDC transmission compared with AC. Most installed HVDC capacity today is LCC HVDC, since it has higher transmission capacity than the VSC HVDC technology [18].

2.2 Power system stability

The stability of a power system, like the stability of any dynamic system, is crucial. It is important to distinguish between power system stability and the stability of an operating point in a power system. The stability of an equilibrium (operating) point relates to its response to inputs or disturbances.

The stability of an operating point is defined as follows: “An equilibrium set of a power system is stable if, when the initial state is in the given starting set, the system motion converges to the equilibrium set, and operating constraints are satisfied for all relevant variables along the entire trajectory” [20].

The stability of power systems is defined as follows: “The ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact” [21].

The stability margin of a stable power system is then defined as the margin between the actual operating point and the stability limit of the power system.

The definition of security is defined as follows: “Security of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances” [21].

Security and stability are closely related, but differ in the consequences resulting from a disturbance. For example, two systems may both be stable with equal stability margins, but one may be relatively more secure because the consequences of instability are less severe. It should be noted that, to be secure, the system must not only be stable but also be secure against other contingencies that would not be classified as stability problems [21]. The consequences of instability are not further analyzed here, meaning that stability and security can be regarded as equivalent. The stability issues treated here concern convergence to a stable and acceptable equilibrium point keeping generators synchronized.

Security assessment in power systems consists of two important parts, namely, static and dynamic security analysis [21], as follows:

- Dynamic security analysis – A number of contingencies are simulated to determine the secure system operating region from the viewpoint of the system’s dynamics. All categories of system stability must be analyzed. This implies
that, to be able to analyze static security, the system must survive the disturbance and settle at a new acceptable equilibrium.

- Static security analysis – The post-disturbance system, in which the power system is in a steady state, must be analyzed so that no equipment ratings and voltage constraints are violated.

Ideally, the security margin of the point of operation should be determined and monitored on-line but, due to the size and complexity of today’s power systems, the margin is often either not determined at all or determined using very simplified system models. Instead, various security criteria are used to ensure that the security margins are sufficient. One such criterion is the N-1 criterion, which was introduced after the 1965 blackout in northeast USA and Ontario, Canada [22]. In a power system, it is impossible to eliminate all faults and failures, so a power system can never be 100% secure. It is always possible, though hopefully not very probable, that a sequence of events may lead to power system instability. If a power system is operating at its stability limit, the system has zero stability margin. Any disturbance or change in its condition, such as the outage of a component or a small increase in load, will then result in an unstable system.

Power system stability can be divided into three types, namely, rotor angle, frequency, and voltage stability [21]; an overview of this classification is shown in Figure 2.1.

![Figure 2.1: Classification of power system stability.](image)

### 2.2.1 N-1 criterion

The N-1 criterion states that a power system must be operated at all times such that, after the unplanned loss of an important generator or transmission facility, it will still remain stable. According to Nordel, the “N-1 criteria are a way of
expressing a level of system security entailing that a power system can withstand the loss of an individual principal component (production unit, line, transformer, bus bar, consumption etc.)” [13]. The N-1 criterion is applied in both the Nordel and UCTE systems [23].

2.2.2 Transfer capacity

The North American Electric Reliability Council (NERC) uses the word “capability” instead of “capacity” as used by European Network of Transmission System Operators for Electricity (ENTSO-E) [24]. Throughout this thesis, the word “capacity” is used.

NERC defines transfer capability as follows: “Transfer capability is the measure of the ability of interconnected electric systems to reliably move or transfer power from one area to another over all transmission lines (or paths) between those areas under specified system conditions” [25].

The ability of interconnected transmission networks to reliably transfer electric power may be limited by the physical and electrical characteristics of the systems, including any one or more of the following:

Thermal Limits – Thermal limits establish the maximum amount of electrical current that a transmission line or electrical facility can conduct over a specified time period before it sustains permanent damage by overheating or before it violates public safety regulations [25].

Voltage Limits – System voltages and changes in voltages must be maintained within the range of acceptable minimum and maximum limits. For example, minimum voltage limits can establish the maximum amount of electric power that can be transferred without causing damage to the electric system or customer facilities. A widespread collapse of system voltage can result in a blackout of all or portions of the interconnected network [25].

Stability Limits – The transmission network must be capable of surviving disturbances through the transient and dynamic time periods (ranging from milliseconds to several minutes, respectively) following the disturbance. Immediately following a system disturbance, generators begin to oscillate relative to each other, causing fluctuations in system frequency, line loadings, and system voltages. For the system to remain stable, the oscillations must diminish as the electric systems attain a new, stable operating point. If a new, stable operating point is not quickly established, the generators will likely fall out of synchronization with one another, and all or part of the interconnected electric system may become unstable. The results of generator instability may damage equipment and cause uncontrolled, widespread interruption of electric supply to customers [25].
2.3 INTRODUCTION TO CONTROL

The transfer capacity is then determined by whichever of the thermal, voltage, or stability limits is lowest.

The test systems described in this thesis do not have thermal limits as the limiting factor. In general, many contingencies must be considered when determining the transfer capacity. This thesis demonstrates that it is possible to stabilize the system at higher power transfer levels under some contingencies, using coordinated control versus no control or conventional control. In reality, one must check all the dimensioning faults that establish the actual transfer capacity.

These contingencies need to be tested at higher power transfer levels using the proposed controller. This determines how much the transfer capacity can be increased.

2.3 Introduction to control

There are three types of control systems: open-loop, feedforward, and feedback. An open-loop controller characteristically does not use feedback to determine whether its output has achieved the desired goal based on the input. This means that the system does not observe the output of the processes that it is controlling. Control is usually based on feedback control, which is error-driven control [26]. A possible problem with feedback is that it does not permit adjustment of the control variable before the control error differs from zero, since the control variable is adjusted as a function of the control error. Improvements can be made by combining this control method with feedforward control. In feedforward control, the input signal is coupled to the control variable and the control variable adjustment is not error based, but is instead based on knowledge of the system once a certain disturbance occurs.

Many well-established analysis and design techniques exist for linear time-invariant systems. However, these methods cannot necessarily be applied directly to nonlinear systems. Nonlinear control theory usually requires additional mathematical analysis to justify its conclusions.

The power system can be described by a set of nonlinear differential equations. To look at small-signal stability, only a linearized model of the power system is needed [27]. Such a model is valid for small changes around its operating point but, as the changes become larger, the model becomes less accurate. To look at transient stability issues, nonlinear dynamics must also be considered; the control of nonlinear systems is more complicated than that of linear systems.

2.4 Controllable devices

Power electronic equipment, in the form of HVDC links and FACTS devices, has been recognized as key to the satisfactory operation of power systems in the future [8]. Modern interconnected electric power systems are characterized by large dimensions, highly structured complexity, and dynamic phenomena associated with
power system operation and control. Power system deregulation has taken place in many countries worldwide, driving many networks to the high utilization of existing infrastructure. In some cases, this has led to a reduced stability margin, as the power systems became more stressed \cite{28,29}. Under these circumstances, it becomes important to seek new possibilities, such as better utilization of controllable devices, for enhancing power system stability. Coordination may improve power system stability and utilizes the controllable devices in a better way.

The Cigre Working Group emphasizes the importance of coordinating FACTS devices and HVDC links, as stated in their report number 14.29 \cite{15}: “It is also feasible but as yet not applied, to have a central controller with real-time sensing of the general condition of the AC system from remote corners of the network. When conditions of concern are detected, centralized, intelligent decision making can direct signals to each DC link to regulate its power so that satisfactory operation of the AC system is maintained.”

This thesis formulates ideas concerning central control using real-time sensing to enhance the rotor angle and voltage stability.

2.5 Power system modeling

Power systems consist of several components that must be modeled appropriately. In analyzing a power system, the models should be kept as simple as possible, while still capturing the important dynamics. Depending on the application, various models can be used. Lines are modeled using the II-model, while transformers are modeled as constant impedances and are not further described here (more information about these components can be found in \cite{27}).

A generator can be modeled at various levels. This thesis uses the one-axis and classical models. The one-axis model of a generator with an automatic voltage regulator (AVR) connected as in Figure 2.2 is described by the following equations:

\[
\begin{align*}
\dot{\delta} & = \omega \\
\dot{\omega} & = \frac{1}{M}(P_m - \frac{E'_{q}}{x_d}U \sin(\delta - \theta) - D\omega) \\
\dot{E}'_{q} & = \frac{1}{T_{do}} \left( E_f - \frac{x_d}{x'_d}E'_{q} + \frac{x_d - x'_d}{x_d}U \cos(\delta - \theta) \right) \\
\dot{E}_f & = \frac{1}{T_c} (-E_f - K_A(U_{ref} - U))
\end{align*}
\]  

where

\(\delta\) is the rotor angle,
\(\omega\) is the rotor speed deviation from synchronous speed,
\(E'_{q} \angle \delta\) and \(U \angle \theta\) are the voltage phasors at the internal and terminal buses,
\(T_{do}\) is the \(d\)-axis transient open-circuit time constant,
2.5. POWER SYSTEM MODELING

$P_m$ is the mechanical power applied to the generator shaft,
$D$ is the generators’ shaft damping constant,
$M$ is the generators’ inertia,
$x_d$ is the $d$-axis synchronous reactance,
$x'_d$ is the $d$-axis transient reactance,
$E_f$ is the generator field voltage,
$U_{ref}$ is the set value of the connecting terminal bus voltage,
$K_A$ is the AVR gain, and
$T_e$ is the exciter time constant.

\[
\begin{align*}
U \angle \theta & \quad \text{Power system} \\
\text{Transformer} & \\
G & \\
\end{align*}
\]

Figure 2.2: Generator connected to a power system via a transformer.

The classical model is created by modeling the generator using only Equations (2.1a) and (2.1b). Equation (2.1d) describes the first-order AVR.

A common model for loads is the so-called ZIP model (i.e., $Z =$ impedance, $I =$ current, and $P =$ power) and also to include a frequency dependence. The load characteristics are modeled as follows:

\[
\begin{align*}
P_L &= P_0 + P_1 U + P_2 U^2 + P_f \dot{\theta}, \\
Q_L &= Q_0 + Q_1 U + Q_2 U^2 + Q_f \dot{\theta}.
\end{align*}
\]

where

$P_0$ and $Q_0$ are the constant power coefficients,
$P_1$ and $Q_1$ are the constant current coefficients,
$P_2$ and $Q_2$ are the constant impedance coefficients,
$P_f$ and $Q_f$ are the frequency dependent coefficients, and
$U \angle \theta$ is the voltage phasor at the connected bus.

Simulations in the integrated power system tool in PowerFactory use detailed modeled components. The AVR in PowerFactory, a lead-lag block is also added, which forms a second-order AVR. The HVDC link modeling is briefly described in Section 2.6 and more details concerning these and other models can be found in the technical references [30].

2.5.1 System linearization

Low damping is a stability problem in power systems that can be greatly ameliorated by controlling the HVDC links. To study this issue, a linearized model of the
power system is sufficient [27]. By linearizing the nonlinear differential equations around the operational point, a linear MIMO model can be created, using the controllable setpoint of the HVDC link as the input. The nonlinear system model is described by:

\[ \begin{align*}
\dot{x} &= f(x, y, u) \\
0 &= g(x, y, u).
\end{align*} \tag{2.3a,b} \]

Here the function \( f \) represents the system dynamics, \( g \) the power mismatch function including the HVDC links, and \( x \) the vector containing the dynamic variables, i.e.,

\[ x = (\delta^T \omega^T E_q^T E_f^T P_m^T)^T. \]

Vector \( y \) contains all the variables not directly governed by any differential equations, namely, the voltage magnitude \( U \) and angle \( \theta \) in each node. The control variables are included in vector \( u \) where \( u = (P_{HVDC}^T)^T \) or \( u = (I_{HVDC}^T)^T. \) If the HVDC links are modeled with dynamics states for this should be included in \( x. \)

In the small-signal stability analysis, (2.3) is linearized at its present operational point and the higher-order terms are neglected. The linearization gives the following structure:

\[ \begin{align*}
\Delta \dot{x} &= f_x \Delta x + f_y \Delta y + f_u \Delta u \\
0 &= g_x \Delta x + g_y \Delta y + g_u \Delta u
\end{align*} \Rightarrow \tag{2.4} \]

\[ \Delta \dot{x} = (f_x - f_y g_y^{-1} g_x) \Delta x + (f_u - f_y g_y^{-1} g_u) \Delta u = J_x \Delta x + J_u \Delta u \tag{2.5} \]

\( f_x, f_y, f_u, g_x, g_y, \) and \( g_u \) are the partial derivatives of \( f \) and \( g \) with respect to \( x, y, \) and \( u, \) respectively. The prefix \( \Delta \) indicates a small increment in corresponding variables.

### 2.5.2 Stability

Lyapunov’s first stability method is the analytical basis of small-signal stability assessment in power systems [27]. It is based on eigenvalue analysis and provides valuable information on system behavior, i.e., the time domain characteristics of a system mode. Each eigenvalue \( \lambda \) is commonly associated with a system mode. Real eigenvalues represent non-oscillatory modes, a negative one corresponding to a decaying mode and a positive one relating to aperiodic instability. Complex eigenvalues are associated with system oscillatory modes; a pair of complex eigenvalues with negative real parts indicates decreasing oscillatory behavior, while a pair with positive real parts indicates increasing oscillatory behavior. The damping of the \( i \)th mode is defined as follows:

\[ \xi_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \tag{2.6} \]
2.6  POWER SYSTEM MODELING IN POWERFACTORY DIGSILENT

where
\[ \sigma_i = \Re(\lambda_i) \]
\[ \omega_i = \Im(\lambda_i) \]

By controlling the HVDC links and thereby affecting the modes i.e., move the eigenvalues in the complex plane, it is possible to change the behavior of the system. The controllable subspace provides information on how the eigenvalues can be moved, i.e., how the system can be controlled.

2.6  Power system modeling in PowerFactory DIGSILENT

The PowerFactory simulation program, as produced by DIGSILENT, is a computer-aided engineering tool for analyzing industrial, utility, and commercial electrical power systems. Its models of synchronous generators, loads, etc., are not described here; more information can be found in the technical references provided by DIGSILENT [30]. Its models of the LCC and VSC HVDC links and their control systems are briefly described below. The HVDC models in PowerFactory differ from the models used for the control development based on adaptive control (linearization) and exact feedback linearization. The following HVDC models are used in the simulations in PowerFactory.

2.6.1  LCC HVDC

The model of the LCC HVDC link consists of the following components, 12-pulse thyristor converters, cable, transformers, and harmonic filters. A detailed description of these components can be found in the technical references [30].

The firing angle, alpha \( \alpha \), is controlled in each converter, giving the ability to control the current (i.e., power) from one end to the other. The rectifier usually controls the current. The firing angle is controlled using the difference between the actual and setpoint values of the current in a PI controller. The inverter usually controls the gamma, \( \gamma \), angle to a minimum value pre-set by a PI controller. The DC voltage/current characteristics of the rectifier and inverter are displayed in Figure 2.3.

2.6.2  VSC HVDC

The model of the VSC HVDC link consists of the following components, pulse width modulation (PWM) converters, capacitors, cables, and transformers, as described in [30]. A detailed description of these components can be found in the technical references [30].

The converter controller is divided into two parts. The first controls either the active power or DC voltage and either the reactive power or AC voltage. The output of this first PI controller is the reference value in the d-q reference frame. The rectifier usually controls the active power while the inverter controls the DC
Figure 2.3: Rectifier and inverter voltage/current characteristics.

voltage; then each converter controls either the reactive power or AC voltage as well. An overview of the converter controller is depicted in Figure 2.4.

Figure 2.4: Overview of the PWM converter controller.
2.7 Review of control strategies

Previous research into control strategies for HVDC links can be divided into two main groups: control strategy research into one controllable component and coordinated control research into multiple controllable components.

Many research papers have examined damping and transient improvement for a single controllable component. A main focus has been on investigating power modulation control for the damping of oscillation modes (see, e.g., [11, 16]).

Many control strategies have been developed for an AC line and HVDC link in parallel. These strategies share the use of a modal analysis approach, using the frequency deviation or angle difference between the connected buses or the power change along the parallel AC line as inputs [31, 32]. A control strategy is then derived based on the application of lead-lag filters, for example, to achieve the correct phase margin and gain. The way to determine the control parameters of the lead-lag filter is to calculate the transfer function of the system from the input to the output, for example:

\[
G(s) = \frac{\Delta \delta(s)}{\Delta P(s)}
\]

(2.7)

The same technique as was used for tuning power system stabilizers (PSSs) with lead-lag filters can then be applied [11, 16]. Other methods have also been applied, for example, optimization techniques such as \( H_{\infty} \) [33].

Several research papers have considered energy functions, for example, [19, 34]. They share the same idea: using the energy function of the system and deriving a controllable energy function for the controllable HVDC link. By deriving a control strategy that fulfills the criterion in the Lyapunov direct method sense, it can be demonstrated that the system gets greater domain of attraction around the equilibrium point i.e., improved transient and small-signal stability. However, it is not that effective in the small-signal sense. Instead, the modal analysis approach with lead-lag compensation is usually used for damping purposes. The energy function approach does not coordinate several HVDC links.

Some papers have investigated system identification for modeling power oscillations [35-45], while others [39, 44, 43] use the numerical algorithms for subspace state-space system identification (N4SID) methods. Some of these papers [35, 38, 39, 43] deal with controlling PSSs using the common phase-shifting lead-lag control. Papers [36, 37, 40, 42] use a single controllable component, such as static var compensator (SVC), thyristor-controlled series capacitor (TCSC), or HVDC link together with system identification techniques to tune the lead-lag filter.

Earlier papers [35-45] use local measurements or output signals related to specific equilibrium operational points, which makes coordinating the devices for the
various modes difficult. Because of these output signals, the state feedback controller cannot be used, so the usual method is phase-compensating lead–lag control in which each device is tuned to a particular mode. The drawback here is that the full potential is not taken advantage of, since a particular device contributes to damping only in a particular mode, unlike state feedback, which coordinates all relevant controllable devices for all significant modes.

Some research papers have used the approach of nonlinear exact-feedback linearization [46–52] in the presence of one HVDC link. The idea is to transform the system, by means of nonlinear feedback, into a linear system and then apply well-known control designs developed for linear systems. This approach is based on input–output linearization, applicable for both small-signal and transient stability.

Little research has considered the possibility of coordinating several HVDC links to improve performance. However, some papers have examined changes in power flow achieved by coordinating FACTS devices or HVDC links [53–55]. The idea is to coordinate the devices in such a way that the AC line power flows are controlled in steady state. Other papers have developed coordinated control strategies for several HVDC links to improve the damping of inter-area modes by coordinating the lead–lag controllers [56–59].

One can conclude that there is great potential to exploit controllability and to coordinate HVDC links to utilize systems more optimally than is done today.

2.7.1 The Nordic Grid Code

The following information concerns the Nordic Grid Code [13], which is the compilation of rules governing the Nordic power system, Nordel. "The Nordic Grid Code concerns the transmission system operators’ (TSOs’) operation and planning of the electric power system and the market actors’ access to the grid. The Code establishes fundamental common requirements and procedures that govern the operation and development of the electric power system" [13].

The total transmission capacity between the Nordic and the UCTE system now exceeds 3000 MW; present plans call for increasing this capacity to approximately 5500 MW within the next few years [13].

If a large disturbance occurs in the Nordic power system, the Emergency Power Control (EPC) of HVDC links is activated. The EPC consists of ramps with a slope of 50–300 MWs$^{-1}$; the most common slope is 100 MWs$^{-1}$ [60], which is activated when the frequency drops below 49.5 Hz or becomes too high or if the voltage exceeds a predetermined range at several local measurement points. The HVDC links are automatically or manually controlled and all the HVDC links in the Nordic system contribute to the EPC if the HVDC link receives an indicating
2.7. REVIEW OF CONTROL STRATEGIES

signal from certain local measurement points. The basic rule is that the instantaneous disturbance reserve is divided equally between the HVDC interconnections. Note that if a link is performing a full import to an area of low frequency, it is unable to contribute to the EPC.

Substantial improvements can be achieved in damping power oscillations in the network around known “bottlenecks,” for example, the Hasle cross-section through southern Norway and central Sweden, by exploiting the damping function of the HVDC connections in the right way. However, general guidelines for setting the HVDC connections’ damping control function have not been determined.

Comment: All existing (and planned) FACTS devices and HVDC links can be better utilized, to improve overall stability and assist in emergency situations.
Chapter 3

Basic coordination

This chapter discusses basic coordination and demonstrates its advantages. Two approaches are presented, i.e., feedforward control and adaptive control. In this chapter, Papers I and II are introduced.

3.1 Feedforward control combined with feedback control

This section develops a feedforward controller combined with feedback control. The controller links the N-1 criterion between two asynchronous systems interconnected by HVDC links.

3.1.1 Rationale for feedforward control

Let us consider the small system depicted in Figure 3.1. It consists of two systems (zones) and two HVDC links interconnecting the systems. Obviously, it is impossible to directly power modulate these HVDC links to dampen oscillations, as no AC line is parallel to any HVDC link.

Let us now only consider Zone A, where one HVDC link is connected to Area j and another is connected to Area k. Seen from this zone, there is an HVDC link parallel to the AC corridor (Lines 1 and 2) if one controls these in the same way but one in the opposite direction. Analogously, seen from Zone B, there is also an HVDC link in parallel. The question is how this possibility can be used efficiently.

Let us start with an example in which we want to transfer as much power as possible from Area j to Area k in both zones A and B. There are two AC corridors, one in each zone, each having two AC lines in parallel. Considering the N-1 criterion in each corridor, we cannot transfer so much power that the system becomes unstable after disconnecting one of the AC lines in either of the two corridors. Let us assume that each corridor is capable of transferring a maximum of x MW to consider the N-1 criterion as being met in the corridor. If one AC line
is tripped, the remaining AC line in that corridor then transfers x MW, which is assumed to be the maximum.

The idea is now to rapidly re-dispatch the power, via the HVDC links, if one of the four AC lines is tripped. In this way, it is possible to transfer more power while still meeting the N-1 criterion. We may increase the power transfer to 1.5x MW in each corridor since, if one AC line is tripped, the HVDC links should re-dispatch the power is such a way that the three remaining AC lines transfers x MW each. This control action is called feedforward, and in this case links the N-1 criterion between the zones.

The size of the power step is set so that the two corridors divide the power properly. In the above example, the power change in the HVDC links becomes 0.5x MW in each link and the direction is determined by which line is tripped.

After tripping an AC line, there is a risk of power oscillation since the lines are transferring close to their maximum amount of power. To dampen possible oscillations, the HVDC links can be coordinated using feedback control (this is further explained below). This action leads to the possibility of increasing the power transfer still further.
3.1. FEEDFORWARD CONTROL COMBINED WITH FEEDBACK CONTROL

3.1.2 Feedforward control combined with feedback control to enhance the transfer capacity

Feedforward control is useful when the influence of a disturbance is known beforehand. The influence of tripping a certain line may be predictable, allowing a scheme to be developed for rapidly re-distributing the power in the HVDC links. Assuming that a trigger signal can be obtained from the relays, indicating that a certain line has been tripped, feedforward control can be applied. Feedforward control can respond more quickly to known and measurable disturbances than feedback control. The feedforward control can be combined with feedback control, which can be based on the well-known lead-lag control, improving the transfer capacity. However, the feedforward and feedback controllers can also be used separately.

**Feedforward control** is here used in combination with feedback control. The following information is assumed to be known:

- for feedforward
  - Knowledge of the system behavior if a line is tripped
  - Information from the relays on whether a line is tripped
- for feedback
  - Phase shift data for the lead-lag block design
  - Frequency measurements at the HVDC connecting buses

This controller focuses on increasing the transfer capacity by linking the N-1 criterion between two systems using rapid power re-dispatch and power modulation. The controller is developed for interconnected asynchronous system (System A, shown in Figure 1.2); it improves both the small-signal and transient stability.

3.1.3 The coordinated controller

The presented coordination approach relies on two-part, coordinated power oscillation damping (POD) and feedforward control.

**Feedforward control**

The feedforward control action must be calculated in advance for various disturbances (e.g., line disconnections) and applied when the fault and disconnection are identified. The feedforward control can be used in the present case study, since the effect of the disturbance (e.g., line disconnection) on the system output is known. The time it takes for the disturbance to affect the output is longer than the time it takes the feedforward controller to affect the output. In this case, the feedforward control consists of rapid re-dispatch (i.e., a power step) of the power flow through the HVDC links.
Power modulation damping

The idea is to use the same control signal for both links but to make one in the opposite direction; this makes both links act as a single long link between areas $j$ and $k$. This can be clarified by looking at Figure 3.1. First one defines the direction from Zone A to Zone B as positive, and then one increases the power in one HVDC link while decreasing it in the other link by the same amount. The power injected in Area $j$ then equals the power injected in Area $k$, but with the opposite sign. This makes it seem, from the perspective of areas $j$ and $k$, as if there is an HVDC link parallel to the AC corridor between these areas. With this as a starting point, we can design a damping controller based on the commonly used phase compensation, as follows:

$$\Delta P_{HVDC} = K \cdot \frac{sT_w}{1 + sT_w} \cdot \frac{1 + sT_1}{1 + sT_2} \cdot \Delta f_{jk}$$  \hspace{1cm} (3.1)

where $\Delta P_{HVDC}$ is the modulated power in the HVDC links, $T_w$ is the wash-out filter time constant, $T_1$ and $T_2$ are the lead-lag block parameters, and $\Delta f_{jk}$ is the frequency difference between areas $j$ and $k$. The parameters are then tuned based on modal analysis to achieve good damping between areas $j$ and $k$. This control makes the power oscillation damping (POD) part of the final controller.

3.1.4 Results

Applying the developed controller with feedforward and feedback to the system shown in Figure 3.1 improves the dynamic stability. The system is implemented in PowerFactory using detailed models of the generators and HVDC links [30]. The generators are equipped with a second-order AVR.

A contingency is applied consisting of a three-phase-to-ground fault on Line 1 cleared by tripping the line. The controller makes it possible to stabilize the system by increasing the power transfer up to 32% from Areas A to A$k$. This is presented in Paper I.

3.1.5 Discussion: Extension to larger systems

Figure 3.2 shows a schematic overview of the HVDC line installations between NORDEL and UCET.

Let us assume that we want to transfer as much power as possible from NORDEL to UCET and that the power is cheaper in NORDEL and $C_{Aarea1} < C_{Aarea2} < C_{Aarea3} < C_{Aarea4} < C_{Aarea5} < C_{Aarea6} < C_{UCET}$, where $C_{AareaN}$ is the production price in area N. Therefore, we want to transfer as much power as possible from Area 1 to UCET and thereafter to Area 2, etc. The $N-1$ criterion sets a limit on the power transfer between the areas.

Let us look at the $N-1$ criterion for the AC lines in Nordel. The bottleneck limiting the theoretical maximum transfer capability is set by disconnecting one
3.1. FEEDFORWARD CONTROL COMBINED WITH FEEDBACK CONTROL

NORDEL

No  Swe  Dk-E

<table>
<thead>
<tr>
<th>Area 1</th>
<th>Area 2</th>
<th>Area 3</th>
<th>Area 4</th>
<th>Area 5</th>
<th>Area 6</th>
<th>Area 7</th>
</tr>
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<tbody>
<tr>
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<td>AC-3</td>
<td>AC-4</td>
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<td>AC-13</td>
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<tr>
<td>AC-15</td>
<td>AC-16</td>
<td>AC-17</td>
<td>AC-18</td>
<td>AC-19</td>
<td>AC-20</td>
<td>AC-21</td>
</tr>
</tbody>
</table>

UCTE

Figure 3.2: NORDEL and UCTE grids interconnected by seven HVDC links. No = Norway, Swe = Sweden, and Dk-E = East Denmark

AC line in a corridor. The limits of the total transfer capability are set by the transient, damping, and voltage stability.

For simplicity, let us assume the parallel AC lines to be identical. Let us also assume the transfer limit between two adjacent areas to be $2P_{jk}$, according to the $N-1$ criterion. This implies that, if an AC line is disconnected, the two remaining lines would transfer $P_{jk}$ each.

The question we ask is “Can we increase the stable (secure) transfer limit in a corridor by coordinating controllers? If so, by how much?”

By studying the capacity of each HVDC link, we can find the margin by which the power transfer in each link can be increased. The rated power through an HVDC link can often be exceeded for short times and sometimes even for long times, depending on the equipment and various conditions, such as ambient temperature. For example, the Sweden to Poland link, SwePol link, may be overloaded by 20% for up to an hour [61].

Let us assume the margin by which the power can be increased in HVDC link $n$ to be $\Delta P_{DCn}$. Then the theoretical transfer capacity in each corridor can be increased from $2P_{jk}$ to:

$P_{Total\ 12\ new} = 2P_{jk} + \Delta P_{DC1}$

$P_{Total\ 23\ new} = 2P_{jk} + \Delta P_{DC1} + \Delta P_{DC2}$

$\vdots$

$P_{Total\ 67\ new} = 2P_{jk} + \Delta P_{DC1} + \Delta P_{DC2} + \Delta P_{DC3} + \Delta P_{DC4} + \Delta P_{DC5} + \Delta P_{DC6}$

If one AC line is disconnected, we instantaneously re-dispatch the power according to the scheme. The outcome is that no AC line transfers more than the allowed
amount of $P_{jk}$.

For example, disconnect AC line 4 and apply the power dispatch. The actual power transfer becomes:

$$P_{Total\ 12} = 2P_{jk} - \Delta P_{DC1}$$
$$P_{Total\ 23} = 2P_{jk}$$

Thus, corridor 2 to 3 transfers $2P_{23}$.

This explains the idea of a feedforward control that can be applied to increase the transfer capacity. To use a feedforward control efficiently, we need to find the limiting and severe contingencies. By analyzing the system, we may identify various situations in which this control action is useful. In addition to this feedback control can also be applied to dampen possible power oscillations, this can be designed as described earlier.
3.2 Adaptive control to enhance the transfer capacity: Modal analysis approach

This section develops adaptive control using a modal analysis approach to increase the dynamic security. The power modulation controllers of the HVDC links are coordinated, and the controller gains are adaptively changed along a forecasted load path.

3.2.1 Rationale for adaptive control

Increased load demands usually increase the power transferred between areas, since the production and consumption do not always occur in the same area. As the loads increase, the domain of attraction of the operating point decreases, reducing the dynamic security. If the loads continue to increase, a time will eventually come when the system becomes unstable. This load increase takes the system closer to the stability limit.

A common way to increase the dynamic security, in the small-signal sense, is to modulate the power in the HVDC links using phase-shifting lead-lag controllers. The system damping depends on the current load-flow situation, system parameters, etc. Due to load changes, the linear system model changes. As the model changes, the controller gains may start to deviate from the optimal value in the sense of maximizing the damping in the system. This section presents a method for adaptively changing the controller gains of the HVDC link modulation controllers to maximize the damping in the system.

Adaptive control is used to enhance the transfer capacity between areas by adaptively changing the controller gains of the HVDC links. The following information is assumed to be known:

- Linear model of the power system
- Load paths
- Frequency measurements at buses

This idea is developed for synchronous systems, System B shown in Figure 1.2. It emphasizes stability improvements in the small-signal sense.

3.2.2 Adaptive control

The idea is to adjust the parameters of the HVDC link controllers so that the point at which instability occurs is moved toward a higher loading level. A common way to control the HVDC links is to modulate the power of an HVDC link in the following way:
The adaptive controller should adjust the controller gains in vector $C$ such that the dynamic security is improved. How to change $C$ depends on how the load-flow changes in the system, i.e., how the generation and consumption change.

If it is possible to obtain information about the current load-flow situation at certain times, this information could be used to update the linear model. Based on this model, new controller gain parameters can be optimized. However, if this information is unavailable, one may instead forecast how the load-flow will change. It is assumed that the load consumption cannot be measured but can be modeled using a stochastic time-varying process describing future demands. This forecast will then be used to enhance the transmission limits by adjusting the parameters of the HVDC link controller for the currently forecasted load-flow situation.

By including the controller equations, the linearized system can now be written as follows:

$$\Delta \dot{x} = A_C(t_i) \Delta x$$  \hspace{1cm} (3.3)

where $A_C(t_i)$ is the system matrix including the HVDC link controllers at certain time instances $t_i$.

The problem to solve is how to adaptively change the gains of the power modulation controllers to maximize the damping in the system along the load path. The controller gains are updated at certain times based on how much the load-flow has changed. The arising optimization problem is then solved using a particle swarm optimization (PSO) method. To apply PSO to this problem, we first compute the equilibrium points of (3.3) along load path $m(t)$ for $t_i$ number of times. Then we initialize the optimization by putting a number of particles on the boundary of the feasible domain. The value of the objective function is then given by the smallest $t_i$ for which one of the eigenvalues of the system’s Jacobian matrix has a positive real part. If one of the particles leaves the feasible domain during optimization, then we can push it back by moving it to the closest part of the boundary of the feasible domain. An overview of the PSO process is depicted in Figure 3.3.
**Results and discussion**

The results are then compared in a Monte Carlo simulation on the popularWSCC three-machine, nine-bus system extended by two HVDC links. The system is implemented in Matlab, modeling the generators using a one-axis model with a first-order AVR. It is assumed that the active power through the HVDC links can be directly controlled.

The objective of the Monte Carlo simulation is to estimate the difference between the loadability of a non-controlled system and the system with adaptive control. The simulation indicates that the transfer capacity is greatly enhanced using the proposed method. In this example, it is possible to increase the load by 18% compared with the uncontrolled case. The developed adaptive algorithm has been tested in a system in which the load changes are modeled as a stochastic process. The length of the interval between times when the parameters are changed is then changed depending on the forecasted load change ramp rates. The details are presented in Paper II.

It is quite straightforward to expand this method to include other controllable devices and for application in large power systems.
Chapter 4

System identification and optimal control in power systems

This chapter describes the use of system identification to estimate reduced-order MIMO models. The model is used for designing an optimal coordinated controller, using wide-area measurement system signals as inputs. This chapter also introduces Papers III, IV, and V.

4.1 Rationale for system identification in power systems

Designing a power oscillation damping coordinating controller calls for a linear model of the open system. One way to obtain such a model is to linearize the system around its present operational point; using this model, the controller can be designed to improve the closed-loop properties of the system. For large power systems, detailed linear models are often unavailable. Even if a linear model is available for a specific equilibrium point, changes in the system state change the linear model. In addition, the system changes are often unknown, so the system model changes are unknown as well.

The fact that large systems are represented by large state-space models makes the analysis and control design challenging. Any controller designed using observer and state estimate feedback and based directly on the system model has the same order as does the system model. However, to be implementable, the controller must be of sufficiently low order. A reduced-order controller can be obtained in two ways, using either a reduced design model of the system or a reduced-order approximation of a high-order controller. The former method is used more widely than the latter because high-order controller design relies on knowledge of high-frequency mode parameters, which is usually inaccurate [26].

In these situations, system identification techniques offer a convenient way to achieve full or reduced-order linear models, which are adequate to describe the
CHAPTER 4. SYSTEM IDENTIFICATION AND OPTIMAL CONTROL IN POWER SYSTEMS

dominant dynamic behavior. Given an appropriate model, a centrally coordinated controller can be designed to enhance the small-signal stability.

Designing a central controller incorporating real-time sensing calls for a proper model. A method for estimating the open system model is presented in this thesis, which also presents a method for designing a central coordinating controller. The development consists of two parts: model estimation including validation and controller design including model state estimation.

**Optimal control** is used to design a damping controller based on an estimated reduced-order model. The following information is assumed to be known:

- Speed measurements from selected generators

This controller, which improves the small-signal stability, is designed for synchronous systems (System B).

4.2 Model estimation

The model is to be estimated from the input and the output signals. System identification is ideally performed based on the unique impulse response of a system. Obviously, obtaining such a response for a power system is beyond our reach, because it would necessitate the injection of an excitation signal of infinite amplitude for a very short time.

By varying the inputs over a wide frequency range, the system's response to this range can be found. The frequency range would then be within the range of the oscillations. Low-energy pulses at the setpoints of the controllable devices excite the system. A wide-area measurement system (WAMS), consisting of phasor measurement units (PMUs), senses the dynamic data of the power system. This creates the input–output data from which the model is estimated.

4.2.1 Inputs and outputs

The controllable setpoint signals of the HVDC links serve as the input signals. The output signals are selected from appropriate global signals, which are signals affected by power oscillations and measurable signals using real-time sensing by means of WAMS with PMUs [62]. The speed deviations of certain generators serve as the output signals. The generators with highest participation factors are selected to serve as the outputs. The rationale for this is as follows. Damping depends greatly on changes in the angular and speed differences of the generators, leading to the choice of these two types as output variables. Speed signals are the better option, since they are independent of the operational point in steady state. This enables the use of a state feedback controller, i.e., centralized coordinated control. The generators are selected by checking the participation vectors for the low-damped modes.
4.2.2 Model validation

From the recorded input-output data, models of a certain model order range are estimated using the numerical algorithms for subspace state space system identification (N4SID) method [63]. Once estimated, the models must be validated to determine whether they reproduce system behavior within acceptable bounds, and then models of a proper order must be selected. This can be done in several ways, the method used depending greatly on the use of the estimated models [64]. In Paper IV, this is described in detail and simulations are run for the Nordic32 system.

4.3 Central coordinated control design

The controller can be designed once the model is estimated. An optimal regulator can be designed, which concerns operating the dynamic system at minimum cost i.e., the use of control effort versus damping of disturbances. One wants to minimize the control effort and maximize the damping in the system. Then one can adjust the control effort for each HVDC link while weighting the importance of the oscillatory modes. The regulator consists of two parts, an optimal state estimator and an optimal state feedback controller.

The input to the observer is the speed deviations of certain selected generators; the output of the observer is the estimated model states. The input to the controller is the state estimates, while the output is the setpoints of the controllable devices. Figure 4.1 shows an overview of the power system and controller interface.

![Diagram](image)

Figure 4.1: An overview of the power system and controller interface.
4.4 Results and discussion

This method is applied to the Nordic32 system including two HVDC links. The system is implemented in PowerFactory using fully detailed models (for further implementation details, see [30]); the system data are given in [65]. A reduced order model is estimated and validated from measurements; the data originate from the system response by changing the input signals. The central optimal controller is designed based on this model, resulting in a controller capable of increasing the power oscillation damping. It is demonstrated to be robust to system changes and noisy measurements. More details can be found in Papers III, IV, and V.

Other controllable devices can easily be included in the model by adding changes in the relevant controllable device’s setpoints to the model estimation. This makes it possible to coordinate all the relevant controllable objects to improve the dynamic stability.
Chapter 5

Nonlinear control

This chapter introduces the application of nonlinear exact feedback linearization to power systems. It also introduces Papers VI and VII.

5.1 Rationale for exact feedback linearization in power systems

Power system dynamics can be described using a set of nonlinear differential equations. The central idea of input-output exact feedback linearization is to algebraically transform the nonlinear system dynamics into a linear control problem using a nonlinear pre-feedback loop. The resulting system can then be treated as a linear control problem and well-established linear control techniques used. The pre-feedback loop performs an exact linearization which cancels the nonlinearities, meaning that a linear relationship can be seen from the input to the output. An overview of this appears in Figure 5.1.

Figure 5.1: An overview of the exact feedback linearization concept.
This approach differs entirely from conventional Jacobian linearization since, instead of using linear approximations, the nonlinearities are canceled by the nonlinear state feedback. The Jacobian approximation of the dynamics around an equilibrium point is only valid for small changes around the equilibrium; the exact feedback linearization, however, is valid for various system operating points.

**Exact feedback linearization** uses the nonlinear model description and assumes that the parameters of the system are known and the state variables are measurable. The following information is assumed to be known:

- Measurements or estimates of the state variables
- All system data

This controller improves the small-signal and transient stability at various operating points. The method is applicable to interconnected asynchronous and synchronous systems. Paper VI uses a small interconnected synchronous system to illustrate the effectiveness of the controller; Paper VII instead uses a larger synchronous system. Paper VII extends the theory developed in Paper VI to general systems and explains how to apply the method to large systems.

### 5.2 Exact feedback linearization with multiple HVDC links

By using the internal node representation the power system can be described by ([19, 66] and explained in Paper VII):

\[ \dot{x} = f(x) + g(x)u \]  

(5.1)

One challenge in performing this nonlinear feedback linearization is choosing the outputs, \( y_{out} \), since the linearization is seen from the input to the output. The output signals are a combination of states, as follows:

\[ y_{out} = h(x) \]  

(5.2)

where the function \( h \) maps the states to the output.

One must choose as many outputs as inputs. Power system stability is related to the differences in rotor angle and speed between the generators, so a proper combination should be selected. There are many feasible combinations of states, both linear and nonlinear, i.e. angles or speeds of the generators. The outputs should emphasize the power oscillations and rotor angle separations that may occur under some contingencies.

Appropriate outputs can be found by studying stability problems that may arise, for example, by applying various contingencies. Outputs can also be found using methods such as single machine equivalent [67, 68] and system coherency identification [69–73]. Once the outputs have been selected, the nonlinear feedback law
can be derived. The derivation of the nonlinear feedback law is presented in Papers VI and VII.

The feedback law

The feedback law that cancels the nonlinearities is as follows:

\[ u = \alpha^{-1}(v - \beta) \]  
(5.3)

where \( \alpha \) and \( \beta \) are matrices which cancel the nonlinearities and \( v \) is the linear control variable. The feedback control law depends on the system's relative degree [74]; the derivation of the feedback law is presented in Papers VI and VII. The feedback law maps the nonlinear system to a linear system; seen from the input to the output, the nonlinear dynamics are canceled by the pre-feedback linearizing loop. The mapping is achieved by finding the transformation, as follows:

\[ v = \beta(x) + \alpha(x)u \]  
(5.4)

and a state transformation:

\[ z = \begin{pmatrix} z_l \\ z_o \end{pmatrix} \]  
(5.5)

where

\( z_L \) is the linearly controllable state vector, and

\( z_o \) is the nonlinear uncontrollable state vector.

Of the form

\[ \dot{z}_l = Az_l + Bv \]  
(5.6a)

\[ \dot{z}_o = r(z_l, z_o) \]  
(5.6b)

\[ y = Tz_l \]  
(5.6c)

where

\( A, B \) and \( T \) are matrices,

\( y \) is the output vector, and

\( r \) is the nonlinear mapping.

Now, the behaviors of \( y \) and \( v \) are the only issue of interest. The input-output exact feedback linearization reduces the control problem to a linear one. One may now design the linear controller to stabilize the system.

Many different linear controllers are applicable to this system; however, in this thesis, only the optimal linear quadratic regulator (LQR) is used. The LQR is robust and guarantees a phase margin of 60 degrees [75], which is in good agreement with the practical guidelines for robust control system design [26]. In this case, the optimality is only evident once the system has been linearized. This means that
some control effort is first needed to linearize the system; then the LQR is applied. The control effort depends on both the nonlinear and linear parts.

The actual input, \( u = [I_{setp_1}, \ldots, I_{setp_m}]^T \), to the HVDC links consists of two parts: part one is the nonlinear pre-feedback and part two is the linear feedback, \( v \).

The final controller is then the sum of the nonlinear and linear feedback parts, written as follows:

\[
I_{setp} = \begin{pmatrix} I_{setp_1} \\ \vdots \\ I_{setp_m} \end{pmatrix} = \begin{pmatrix} I_{Nsetp_1} + I_{Lsetp_1} \\ \vdots \\ I_{Nsetp_m} + I_{Lsetp_m} \end{pmatrix}
\]

(5.7)

where \( I_{Nsetp} \) is the nonlinear part and \( I_{Lsetp} \) is the linear part.

5.3 Results and discussion

This approach is applied to two test systems to demonstrate the effectiveness of the controller. The systems are implemented in Matlab using the classical model of the generators and loads modeled as constant impedances. The nonlinear pre-feedback loop cancels the nonlinear dynamics and an optimal LQR controls the resulting linear system. Both the small-signal and transient stability can be improved under various conditions. It was demonstrated in Paper VI, using an example system, that the critical clearing time could be increased by 34%. It was also demonstrated in Paper VII, using another example system, that the stable power transfer in an AC corridor could be increased by 60% compared with no control and by 30% compared with conventional local lead-lag control.

The challenge of choosing output signals depends on the system and its potential stability problems, which in turn depend on the system’s operating points. It may be feasible to select different output signals depending on current conditions if, for example, the small-signal stability problem involves other generators than those involved in transient instability. It may be that it is not beneficial to choose output signals that have low controllability, i.e., if the HVDC links are electrically far from the generators.
Chapter 6

Conclusions and future work

This chapter summarizes the key conclusions of the thesis, and discusses ideas for future research work.

6.1 Conclusions

This thesis has demonstrated that it is beneficial to coordinate HVDC links. Four control methods are developed that improve the dynamic security.

A controller based on feedforward control combined with feedback control, which links the N-1 criterion between two interconnected asynchronous systems, has been developed. Using this controller, it was demonstrated that the system could be stabilized at higher power transfer levels while improving both transient and small-signal stability. In an example system, it was possible to stabilize the system while transferring up to 30% more power from one area to another through an AC corridor.

One developed controller uses adaptive control to adjust the controller gains to optimize the damping in the system; the gains are optimized based on forecasted load paths. This controller improves the small-signal stability of the applied synchronous system. Monte Carlo simulations were used to demonstrate that the point of instability was moved to a higher loading level. The loading level could be increased by 18% in an example system.

A method based on system identification indicated that it is possible to estimate reduced-order models. The reduced-order models describe the power oscillatory behavior of a synchronous power system. Based on the model, a power oscillation damping controller can be designed that uses real-time measurements provided by the wide-area measurement system as input data. This controller improves the small-signal stability. It was demonstrated, using a modified version of the Nordic32 test system, that damping could be increased from 2% to 11% using this method.

The controller based on exact feedback linearization applies a nonlinear pre-feedback loop to achieve a linear relationship from the input to the output. The
remaining linear system is controlled by a linear quadratic regulator. This controller improves the small-signal and transient stability. In an example system, it was demonstrated that the critical clearing time could be increased by 34%. It was also demonstrated, in another example system, that the stable power transfer in an AC corridor could be increased by 60% compared with no control and by 30% compared with conventional local lead-lag control.

All these control methods improve the dynamic security of the system. This in turn makes it possible to transfer more power, which makes the electricity market more flexible. Depending on the chosen control method, different assumptions are made as to the availability of the dynamic system model, parameters, measurement signals, and system topology.

6.2 Future work

Though coordinated control is important, little research has been done in this area; the list of future research topics is therefore long. It is mainly ideas for future research related to the control approaches presented here that will be discussed.

In general, other test systems can be used for all these methods. These methods can be applied to larger or more realistic systems to evaluate their effectiveness. Many different contingencies and operational situations should be tested. However, it is not straightforward to implement the methods in other systems; as many aspects must be considered, implementation needs to be studied specifically for each method.

The influences, for example, of time delays, model deviation, and uncertainties need to be examined to evaluate the robustness of the different methods.

Feedforward with feedback control

In the future, it would be useful to implement this controller in a test system based on a real system. It would then be possible to devise situations in which it would be beneficial to use the approach.

Adaptive control

This method can be extended to include other controllable components, such as static var compensators (SVCs). It would also be interesting to check different load models and investigate how often the parameters should be updated.

Optimal damping control

The developed method based on system identification can be extended by including other controllable devices. It would then be possible to coordinate all the relevant devices to improve the dynamic security. A method for optimizing the selected output signals also needs to be examined. Other linear system controllers are available that might be more suitable in some cases.
6.2. **FUTURE WORK**

**Exact feedback linearization**

This method can be further developed using VSC HVDC instead of LCC HVDC. With VSC HVDC it is also possible to control the voltage at certain buses by controlling the reactive power at the converter ends. Deeper analysis of output signal selection may identify a method applicable to general systems.
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[60] “Spoken reference: Magnus danielsson, svk (swedish national grid).”


Papers

Paper I

Paper II
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Paper III

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Paper VI

Paper VII