CONTROL OF HIGH VOLTAGE DC AND FLEXIBLE AC TRANSMISSION SYSTEMS

by

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ABSTRACT

Analytical modeling of HVDC systems has been a difficult task without a to-date reported model convenient for serious analysis of practically reported HVDC stability problems. In order to cover the frequency range $f<100Hz$, and to cater for different model requirements, three different HVDC-HVAC models are developed in this Thesis: Detailed linear-continuous model, simplified linear continuous model and linear discrete model.

Detailed HVDC-HVAC system model is intended for small signal analysis of HVDC-HVAC interactions and resulting stability problems. It demonstrates good response matching against PSCAD/EMTDC simulation, where the CIGRE HVDC Benchmark model is used as the test system. All model variables (states) and parameters have physical meaning, and the model consists of modules, which reflect actual physical subsystems.

Simplified HVDC-HVAC system dynamic model is developed as a fourth order dynamic model, which is less accurate but more convenient for the analysis, than the detailed model. The model proves to be reliable for controller design for mitigation of composite resonance and for the study of non-linear effects in HVDC systems. The developed linear discrete model is primarily intended for the system analysis at frequencies close to *100Hz* on DC side of HVDC system.

A new approach in modeling of TCR/TCSC, based on the same principles for HVDC modeling, is presented in this Thesis. The model development is far less difficult than the similar models presented in literature. PSCAD/EMTDC simulation confirms the model validity.

The simplified, linear-continuous model is used for the analysis of dominant non-linear effects in HVDC systems. The analysis of non-linear mode transformation between constant beta and constant gamma operation, shows that limit-cycle oscillations are not expected to develop, for normal operating conditions. The analysis of converter firing angle modulation shows that converter behaves as a non-linear element only for some unlikely operating conditions.

In this Thesis, it is attempted to counteract the composite resonance phenomenon by modifying the resonant condition on DC system impedance profile. This is accomplished by designing a supplementary HVDC controller that acts on HVDC firing angle on both line ends. PSCAD/EMTDC simulation results show that significant reduction in DC side first harmonic component (in some cases to *1/4* of the original value) is possible with the newly designed controller.

Chapter 5 studies *100Hz* oscillations on DC side of HVDC system. A methodology for designing a new controller to counteract negative affects of these oscillations is presented. Linear simulation of the detailed controller design confirms noticeable reduction in second harmonic on DC side.

The eigenvalue decomposition and singular value decomposition is used for small-signal analysis of HVDC-HVAC interactions. The analysis of sensitivity of the dominant system eigenvalues with respect to the AC system parameters, shows the frequency range for the possible oscillatory instabilities at rectifier and at inverter side. The rectifier side of the system is most likely to experience instability at higher frequencies, whereas at inverter side the instabilities can be expected at lower frequencies. Further analysis shows that reduction in the AC system strength

will predominantly affect the eigenvalues at lower frequencies, where the SCR reduction at inverter side much more affects the system stability. The analysis of interactions between AC and DC systems through the influence of inherent feedback loops gives recommendations for the possible control of interaction variables with the aim of system stability improvement.

The root locus technique is used for the stability analysis of HVDC control loops, where all conventional and some alternative control methods suggested in the literature are investigated. It is found that DC feedback, at rectifier side, significantly improves the system stability at lower frequencies, however, at frequencies close to the first harmonic this feedback control degrades the system stability, actually accelerating the development of composite resonance. At inverter side, most of the feedback loops improve the system stability in a certain frequency range, whereas at other frequencies they noticeably deteriorate stability. Among all reported inverter control methods, reactive current feedback is found to be the best option.

The last Chapter develops a new controller for HVDC system operation with very weak inverter AC systems. The selection of feedback signal for this controller, is based on the analysis of positioning of zeros for candidate feedback signals. It is found that AC current angle is the best inverter feedback signal. This feedback signal can move the unstable complex eigenvalues left, into the stable region, without significantly affecting remaining eigenvalues. For the additional improvement in the system performance, a second order filter, designed using H_∞ control theory, is placed into the feedback loop. The main design objective is the system robustness with respect to the AC system parameters changes. The controller designed in this Thesis, tolerates very wide changes in system strength, $1.7<SCR<3.5$, with the nominal operating point at $SCR=2.5$. This wide change of operating parameters, although very unlikely in practice, demonstrates large improvement in the system performance with the new controller. The similar controller especially designed for extremely low SCR, shows that HVDC system can satisfactory operate with $SCR=1.0$ at inverter side and heralds the possible controller use instead of synchronous condensers or SVC elements at inverter AC bus.

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GLOSARY

Symbol	Description
a	Transformer ratio
a	Magnitude of input signal, transformer ratio, elements of matrix A
A	System matrix, area, describing function coefficients
B	Input matrix
C	Output matrix, capacitance
e	Controller error
e_s	AC source voltage
e_{ac}	Converter AC voltage
E_{th}	Equivalent Thevenin source
E_{ac}	AC system voltage (DC side of converter transformers)
$E_{a,b,c}$	a,b,c Phase AC voltage
E^d	Disturbance voltage
f	Frequency, function, number of AC systems, feedback controller gain
g	Transfer function
G	Transfer function
i	Instantaneous current, inverter
i_{ac}	Converter AC current
i, j	$\sqrt{-1}$, Imaginary number.
j	Generic index 1- rectifier, 2- inverter
I	Identity matrix
I_d	Direct current, d-component of AC current
I_m	Current margin
I_{ord}	Current order
I_q	q-component of AC current
I_r	Rectifier direct current
I_i	Inverter direct current
J	Bessel coefficients
k	Controller gain
K	Linearised (converter) gain, gain matrix, controller, controller gain
l	Instantaneous value of reactance
L	Reactance
m	Harmonic order
M	Magnitude of input signal
$n(*)$	Non-linear element
$N(*)$	Describing function
P	Park's transformation matrix, power, correction matrix
R	Real numbers, correction matrix, resistance
R_c	Equivalent commutating resistance
s	La Place operator
S	Sampler, matrix, correction matrix, sensitivity function

t	Time interval
T	Time constant, matrix, complementary sensitivity function, transformation matrix
T_f	Filter time constant
T_s	Sampling time constant
T_u	Time delay
v	Instantaneous voltage, any AC variable
$V_{dr,i}$	Rectifier, inverter direct voltage
V	Voltage magnitude, Output singular vector
V_{ac}	AC system voltage (AC side of converter transformers)
V_{dac}	D-component of AC voltage
V_{qac}	Q-component of AC voltage
u	System input, commutation overlap
U	Input singular vector
w	Disturbance
W	Transfer function, matrix
x	State variable
x'	Single phase state variable
X_c	Equivalent commutation reactance
y	System output
z	Z-transformation operator, impedance
Z	Z-transformation
α	Converter firing angle
β	Converter angle ($\beta = \pi - \alpha$)
γ	Converter extinction angle, condition number,
σ	Singular value
∂	Partial derivative
ψ	Current phase angle
φ	Voltage phase angle
θ	PLL output angle
ϕ	Converter actual firing angle, power factor angle
ω	Angular frequency
Δ	Model uncertainty
Σ	Matrix of singular values

	abbreviations
CCCM	Combined and Coordinated Control Method
CRC	Constant Reactive Current control method
DSF	Damping Sensitivity Factor
HVDC	High Voltage Direct Current
HVAC	High Voltage Alternating Current
MIMO	Multi-input multi-output system
NP	Nominal Performance
NS	Nominal Stability
PLL	Phase Locked Loop
RP	Robust Performance
SCR	Short Circuit Ratio
SVD	Singular Value Decomposition

TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Capacitor

INTRODUCTION

I. BACKGROUND

Since the first introduction of HVDC power transfer technology, various analytical models for HVDC analysis and design have been developed [1-4]. These modeling approaches are mainly concerned with accurate modeling of AC-DC converters. The developed models can only be used for the very basic system stability analysis.

As the number of HVDC links worldwide has grown, more accurate analytical models have emerged [5-8]. Much more light has been shed on HVDC modeling principles in these models. Possibly, a single most comprehensive model developed to-date is reported in [7]. Still, this model does not give detailed representation of AC-DC interactions, it does not represent PLL dynamics, and AC systems are overly simplified.

With the fast expansion and development of digital based technologies in the last 20 years, a number of very accurate non-linear HVDC simulation software have emerged with the prominent one described in [9]. These software have been used as the main tool in industry for stability study of HVDC links. They are accurate, reliable and user friendly. The inherent shortcoming of these models is the lack of analytical representation of internal system properties (dynamics). They can be used only for a trial and error study. Extensive and repetitive simulation runs are necessary for any serious system analysis and, general, qualitative conclusions are seldom derived. Controller design is also usually based on the testing of successively incrementing controller gains.

A convenient and accurate analytical system model offers a tool for qualitative study of the system behavior without a need for simulation of the system responses. Analytical models can offer conclusions applicable to all systems with similar structure, regardless of the values for their actual parameters. They offer a platform for readily designing controllers that can significantly improve the system properties. In this Thesis, it will be firstly attempted to develop an accurate and convenient analytical model of an HVDC system.

An important step in HVDC modeling is the development of CIGRE HVDC benchmark test system [10]. Although it does not represent any particular HVDC system, this test system is designed to emulate typical HVDC configuration with system parameters (SCR and resonant conditions) calculated to make a difficult-to-control case. In [11] this test system is further modified to create very weak inverter AC system. These two test system will be primarily used in this Thesis.

Apart from modeling of HVDC systems, the analytical modeling approaches for the basic FACTS elements (TCR and TCSC) will also be studied in this Thesis. Because of the use of AC-DC converters, PLL circuits and two different frequency domains, the modeling of TCR/TCSC has many similar aspects as modeling of HVDC systems.

The most influential TCR/TCSC analytical models are presented in [12], [13] and [14]. Although their accuracy is demonstrated, these models are suitable for a particular purpose only, and for a simple AC transmission system. In all three models, special discretisation process is necessary, and the model development becomes difficult and tedious. This Thesis offers a generalized approach to development a TCR/TCSC model, based on independent modeling of various subsystems in a manner similar to that used in HVDC modeling.

The most important HVDC operating problems reported to-date can be classified into several categories: converter composite resonance including core saturation instability, second harmonic oscillations on DC side of HVDC system and problems related to weak AC systems connected HVDC systems. The frequency range for the above operating difficulties can be broadly classified as $5Hz<f<100Hz$ as seen on DC side. All of these stability problems are essentially AC-DC interaction problems. The most important factor for poor dynamic analysis of HVDC operating difficulties is the lack of suitable, reliable analytical models. In practice, soon after the difficulties are experienced these are usually successfully simulated on digital simulators and the mechanism for development is explained, in general. However, in order to accurately predict the occurrence of the instability, to identify the parts of the system mostly responsible, and to design an effective controller for its elimination, it is necessary to have good knowledge of the system internal dynamic properties and the change of these properties as the operating conditions change and as the control logic is changed.

Core saturation instability has occurred on at least two HVDC systems [15], [16]. Pole 1 of New Zealand HVDC system is known to have resonant conditions that can cause instability [17]. This form of instability is manifested as a spontaneous growth of second harmonic oscillations on AC side, and first harmonic on DC side of the system [18]. The instability is accelerated by the additional generation of second harmonic as a consequence of transformer core saturation. It can take form of fast growing oscillations until some of the protection circuits trip the affected part of the system and cause an outage. In some cases, because of the non-linear system characteristics, the oscillations of certain magnitude can persist for a longer time introducing distortion in the system [16], and affecting power quality. Composite resonance is a phenomenon of complementary AC-DC resonance; a high impedance parallel resonance on the AC side coupled with a low impedance series resonance at an associated frequency at DC side [19]. This form of instability may accelerate development of core saturation instability.

References [20-23] offer further study of the above instabilities, present reported cases and address some control solutions. Theoretical research reported in [24] shows that the most important factors for the development of core saturation instability are the DC side impedance profile together with DC controls, and the AC side impedance characteristics. Similarly, reference [19] emphasizes the importance of system impedance profile and DC controller gains for the composite resonance phenomenon on HVDC systems. Therefore, development of these form of instability will be determined by the inherent system damping of a small signal excitation at particular frequencies. As an example, the resonant frequency of the DC system is determined by the DC line natural impedance profile in combination with smoothing reactors at both line ends. Despite the known causes of the instability, and analysis of the existing control loops, very little research has been performed to offer a controller design procedures for the system under the above conditions. In this Thesis, it will be attempted to modify the natural impedance profile of DC system by using different HVDC control strategies.

New Zealand HVDC system was experiencing *100Hz* on DC side for a long time [25]. Although it has not been reported on many other systems, the mechanism is universal [26], and similar oscillations could occur on other systems. It is known that these *100Hz* oscillations on DC side are a consequence of an unbalanced AC supply voltage [26]. The phenomenon is manifested as *100Hz* oscillations on DC current and on extinction angle gamma. In the case of constant beta and predictive type gamma controller, the oscillations on extinction angle will reduce the minimum gamma values, and the safe commutation margin may be endangered. The available HVDC references do not offer any study on the possible (control) countermeasures for this phenomenon. In this Thesis, it will be shown how the existing HVDC controllers can be used to reduce the *100Hz* oscillations.

Except for the reference [27], there has not been a significant research on the possible HVDC control methods at rectifier side. The same direct current feedback has been used on most of the HVDC systems since their first practical implementation. At inverter side, however, the applied control method varies with different systems. The most often used control strategies are direct current feedback, direct voltage feedback and AC voltage feedback, whereas a number of alternative control methods has also been reported [27], [28]. The various inverter control strategies have not been compared in the references, from the dynamic point of view, and there are no clear recommendations for the inverter controller in the future HVDC systems. This Thesis uses the detailed analytical system model to offer a small-signal analysis of reported HVDC control strategies at both, rectifier and inverter side.

The inability of HVDC systems to operate with weak AC systems can be regarded as the most important factor in limiting the use of HVDC power transfer technology, both in number and in capacity. In large number of HVDC links, the rating of the link has been determined on the basis of minimum safe Short Circuit Ratio (SCR). Also, some HVDC projects have been abandoned, or locations for some terminals had to be altered because of very weak receiving AC systems. The recommendation has been traditionally accepted that for successful HVDC system operation, the strength of connected AC systems should be $SCR>2$. In references [27] and [28] the dynamic instabilities caused by the weak receiving AC systems are presented. The main operating problems with the HVDC systems connected to weak AC systems are manifested as the high-magnitude AC voltage oscillations and the difficulty in recovery from disturbances [29], [30]. These AC voltage fluctuations, even without actual instability, can be harmful for AC equipment and the quality of power supply. On the DC side, the probability of commutation failure will increase.

The traditional, most commonly used option for strengthening of AC systems is the use of Synchronous Condensers. Since this method suffers high losses and high operational cost, an alternative option, the possibility of the use of HVDC controls, specially designed for weak AC systems, will be investigated in this Thesis.

II. THESIS OBJECTIVES

The first objective of this thesis is to develop an analytical model suitable for the study of the most common HVDC operating difficulties described in Section 1.0 above. The model should have high fidelity in the frequency range $f<100Hz$. It is also important that the model is convenient for analysis of HVDC-HVAC interactions, since all the above instabilities arise from HVAC-HVDC coupling. A complex HVAC-HVDC-HVAC system consists of a several subsystems whose individual properties are usually known. The properties of the overall system are however difficult to predict. The model should follow this modular structure with the clear physical meaning for each subsystem, which will enable qualitative conclusions about their influence on the dynamics of the overall system. The main subsystems can be identified as AC systems on both HVDC ends, Phase Locked Loops and their controllers and DC system with its controls. The preferable model form is the linear continuous, represented in state-space domain.

This model representation is convenient for the system analysis and controller design using the linear systems control theory.

The same modeling principles and approaches apply to the development of FACTS models. The Thesis attempts to develop a small-signal model of TCR and TCSC in the form convenient for the system analysis and design, yet accurate in the frequency range of interest.

By varying the operating conditions in the above model(s), the reported instabilities could be simulated. Various sensitivity indices could also be used to predict the operating difficulties. The well-known engineering terms which describe a particular system (like SCR, impedance profile, etc.) should primarily be used in the analysis, in order to give practically useful indicators of possible stability problems. The model with the physically meaningful variables and parameters would enable firm connection between the conclusion from the theoretical, dynamic study and the parameters and operating conditions in the actual system. The influence of various controller parameters and operating modes on the development of the instabilities should similarly be studied. Sometimes, the operating problems can be avoided just by properly tuning the existing controllers, or by compromising other system properties, like speed of response or reference tracking.

The majority of the design stage countermeasures for the operating problems described in previous sections, are directed towards main circuit modifications. As an example, because of known stability problems HVDC systems are not coupled with weak AC systems [28],[30]. In this case, a connection point for HVDC system is changed or power transfer level is limited or the AC system is strengthen. Also a special main circuit modifications are employed (TCR, AC filters) if a condition for composite resonance exist [15]. A number of HVDC control system studies and novel designs, for each particular problem, have also been presented. A good example are the controller studies for composite resonance (core saturation instability) [25-29], and alternative inverter control strategies [28],[31]. Further in this line, the role of traditional HVDC controls and a possible use of novel control techniques in the analysis of stability problems, will be primarily studied in this Thesis. A control solution, although it requires very high level of the system knowledge, detailed dynamic models, mathematically complex design procedures and highly skilled personnel, very often has advantage over the main circuit modifications in terms of the overall project cost. It is known that HVDC converters have very high controllability. Nevertheless, the present day HVDC control methods are very similar to those applied at first HVDC schemes, with only a partial utilization of its capacity, which is especially true at inverter side. One of the primary objectives of this Thesis is to try to use HVDC controls to its full potential. It is investigated in this Thesis if it is possible to use the inverter controller for other control objectives (stability improvement and similar) and if there is a frequency range for further control action at rectifier side in order to counteract a particular operating difficulty.

Most of the traditional HVDC control theory is based on the static (V-I) operating curves, and therefore valid only at very low frequencies. This Thesis is primarily concerned with small signal stability analysis around the nominal operating point and in the frequency range below the second harmonic on DC side. This dynamic system analysis is far more general than the analysis based on the static diagrams. The conclusions obtained from the dynamic system analysis are, in some cases, opposite to the conclusions about a "more stable" or "less stable" conclusions, often derived from the static diagrams and static stability factors.

Far too often in the traditional approach, HVDC system has been viewed as an isolated system, bounded by the converter transformers. The influence of the connected AC systems is overly simplified in this type of analysis. In this Thesis, HVDC system is considered as a dynamic subsystem inside a large HVAC-HVDC-HVAC system. The design of HVDC controllers is directed towards improvement in the stability of the overall system, and not just the HVDC subsystem. In this way, a converter can be viewed as a powerful controlling element inside a large, complex transmission system.

The design of a controller (or modification of the existing controller) is the most important step in the process of elimination of the instabilities by the use of control methods. The analysis of possible control methods requires a thorough analysis of controller objectives and the possible compromises, which need to be made in other parts of the system, or in other frequency domains. The controller design itself is based on careful selection of controller inputs, selection of controller structure and feedback signals, and the calculation of filter parameters. There are numerous possible controller designs for the same controller goals. This Thesis tends to develop the best control solution for the particular operating difficulty under the study. More importantly, by developing suitable system models, and thoroughly discussing the controller objectives, this thesis paves the way for the future design of better, optimal HVDC control solutions.

III. THESIS OUTLINE

Chapter 1 presents three different HVDC modeling approaches. Different models are developed to cater for the different modeling purposes.

Detailed HVDC-HVAC model includes detailed dynamic models of both AC systems, dynamic DC system model, dynamic models of both PLL circuits and detailed representation of AC-DC converter interactions. It is intended for analysis of HVAC-HVDC interactions in the frequency domain $f<100Hz$. The model is of 45^{th} order.

Simplified, linear-continuous model is much easier to develop and it is much more convenient for the system dynamic analysis. It is used for the analysis of AC-DC composite resonance and for the analysis of non-linear effects in HVDC (control) systems.

Linear-discrete HVDC system model is developed using the sampled data systems theory. It is used in the frequency domain close to second harmonic, $f\approx100Hz$.

Chapter 2 presents a basis for a novel approach in TCR/TCSC modeling. Using Park's transformation to connect the control system model with the main circuit model develops the model. Since the model uses the same principles as the detailed HVDC system model, the model can be readily coupled with HVDC model, for the purpose of analysis of HVDC-HVAC-FACTS interactions.

Chapter 3 is concerned with the analysis of non-linear effects in HVDC systems. Two groups of non-linearities are analysed: non-linear effects as a consequence of HVDC control mode changes and non-linear signal transfer through AC-DC converters.

Chapter 4 analyses the composite resonance phenomenon on HVDC systems. A new controller is designed by using the state feedback theory, in an attempt to eliminate or modify the DC system natural resonance condition. Simulation results show that a noticeable reduction in DC side first harmonic is possible.

Chapter 5 studies the phenomenon of second harmonic oscillations on DC side of HVDC system. The causes of the oscillations and the negative effects on HVDC-HVAC system are thoroughly analysed. A new control method, based on DC feedback, is presented and an example of controller design is given. The possible controller use for the elimination of other negative effects is also studied.

Chapter 6 is focused on small-signal analysis of HVDC-HVAC interactions. The eigenvalue sensitivity analysis is used to study the sensitivity of the dominant eigenvalues with respect to the AC parameters. The study of influence of SCR changes on the system dynamic stability reveals completely different influence at rectifier side from that at inverter side. Analysis of inherent feedback loops between the AC and DC systems offers conclusions about interaction variables that should be controlled and those that are better to be left uncontrolled since they inherently improve the system stability.

Chapter 7 studies the dynamic stability of HVDC control loops, at both rectifier side and inverter side. The benefits and possible stability degradation are presented for all of the conventionally used control loops and for some of the alternative control methods, suggested in literature. The possible use of these control loops in the case of very weak AC systems is also studied in this Chapter.

Chapter 8 is focused on stability problems with very weak AC systems. A particular oscillatory mode mostly affected by SCR reduction is identified. The crucial part in the design of new controller is the selection of proper feedback signal, the signal that will move the affected mode without significantly affecting the remaining system eigenvalues. To maximize the controller performance, a simple second order H_∞ controller is placed in the feedback loop. The primary controller objective is improvement in the system robustness with respect to the AC system SCR changes.

At the very end of the Thesis, a list of the references closely related to the Thesis work is shown.

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