# Modeling, Control and Stability Analysis of VSC-HVDC Links Embedded in a Weak Multi-Machine AC System

by

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*Dedicated to my family, my husband, Xike, and my beloved Yaoyi*
*for their constant support and unconditional love.*
*I love you all dearly*.

# Abstract

The primary aim of this thesis is to investigate the small-signal dynamic performance of high voltage direct current (HVDC) transmission links based on voltage source converter (VSC) technology operating in parallel with the existing longitudinal Australian power system. This thesis presents the principle design methodology to achieve robust controllers for VSCs including inner current controller, outer power and voltage controllers as well as the supplementary damping controllers for enhancing the small-disturbance rotor-angle stability of a weak multi-machine power system with embedded VSC-HVDC links.

Three types of linear current controller schemes (proportional-integral, proportional-resonant and Dead-Beat schemes) are investigated and discussed in detail to identify the most suitable control method. Due to its wider bandwidth and superior performance under unbalanced operating conditions, the Dead Beat current controller is set as the inner current controller that has not been analysed in detail in the literature.

A new methodology for the selection and optimization of the parameters of the proportional-integral compensators in the various control loops of a VSC-HVDC transmission system using a decoupled control strategy is also proposed in this thesis. It was found that the new methodology is effective in a relatively strong system. However, since the method did not take various operating conditions and system disturbances into account, it will not be effective in a relatively weak system. The analysis shows that the design of robust outer loop controllers is challenging due to the limited bandwidth of the inner current controller in a weak AC system. Therefore, the second primary objective of the project was to develop a simple fixed parameter controller, which can perform well over a wide range of operating points within the active/reactive power (PQ) capability chart of the VSCs. To achieve this second objective, various grid conditions including various Short Circuit Ratios (SCRs), different X/R ratios and PQ capabilities of the VSC system were studied.

To support the primary objectives, a detailed higher order small-signal model of the DB controlled VSC is developed and systematically verified. As an original contribution, the study developed a new methodology to linearize the modulator/demodulator blocks which are used to develop the small signal models for several key components such as the sampling block, the delay block and the DB inner current controller.

The initial values of the PI/PID compensator parameters are obtained by applying the classical frequency response design methods to a set of detailed linear models of the open-loop transfer functions of the VSC-HVDC control system. It was concluded that an iterative process may be required after examining the co-operation performance of these controllers designed.

In the final chapter of this thesis, the small-signal rotor-angle stability of a model of the Australian power system with embedded VSC based HVDC links was examined. For the analytical purposes of this thesis a simplified model of the Australian power system is used to connect the high capacity, but as yet undeveloped, geothermal resource in the region of Innamincka in northern South Australia via a 1,100 km HVDC link to Armidale in northern New South Wales. It is observed that the introduction of the new source of geothermal power generation has an adverse impact on the damping performance of the system. Therefore, two forms of stabilization are examined: (i) generator power system stabilisers (PSS) fitted to the synchronous machines which are used to convert geothermal energy to electrical power; and (ii) power oscillation damping controllers (PODs) fitted to the VSC-HVDC link. In the case of the PODs two types of stabilizing input signals are considered: (i) local signals such as power flow in adjacent AC lines and (ii) wide-area signals such as bus voltage angles at key nodes in the various regions of the system. It was concluded that the small-signal rotor-angle stability of the interconnected AC/DC system has been greatly enhanced by employing the designed damping controllers.

# Statement of Originality

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# List of Publications

**Published**

[1] W**. Liying** and N. Ertugrul, "Selection of PI compensator parameters for VSC-HVDC system using decoupled control strategy," in *Universities Power Engineering Conference (AUPEC), 2010 20th Australasian*, pp. 1-7.

[2] **W. Liying**, N. Ertugrul, and M. Kolhe, "Evaluation of dead beat current controllers for grid connected converters," in *Innovative Smart Grid Technologies - Asia (ISGT Asia), 2012 IEEE*, 2012, pp. 1-7.

**Papers in Preparation**

[1] **W. Liying**, David J. Vowles and N. Ertugrul, "Reference Frame Transformation Approach for Small Signal Modeling of VSC with Stationary Frame Controllers"

[2] **W. Liying**, David J. Vowles and N. Ertugrul, " Generalized small signal modeling of DB controlled VSC"

[3] **W. Liying**, David J. Vowles and N. Ertugrul, "Robust controllers design for DB controlled VSC linked to a weak AC system"

[4] **W. Liying**, David J. Vowles and N. Ertugrul, "Damping controller design of DB controlled VSC operating in parallel with a Weak Multi-machine AC Power System "

# Symbols

| | |
|---|---|
| $A$ | system matrix |
| $_f$ | filter-bus values of the VSC |
| $P$ | active power |
| $_{ac}$ | alternating current quantity |
| $_N$ | base value |
| $C$ | capacitance |
| $_c$ | converter terminal values of the VSC |
| $I$ | current |
| $_d$ | d component in the dq frame |
| $D_e$ | damping torque |
| $K_d$ | derivative gain |
| $_{dc}$ | direct current quantity |
| $D$ | feedthrough matrix |
| $_I$ | imaginary component in the grid RI frame |
| $L$ | inductance |
| $B$ | input matrix |

| | |
|---|---|
| $K_i$ | integral gain |
| $s$ | Laplace factor |
| $_{max}$ | maximum value |
| $_{min}$ | minimum value |
| $_{o}$ | operating point value |
| $C$ | output matrix |
| $_{peak}$ | peak value |
| $\theta$ | phase angle |
| $_{abc}$ | phase quantities |
| $_{PLL}$ | PLL quantity |
| $K_p$ | proportional gain |
| $_{q}$ | q component in the dq frame |
| $^{C}$ | quantity in converter dq frame |
| $^{G}$ | quantity in grid RI frame |
| $Q$ | reactive power |
| $_{R}$ | real component in the grid RI frame |
| $_{ref}$ | reference value |
| $T_s$ | sampling time constant |
| $_{s}$ | source values of the interconnected grid |
| $_{P}$ | values of controlled plant |
| $_{db}$ | values of DB current controller |
| $K_v$ | gain of the voltage controlled oscillator |
| $U$ | voltage |
| $_{\alpha}$ | α component in the αβ frame |
| $_{\beta}$ | β component in the αβ frame |

# Acronyms

| | |
|---|---|
| AC | Alternating Current |
| AVM | Average Value Modeling |
| AVR | Automatic Voltage Regulator |
| DB | Dead Beat |
| DC | Direct Current |
| DG | Distributed Generation |
| EMT | Electro-Magnetic Transient |
| FIR | Finite Impulse Response |
| GM | Gain Margin |
| GPS | Global Positioning System |
| GTOs | Gate Turn-off Devices |
| $H\infty$ | H Infinity |
| HSV | Hankel Singular Value |
| IGBT | Insulated Gate Bipolar Transistors |
| Im | Imaginary |
| IMC | Internal Model Control |
| ITAE | Integral of the Time Absolute-Error Products |

| | |
|---|---|
| KCL | Kirchhoff's Current Law |
| KVL | Kirchhoff's Voltage Law |
| LCC | Line-Commutated Control |
| LL | Lead-Lag |
| LMI | linear Matrix Inequality |
| LTI | Linear Time Invariant |
| Max | Maximum |
| MIMO | Multi-Input Multi-Output |
| Min | Minimum |
| MTDC | Multi-Terminal Direct Current |
| PCC | Point of Common Coupling |
| PM | Phase Margin |
| PI | Proportional-Integral |
| PLL | Phase Lock Loop |
| POD | Power Oscillation Damping |
| PQ | Active-/Reactive- Power |
| PR | Proportional-Resonant |
| PSS | Power System Stabilizer |
| pu | Per Unit |
| PWM | Pulse Width Modulation |
| Re | Real |
| RHP | Right Half Plane |
| SCR | Short Circuit Ratio |
| SISO | Single-In Single-Out |
| SVCs | Static Var Compensators |
| TF | Transfer Function |
| VCO | Voltage Controlled Oscillator |
| VSC-HVDC | Voltage Source Converter- High Voltage Direct Current |
| WAPOD | Wide Area Power Oscillation Damping |
| ZOH | Zero Order Holding |