Estimation of the Short Circuit Ratio and the Optimal Controller Gains Selection of a VSC System

J. Z. Zhou, A. M. Gole

***Abstract*-- The optimal control gains of the VSC HVDC converter are very dependent on the Short Circuit Ratio (SCR) of the ac system to which the converter is connected. This paper introduces off-line SCR estimation based on pre-set switching status of the ac system. The control gains of the VSC HVDC system can be adjusted on-line to achieve optimal performance based on a calculation of the SCR. However, when a delay in changing the gain occurs, the quality of the on-line gain scheduling performance declines.**

***Keywords*: VSC-HVDC, SCR estimation, EMT simulation, gains scheduling.**

I. INTRODUCTION

IN an HVDC application, the interaction between the ac and dc systems can be parameterized by the strength of the ac system relative to that of the dc system. Studies have demonstrated that the strength of an ac system has a significant impact on the behavior of a VSC-HVDC system connected to it. The control of the VSC-HVDC system has to be designed or adjusted to enable optimal performance at different ac system strengths. Knowing the strength of the ac system at the converter bus provides very useful information for the optimization of the operation of the VSC-HVDC system.

To quantify the strength of the ac system at the converter bus of an HVDC system, the concept of Short Circuit Ratio (SCR) is used [1]. The SCR is defined as the ratio of the short-circuit MVA of the ac system at the ac bus to the rated dc power at that bus. For the system shown in Fig. 1, the ac system SCR at the converter bus is calculated as in (1).

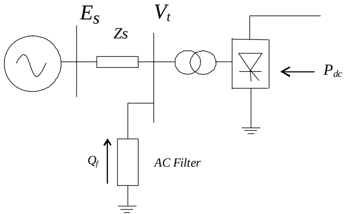


Fig. 1: The converter connected to an ac bus

$$SCR = \frac{MVA_{sc}}{P_{dc}} = \frac{V_t^2 / Z_s}{P_{dc}} \tag{1}$$

Where, Z_s is the Thévenin impedance of the ac system, P_{dc} is the rated dc power, and V_t is the rated line RMS voltage.

As can be seen, the SCR is essentially a measure of the Thévenin impedance of the ac system. A simple circuit analysis can be used to calculate the Thévenin impedance if the parameters of the circuit are known; however, different operating conditions (such as various loading, maintenance, contingencies, and fault conditions) cause the parameters of the circuit to continually change. The changing parameters of the circuit and the changing topology of the power network make determining the SCR difficult.

This paper shows the optimal control gains of the converter are very dependent on the SCR of the ac system the converter is connected to. One method to ensure the control gains are changed so they are optimal for the system operating condition is to estimate the SCR of the ac system and select the control gains using a look-up table. In this paper, SCR estimation using the monitored breaker status information and on-line gain scheduling using a look-up table are introduced. However, this paper shows when a delay in changing the gain occurs, the quality of the on-line gain scheduling performance declines.

II. SCR ESTIMATION

A. SCR Estimation using Monitored Information

A phaser monitoring unit (PMU) (synchrophasor) measures the phase and magnitude of voltage or current waveforms on an electric power grid using a common time source for synchronization [2]. This type of network is used in wide area measurement systems (WAMS). A supervisory control and data acquisition (SCADA) system at the central control facility presents system-wide data on all generators and substations in the system. As we know calculating the Thévenin impedance, hence the SCR is a simple circuit analysis exercise if all the relevant information regarding the power network is known (from a WAMS or from another method). Hence, the monitored information could be used to estimate the SCR, and from the SCR the network changes could be reflected quickly and the proper actions taken in a timely manner. However, SCADA system requires two to ten seconds to update the system information, and during this time the power network may experience unstable operations and may not be able to return to a steady state if the proper actions

---

J. Z. Zhou is with Teshmont Consultants LP, Winnipeg, Canada (e-mail: jzhou@teshmont.com).

A. M. Gole is with University of Manitoba, Winnipeg, Canada (e-mail: gole@ee.umanitoba.ca).

Paper submitted to the International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada July 18-20, 2013.

are not taken in a timely manner. Thus, SCR estimation could not be delegated to a SCADA system.

B. SCR Estimation Off-line

The SCR could be determined by off-line studies in which information regarding the status of breakers on various lines is used to consult a table that gives an estimate of the SCR.

Most utilities maintain load flow stability program data (e.g., in the format used by the popular Siemens/PTI stability modeling tool PSS/E). This information can be used to estimate the SCR of the larger ac network by the procedure discussed below. The following procedure shows how the SCR can be calculated for a given system configuration.

Assume the power system has *n* buses, *m* generators, *k* loads, and the HVDC is connected to bus number *n*. The diagram of the system is shown in Fig. 2.

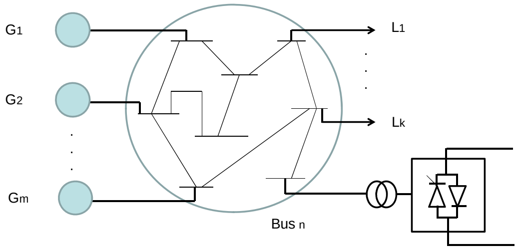


Fig. 2: Converter connected to an n bus ac system

The relationship between network bus (node) voltages and currents may be represented by node equations. The effects of generators, nonlinear loads, and other devices (dynamic reactive compensators and HVDC converters) connected to the network nodes are reflected in the node current. Hence, the network equation in terms of the node admittance matrix can be written as follows:

$$\begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \cdots & & & \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \cdots \\ V_n \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ \cdots \\ I_n \end{bmatrix} \tag{2}$$

In per-unit terms, the SCR at bus *n* is the reciprocal of the impedance of the network observed from bus *n*. When SCR is calculated, it is commonly accepted that a generator is treated as a voltage source behind the transient impedance X_d'. The loads can be treated as impedance embedded in the network or as current sources representing nonlinear loads. Based on this, the circuit diagram is changed to the one in Fig. 3.

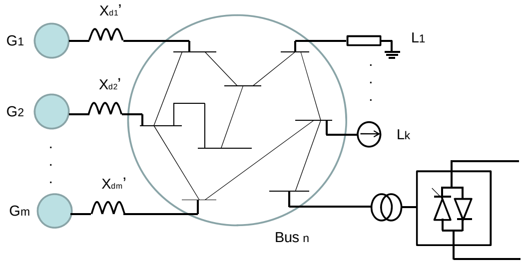


Fig. 3: Circuit diagram of a converter connected to an n bus ac system

In order to calculate the Thévenin equivalent impedance at bus *n*, the voltage sources are treated as short circuit and the current sources are treated as open circuit, as in Fig. 4.

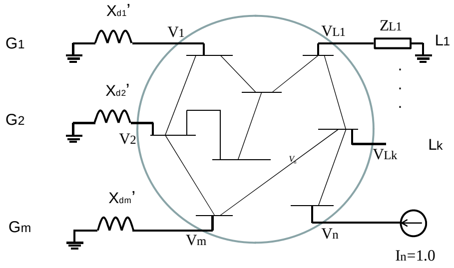


Fig. 4: Thévenin equivalent impedance at the converter bus

If a unit current source at bus *n* is applied, the voltage at that bus V_n is the Thévenin equivalent impedance. Based on (2), the above computation can be described as (3).

$$\begin{bmatrix} \left(Y_{11}+\frac{1}{X'_{d1}}\right) & Y_{12} & \cdots & Y_{1m} & Y_{1(m+1)} & \cdots & Y_{1(m+k)} & \cdots & Y_{1n} \\ Y_{21} & \left(Y_{22}+\frac{1}{X'_{d2}}\right) & \cdots & Y_{2m} & Y_{2(m+1)} & \cdots & Y_{2(m+k)} & \cdots & Y_{2n} \\ \cdots & & & & & & & & \\ Y_{m1} & Y_{m2} & \cdots & \left(Y_{mm}+\frac{1}{X'_{dm}}\right) & Y_{m(m+1)} & \cdots & Y_{m(m+k)} & \cdots & Y_{mn} \\ Y_{(m+1)1} & Y_{(m+1)2} & \cdots & Y_{(m+1)m} & \left(Y_{(m+1)(m+1)}+\frac{1}{Z_{L(m+1)}}\right) & \cdots & Y_{(m+1)(m+k)} & \cdots & Y_{(m+1)n} \\ \cdots & & & & & & & & \\ Y_{(n-1)1} & Y_{(n-1)2} & \cdots & Y_{(n-1)m} & Y_{(n-1)(m+1)} & \cdots & Y_{(n-1)(m+k)} & \cdots & Y_{(n-1)n} \\ Y_{n1} & Y_{n2} & \cdots & Y_{nm} & Y_{n(m+1)} & \cdots & Y_{n(m+k)} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \cdots \\ V_{n-1} \\ V_n \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \cdots \\ 0 \\ I_n \end{bmatrix} \tag{3}$$

Denote the admittance matrix, the first matrix on the left in (3), as the extended admittance matrix, Y_{ext}. Then the Thévenin equivalent impedance at the converter bus (bus *n*) is:

$$Z_{eq} = V_n = \left(Y_{ext}{}^{-1}\right)_{nn} \tag{4}$$

And the SCR at the converter bus (bus *n*) is:

$$SCR = \frac{1}{Z_{eq}} = \frac{1}{\left(Y_{ext}{}^{-1}\right)_{nn}} \tag{5}$$

In order to do an on-line change of the control gains based on the SCR information, a fast generation and breaker status monitoring system is needed. SCR values could be tabulated for various key operating configurations corresponding to the statuses of generators and breakers in the region surrounding the converter. These statuses could be determined by monitoring and reporting using high-speed communication links. Hence, by the use of a table look-up procedure, the reported breaker status data could be used to report the SCR value. When the optimal parameters of the converter for each SCR were calculated, by using the reported SCR values, the appropriate parameter set could be switched in, an approach known as gain scheduling [3].

III. SELECTION OF OPTIMAL CONTROL GAINS

A. Optimization-Enabled Transient Simulation

Using an emtp-type program in the controller design process to determine the optimal values of the design parameters requires conducting a number of runs, each with a different set of controller parameters. Many of these emtp-type programs contain a multiple-run feature that permits a series of runs with the parameter values varied in a random or sequential manner to be conducted. The user examines the results and selects the parameter values that provide the optimum results. This method deploys no intelligence in the way it spans the search space, and the search process can require a large amount of computational time.

Optimization-enabled electromagnetic transient simulation (OE-EMTS) for the design of control parameters for complex systems has been introduced recently. In OE-EMTS, the trial parameter settings in each run are selected by a nonlinear optimization algorithm and a sequence of simulation runs is conducted [4]. During each run, an objective function (OF) is evaluated; the smaller the OF is, the closer to the achievement of the objectives it is. This strategic selection of parameters usually results in an orders of magnitude reduction in the number of emtp runs required compared to the number of sequential search runs and random search runs required by the multi-run approach.

B. Parameter Optimization for Operation over a Range of Different SCRs

By using the OE-EMTS, control gains optimization was applied on a one-terminal VSC-HVDC system. Fig. 5 shows the simulated VSC-HVDC model with the VSC converter rated at ±320 kV (dc) and 500 MW. The nominal point common connection (PCC) voltage was 230 kV.

The modeled VSC converter was connected to a dc voltage source representing the remote converter (assumed to in control of the dc voltage) by a 50 km dc cable. The simulated system details are provided in the Appendix.

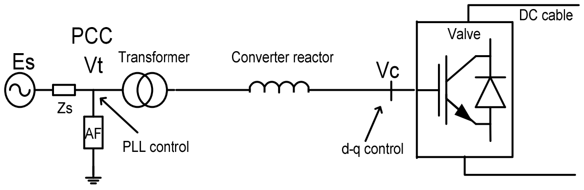


Fig. 5: EMT simulation VSC-HVDC model

The control system of the VSC was based on a fast inner-current control loop that controls the ac current. A synchronously-rotating two-axe (d-q) reference frame was used for the inner current control, which allowed fully-independent control of the active and reactive power flows of the VSC system. The references of the inner current control, i_d and i_q, were generated by the two outer controllers, ac voltage control and dc power control.

In this paper, the controller gains for the ac voltage controller and dc power controller were selected using a non-linear optimization method coupled with EMT simulation. All simulations have been conducted using the PSCAD/EMTDC program [5].

1) Selection of optimization method and objective function

The choice of nonlinear optimization algorithms is subjective. In the paper the Simplex method of Nelder and Mead [6] has been used as it is known to work well when the number of unknowns is less than 10 or so.

Selecting the correct objective function (OF) is an important part of any non-linear optimization problem. In this case, the objective function was designed to achieve the following design objectives:

- Control the dc power to the desired value
- Maintain the ac voltage at the desired value
- Keep the ac voltage free of lower-order harmonics

The OF is selected as in (6), and is the sum of three sub-objective functions, that are integral square errors (ISE) of each of the above objectives. Therefore, selecting parameters in the simulation that minimize ISE provides the best fit of the desired objectives.

$$
\begin{aligned}
&OF\_Pow(K_{p\_P}, T_{i\_P}, K_{p\_V_{ac}}, T_{i\_V_{ac}}) = OF_{\_P} + OF_{\_V_{ac}} + OF_{\_V_h} \\
&= w_1 \int_{t=T_{deblock}}^{t=T_{ss}} (P_{\_err})^2 dt + w_2 \int_{t=T_{deblock}}^{t=T_{ss}} (V_{ac\_err})^2 dt + w_3 \int_{t=T_{deblock}}^{t=T_{ss}} (\sum_n V_{h\_n})^2 dt
\end{aligned}
\tag{6}
$$

The first ($OF_{\_P}$) penalizes any deviation of dc power from its reference. The second ($OF_{\_Vac}$) penalizes the ac voltage magnitude error; and the third ($OF_{\_Vh}$) the sum of the square of the ac harmonics, i.e., the square of the total harmonic distortion (THD). Strictly speaking, the third sub-objective function, ought not to be required, as the PWM algorithm should eliminate low order harmonics. However, if the controllers act too fast, i_d and i_q are not quasi-constant, and the reference to the PWM controller is no longer sinusoidal. Adding the last term minimizes such an occurrence. The relative weights w_1, w_2, and w_3 for the three sub-objective functions are chosen by trial and error and are given to reflect the different importance of the sub-objective functions and to ensure their comparable contributions to the *ISE* based on the per unitized system parameters [7].

2) *Parameter optimization for a range of SCRs*

The gains for a range of different SCRs (SCR = 1.6, 1.8, 2, 3 and 4) were selected using OE-EMTS. The relative weights w_1, w_2, and w_3 for the three sub-objective functions are chosen by trial and error and the values $w_1=5$, $w_2=3$, and $w_3=7$ were used. The optimized PI controller gains are shown in table 1. K_{p_Vac} and T_{i_Vac} are ac voltage controller gains; and K_{p_P} and T_{i_P} are dc power controller gains. It can be seen that when the ac system SCR changes, a different set of controller gains give optimal performance for that particular SCR.

TABLE 1

OPTIMIZED GAINS FOR A POWER CONTROLLING CONVERTER

SCR	K_{p_P}	T_{i_P}	K_{p_Vac}	T_{i_Vac}
1.6	0.415	0.034	0.572	0.018
1.8	0.458	0.033	1.160	0.014
2	0.524	0.034	0.607	0.018
3	0.662	0.011	2.549	0.011
4	2.158	0.010	0.214	0.011

IV. ON-LINE GAIN SCHEDULING

A. *System Operating Condition Description*

This example, which assumes that an SCR change can be determined (perhaps by using the proposed breaker monitoring method discussed above), demonstrates that the optimal gains of table 1 can be selected so the system uses the best gains for the operating condition present. The VSC system in Fig. 5 is in rectifier operation at full rated power (500 MW) and connects to an SCR = 3 ac system.

The ac network connecting the real power controlling converter is shown in Fig. 6.

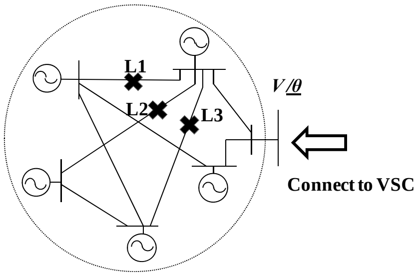


Fig. 6: VSC1 connected ac network

The lines L1, L2, and L3 will be switched on and off during the simulation, thereby changing the SCR. The ac system SCR is, in consequence, changed from SCR = 3 (all lines switched on) to SCR = 1.6 (L1, L2, and L3 switched off) to SCR = 1.8 (L1 switched on) to SCR = 2.0 (L2 switched on) and then back to SCR = 3 (L3 switched on) in three seconds, as shown in Fig. 7.

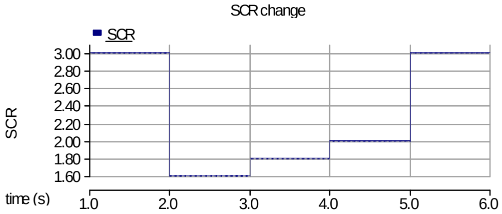


Fig. 7: SCR change of VSC1 connected ac network

The corresponding SCRs are calculated off-line based on the breaker status, and the optimized control gains used are available in a look-up table. If the SCR lies between two table entries, the gains corresponding to the lower (more critical) SCR are used. For example, as the tabulated values are only for SCRs of SCR = 2 and SCR = 3, the gains corresponding to SCR = 2 would be used when the actual SCR is SCR = 2.5. In this study, the optimized control gains sets for different SCRs are from table 1.

B. *Operation with No Gain Change*

Fig. 8 shows operation with a given set of gains that do not change as the SCR changes. These gains correspond to the optimized gains for SCR = 3. The study results show the system goes to unstable after the SCR changes, making the system a suitable candidate for gain scheduling.

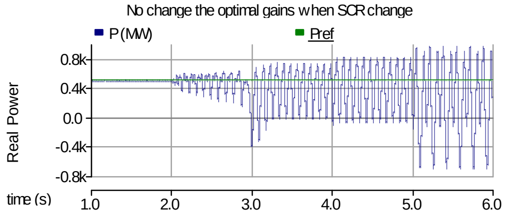


Fig. 8: Performance with gains optimized for SCR = 3

C. *Operation with Gain Scheduling*

Unlike the above case where gains were not allowed to change as a function of system strength, in this section gain scheduling is conducted plug in the optimal gains matched to the actual SCR. In gain scheduling, the strength of the system is determined by off-line studies. By assessing the status of several breakers in the network, an estimate for the Thévenin impedance and hence SCR can be made via a lookup table. This approach is further investigated below.

For operation with gain scheduling two studies were conducted. In the first study, in which the fast generation and breaker status monitor system is assumed to be available, the control gains scheduling was set to activate at the instant the SCR changes. However, in reality, even though the fast monitor system is available, there is always a time in detecting the SCR change. Hence, in the second study, the control gains scheduling was set to activate at various delay times as the SCR changes, although results are only shown for an estimated delay of 200 ms in this paper.

The phase angle difference between the ac voltage terminal and the converter ac bus is a measure of how quickly the system settles down into a stable steady state because it directly affects the active power transfer. Hence, the real power *P* and the phase angle difference *Delta* are shown in the figures below.

For the first study of this type of approach, a no delay (i.e. delay = 0 ms) was assumed between the breaker opening and the change of gains, and the optimal control gains were set from the preset look-up table. Fig 9 shows the system had good performance.

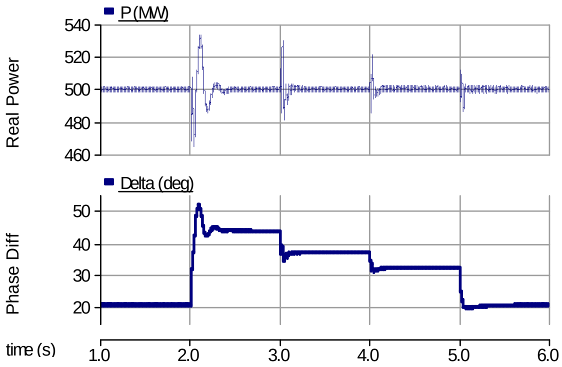


Fig 9: Control gains setting with no time delay

However, for the second study, when the optimal gains were set to 200 ms after the SCR changes (as shown in Fig. 10), the system was stable but had somewhat poorer performance, which is particularly onerous for the weaker SCR systems. As can be seen, the length of delay time plays a very important role in system performance. If the delay time is too long, the system will go to unstable.

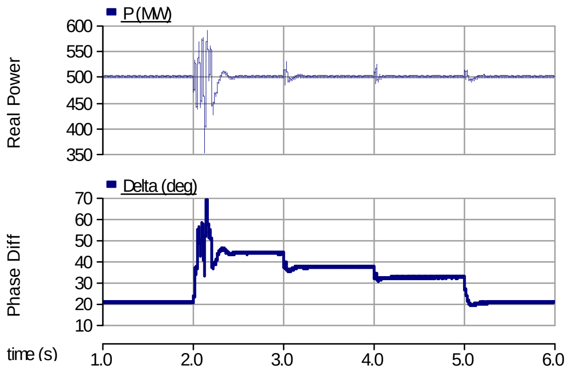


Fig. 10: Control gains setting with a 0.2 s time delay

V. CONCLUSIONS

The control gains of a VSC-HVDC system can be optimized by using optimization-enabled electromagnetic transient simulation (OE-EMTS). In this paper, VSC-HVDC system control gains were optimized using the PSCAD/EMTDC program. It was demonstrated that the optimal control gains of the converter are very dependent on the SCR of the ac system the converter is connected to. Different sets of control gains were optimized individually for different ac system SCRs.

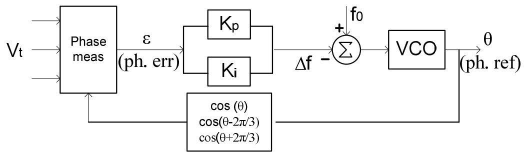
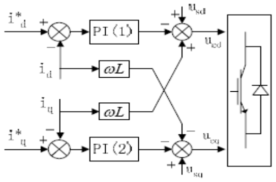
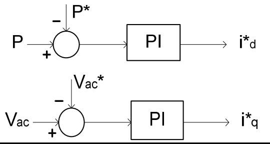
This paper showed by using the monitored breaker status, the SCR can be determined by off-line calculation and the use of the gain scheduling approach to obtaining optimal gains for dc grid converters on-line is possible. It was demonstrated that an optimized system performance for all system operation conditions was obtained by on-line setting of the control gains. However, when delays in changing the gains are included, the on-line gain scheduling performance becomes poorer. Even though an individual control gains set is optimal for one operating condition, it may cause instability for another operating condition during the control delay.

VI. APPENDIX

VSC-HVDC System Parameters

Rated ac system voltage (base)	230 kV, 60 Hz
Ac system impedance angle	80°
Rated dc power rating (base)	500 MW
DC voltage	±320 kV
Converter transformer rating	583 MVA
Converter transformer ratio	230 kV/333 kV
Converter transformer and reactor impedance	0.088 H (0.15 pu)
Passive high-pass filter	75 Mvar (15%)
Converter	2-level PWM
Switching frequency	900 Hz
DC capacitor	500 µF
DC cable: 321.5 kV and 1563 A, copper	50 km, 2400 mm^2

Controller Parameters

<table>
<tr><td colspan="2">PLL controller: K_p=50, K_i=250

</td></tr>
<tr><td>Inner controller:
K_p=0.5, K_i=50</td><td>
</td></tr>
<tr><td>Outer controllers:
P controller: K_p=0.5, K_i=35
V_{ac} controller: K_p=0.6, K_i=50</td><td>
</td></tr>
</table>

VII. REFERENCES

[1] IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities, IEEE Std 1204-1997.

[2] B. Milosevic, M. Begovic, “Voltage-Stability Protection and Control Using a Wide-Area Network of Phasor Measurements", *IEEE Trans. PWRS*, vol. 18, no. 1, pp 121-127, Feb. 2003.

[3] D. J. Leith, W. E. Leithead, “On Microprocessor–based arc voltage control for gas tungsten arc welding using gain scheduling”, *IEEE Trans. Control Systems Technology*, vol. 7, pp. 718-723, Nov. 1999.

[4] A. M. Gole, S. Filizadeh, R. W. Menzies, and P. L. Wilson, “Optimization-enabled electromagnetic transient simulation,” *IEEE Trans. Power Delivery*, vol. 20, no. 1, pp. 512-518, Jan. 2005.

[5] EMTDC User’s Guide. Winnipeg, MB, Canada: Manitoba HVDC Research Center, 2005

[6] J. A. Nelder and R. Mead, “A simplex method for function minimization,” Comput. J., vol. 7, no. 4, pp. 308–313, 1965.

[7] S. Filizadeh, A. M. Gole, D. A. Woodford and G. D. Irwin, “An optimization-enabled electromagnetic transient simulation-based methodology for HVDC controller design,” *IEEE Trans. Power Delivery*, vol. 22, no. 4, pp. 2559 - 2566, Oct. 2007.