A DC Link for the Power System Simulator

As a teaching tool

P.M. Abeyrathne[1], A.M.G.T. Abeysinghe[2], I.M. Karunanayake[3], P.M.H. Ranasinghe[4], M.P. Dias[5], J.R. Lucas[6]
Department of Electrical Engineering, Faculty of Engineering
University of Moratuwa
Moratuwa, Sri Lanka
pahanmadhawa@gmail.com[1], guvanthi@gmail.com[2], madhawa54imk@gmail.com[3], maheshhiran@gmail.com[4], dias@elect.mrt.ac.lk[5], lucas@elect.mrt.ac.lk[6]

***Abstract*—High Voltage Direct Current (HVDC) links are used for bulk power transmission due to its advantages over the alternating current (ac) transmission. A HVDC link between India and Sri Lanka has also being proposed. Hence it is a timely needfor the students in local universitiesto be able to study the behaviour of HVDC transmission. This paper presents the design of a DC link for a locally assembled Power System Simulator as a teaching tool.The objective is to use this design as a learning tool to study the behaviour of HVDC transmission under normal and abnormal operation. It is expected to be used for laboratory experiments related to HVDC transmission and Power Electronics, hence providing the opportunity for visualization of the behaviour of performance parameters at the significant points of the model.**

***Keywords*—Graetz Bridge, harmonic filter, gate pulse circuit, rectifier, inverter, converter**

I. INTRODUCTION

HVDC transmission offers advantages such as ability to transfer more power,absence ofstability issues, existence of lower short circuit fault levels and ease of tie line power flow control. Limitations of HVDC transmission are high cost of converters, reactive power requirement, generation of harmonics, and absence of overload capacity. [1]Since HVDC transmission has emerged as the most preferred technology for long distance bulk power transmission the proposed transmission link between India and Sri Lanka is HVDC, and it is a timely to provide with the teaching tool to study HVDC transmission.

A power system simulator is a teaching tool to observe the behaviour of a real power system. This paper presents the incorporation of a dc link to an existing power system simulator to model the behaviour of HVDC transmission. Fig. 1 shows the proposed incorporation of the DC link to the power system simulator.

The proposed DC link hasconverters on either side, each with the ability to operate either as a rectifier or an inverter allowing power flow in both directions. The Graetz Bridge, which is a six thyristor bridge, is used as the converter in the model. Filters are installed to minimize the effect from harmonics to the ac side. The controller will control the firing of the thyristors and control the power flow in the DC link. Fig. 2 illustrates the basic structure of the DC link.

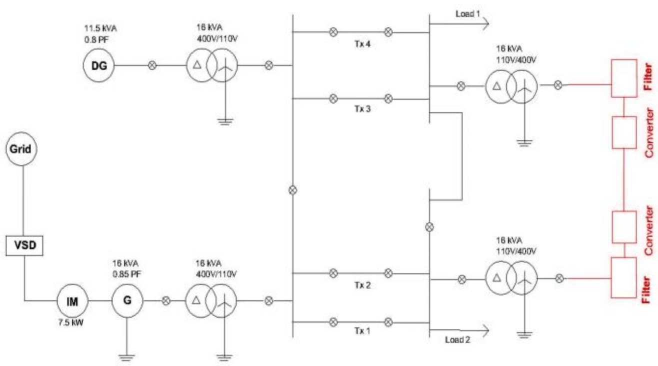


Fig. 1. Proposed incorporation of the DC link to the existing power system simulator

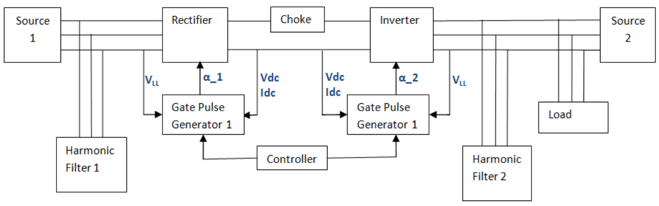


Fig. 2. Structure of the DC link model

The final outcome of this model will give the opportunity to observe the behaviour of the voltage and current parameters of both ac and dc sides, gate pulse signals for the converters, effect of filters on harmonic reduction and behaviour of the dc link on either failure of misfiring from the waveforms.

II. DEVELOPMENT OF THE DESIGN

A. *Specifications of the DC link*

The specifications for the DC link and its connection for the selected scenario are as follows.

- ac source: three phase delta – star transformers of 110/400V, 50 Hz, 16 kVA

Going by the operation of the actual HVDC links, this DC link too will be constant current controlled.

- DC link constant current (I_d): 10 A
- DC link maximum power flow: 5 kW
- Hence, DC link maximum voltage (V_d): 500 V

B. Converters

Three phase converters are designed as six thyristors bridge (Graetz Bridge). Thyristors are selected as the switching elements over IGBTs as they are desired for high power applications and even though this model is for simulation purpose, it is important to get the real picture in practice. It is also possible to join two six-thyristor bridges to form a twelve-thyristor converter for a smooth dc voltage. However in this scenario only a six-thyristor bridge is used for the simplicity of the design.

Preferred thyristor ratings are an on-state current of 10A, and a repetitive peak off-state voltage (V_{DRM}) of 500V. The requiredgate pulse for these are in the range of 15 ~ 20 mA. Fig. 3 shows a diagram of a converter unit connecting ac and dc sides. The thyristors are required to conduct as in the order of Fig. 4 for zero firing angle, for a duration of 120^0 per each cycle. Hence the gate pulses are provided as pulses of sufficient pulse width (in this case 30^0) at the beginning of each thyristor's conduction period. The gate pulse can be delayed to increase the firing angle.

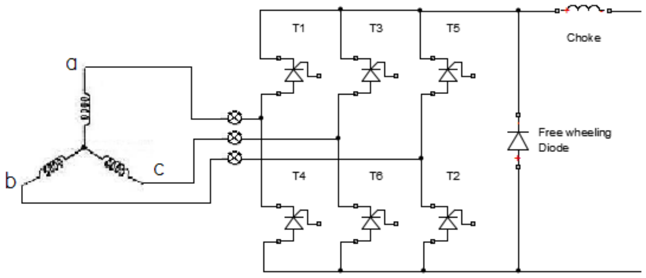
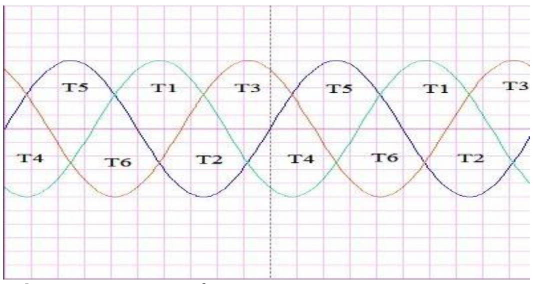
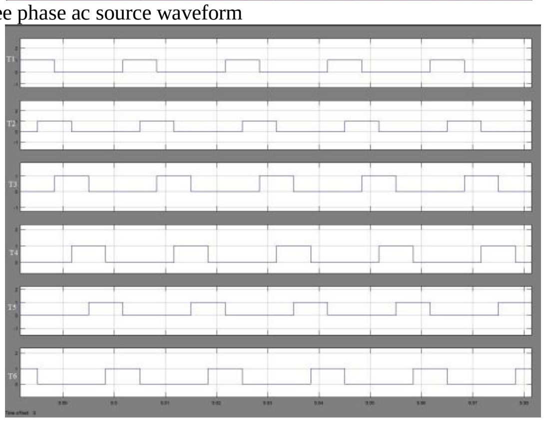


Fig. 3. Converter unit connected to ac and dc sides



(a) Three phase ac source waveform



(b) Period of each thyristor conduction

Fig. 4. Thyristor firing sequence

C. Gate pulse generation

The gate pulse of zero firing angle is generated from dedicated gate pulse generation circuits for the two converters and input to the controller to feed it adjusted with the calculated firing angle to the thyristors. The controller has two sub control systems (namely gate pulse controllers) for the two converters.

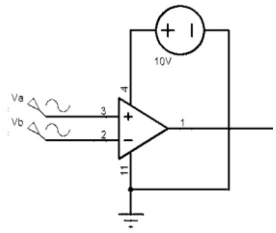
The gate pulse is derived from the ac source itself, so that it will be sensitive to frequency fluctuations in the source. Waveforms of each of the two phases from the source are compared with each other to detect the points of intersection, i.e. the zero crossing of the respective line to line waveform (V_{ab}, V_{bc}, V_{ca}) using comparators (OpAmps).

All the rising edges of the resulted signal are used to derive the gate pulse of zero firing angle for bottom thyristors of one leg and, the falling edges are used to derive the respective gate pulse for top thyristors of the respective leg. Fig. 5 and Table I explain this procedure using single comparator.

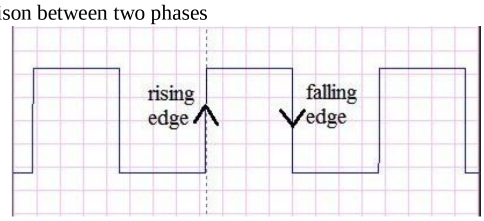
D. Controller

The controller has to maintain constant current and allowable voltage in the DC link. Hence feedback of the parameters of ac side line voltage, DC link voltage and current are input to the controller to compute the necessary firing angle to control the DC link voltage so as to maintain constant DC link current.

Depending on the direction of the power flow one converter operates as the rectifier and the other as the inverter.The rectifier is to operate in constant current control mode and the inverter in constant extinction angle control.



(a) Comparison between two phases



(b) Output from the comparator consisting 180^0 pulses

Fig. 5. Use of a comparator to compare two phases

TABLE I. COMPARATOR INPUT AND OUTPUT TO DERIVE GATE PULSE

Comparator input		Comparator output	
Non-inverting input (V+)	Inverting input (V-)	Rising edge	Falling edge
a	b	T6	T3
b	c	T2	T5
c	a	T4	T1

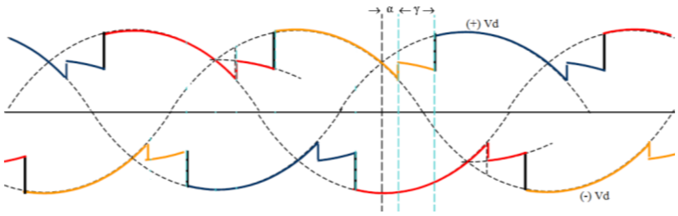


Fig. 6. Rectifier output waveform denoting angles

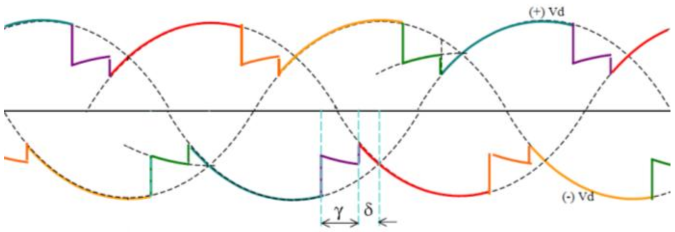


Fig. 7. Inverter waveforms denoting angles

From the basic equations for the three phase thyristor rectifier, with firing angle α ($0^0 \leq \alpha \leq 90^0$) and commutation angle γ, (1) can be derived.

$$V_d = \frac{3\sqrt{2}}{2\pi} V_{LL}[cos\alpha + \cos(\alpha + \gamma)] \quad (1)$$

From further simplifications (1) can be reduced to (2), where Ls refers to internal inductance of the ac source. (Fig. 6)

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} cos\alpha - \frac{3\omega L_s I_d}{\pi} \quad (2)$$

In this scenario, the ac source on either sides are three phase delta – star transformers of 110/400 V, 50 Hz, 16 kVA. Hence based on the assumption that internal reactance (ωLs) is 5% of base impedance, internal reactance can be obtained as 0.5 Ω from basic calculations.

The required firing angle α to allow constant current flow in the DC link can be obtained by substituting the values of V_d and V_{LL} feedback from the circuit, to the equation 2 (with I_d = 10A).

The inverter has to operate in the constant extinction angle control. By similar derivation of formulae as for the rectifier, the formula for the inverter can be derived as in (3) where δ is the extinction angle for the inverter ($90^0 \leq \alpha \leq 180^0$) (Fig.7). [2]

$$-V_d = \frac{3\sqrt{2}}{\pi} V_{LL} cos\delta - \frac{3\omega L_s I_d}{\pi} \quad (3)$$

However, once the current of the DC link is fixed for all values of power flows (less than 5 kW), hence allowing constant current control of the rectifier, the extinction angle has to be varied with the power flow. Then a number of characteristics may exist for the inverter for variable power flow and the controller has to identify the point of intersection of the two characteristics of the rectifier and the inverter. Fig.8 shows the graphical interpretation for the point of operation for the rectifier and inverter for a predefined constant power flow. The points of intersection of two characteristics in positive and negative y axis are for the power flow in two directions [7].

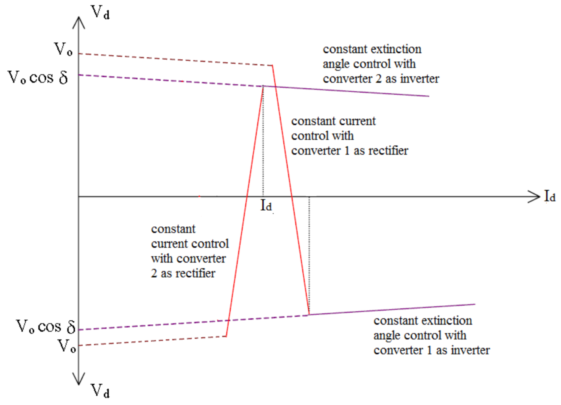


Fig. 8. Characteristics of the converters for power flow to both directions

E. Power flow control

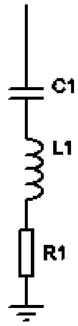
A phase angle difference between two ends is necessary to create a power flow. For this purpose, pulse isolation transformer is to be installed at one side to create a difference in phase angle. This pulse isolation transformer will have the turns ratio of 1:1.

The direction of power flow is input to the controller, so that it will formulate the appropriatefiring angle for the rectifier and the extinction angle for the inverter and, send the relevant gate pulses via gate pulse controllers. The power flow control in the DC link is achieved by controlling the current in the DC link. The controller will use the previously described feedback control system to operate the DC link under constant current.

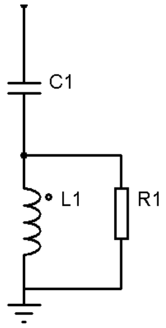
F. Filter Design

Harmonics are generated in the ac sides of both the converters as a result of the current commutation action of the thyristors. These are required to be suppressed using harmonic filters, or else will lead to increased losses or overloading of the system equipment.Since the ac waveforms are sinusoidal and three phase, even harmonics and harmonics of multiples of three are naturally nullified and the harmonic filters should be installed to reduce the effect of other harmonics. Meanwhile the filters are also expected to contribute for the reactive power requirement for the converters. The basic principle of operation for the harmonic filters is to divert the high frequencies (i.e. harmonics) via low impedance paths. They are capacitive at the fundamental frequency, hence providing reactive power requirement.

In this scenario, four single tuned band-pass filters are designed to eliminate the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics. A high pass filter is to be used to eliminate the rest of higher order harmonics. These three phase filters basically consist of resistor, inductor and capacitor elements as shown in Fig. 9. The values of the parameters can be calculated from the equations given (4) to (11) accordingly.



(a) Single Tuned Filter



(b) High Pass Filter

Fig. 9. Harmonic filters

The single tuned band-pass filter eliminates a specific harmonic (with frequencies namely $\omega_r = n\omega_0$). As per the Fig. 9-(a), the resonance frequency can be equated by(4). The values of the elements for the filter can be calculated from (5) to (7).$\omega_0$refers to the fundamental frequency, n_r refers to the order of harmonic to be eliminated, q refers to the quality factor,which is a measurement of the sharpness of the filter and Q_F refers to the reactive power requirement. [3]

Reactive power requirement for a converter is in the range of 40% to 60% of the power rating of the dc link. [8] For this model, the reactive power requirement is approximated as 2500 var (50% of the power rating) and a part of it is shared among the filters.Value of q for single tuned band pass filters should normally lie in the range of 40 to 80, in this case selected as 50.

$$\omega_r = n_r \omega_0 = \frac{1}{\sqrt{L_1 C_1}} \quad (4)$$

$$C_1 = \frac{{n_r}^2 - 1}{{n_r}^2} \times \frac{Q_F}{\omega_0 {V_p}^2} \quad (5)$$

$$L_1 = \frac{1}{{n_r}^2 {\omega_0}^2 C_F} \quad (6)$$

$$R_1 = \frac{n_r \omega_0 L_F}{q} \quad (7)$$

Table II interprets the calculated values for the filter parameters. Based on the theoretical values obtained, practical values are given to tally with the capacitors available in the market.

The parameters of high pass filter can be calculated from (8) to (10). Value of q for high pass filters should normally lie in the range of 2 to 10, in this case selected as8.[4]

$$C_1 = \frac{q}{\omega_0 V_{LL}^2}\left(1 - \frac{1}{n^2}\right) \quad (8)$$

$$L_1 = \frac{1}{(\omega_0 n)^2 C_1} \quad (9)$$

$$R_1 = n\sqrt{\omega_0 L_1} \quad (10)$$

For this model calculated values for high pass filter are C_1 = 159nF, L_1 = 221mH and R_1 = 142 Ω.

Meanwhile non-characteristic harmonics (other harmonics of different order)due to non-ideal behaviour of the converters are also possible, but since the practical applications do not show a significant impact on the power quality, their impact is being neglected in this model.

In order to smoothen the dc link current flow, simply an inductor (choke) can be introduced to the dc link. Since any load is not directly connected to the dc link, comprehensive filters for dc side is unnecessary. The value of the inductor to be used can be calculated from (11). [5]

$$L_c = \frac{\pi - 3}{\pi} V_{LL} \quad (11)$$

Accordingly, for this model, an inductor of 6 mH should be incorporated.

G. *Incorporation to the Power System Simulator*

In integrating the aforementioned subsystems to the existing power system simulator, circuit breakers with sufficient capacity included with relays for protection needs to be installed. Breakers to isolate the filters from the system can also be installed so as to observe the effect of the filters on harmonics.

III. Practical Considerations

Despite the theoretical design a number of additional steps are included due to practical limitations and protection requirements.

A. *Isolation of Gate Pulse circuit*

It is important to isolate the gate pulse input to the thyristors either optically or magnetically for the protection of the thyristors. Either dedicated pulse isolation transformers can be used for magnetic isolation or dedicated opto-isolators can be used for optical isolation. Presently, optical isolation is preferred over magnetic isolation due to its increased reliability, accuracy and efficiency. [6] Hence a circuit with dedicated opto-isolators for power switching devices is used for this design to transmit the output gate pulse from the controller to the thyristor. The basic principle of building the opto-coupler circuit is shown in Fig. 10 with connections to a single thyristor.

TABLE II. Parameters of Single Tuned Filters

Harmonic	q factor	Reactive Power	Theoretical C_1 (uF)	Practical C_1 (uF)	Actual Reactive Power (var)	Theoretical L_1 (mH)	Practical L_1 (mH)	R (Ohm)	Practical R (ohms)
5	50	230	13.3	10.0	173.1	30.5	40.5	1.0	1.0
7	50	150	8.8	8.2	139.1	23.4	25.2	1.0	1.0
11	50	100	6.0	5.6	93.8	14.0	15.0	1.0	1.0
13	50	80	4.8	4.7	78.6	12.5	12.8	1.0	1.0
Total		560			484.6				

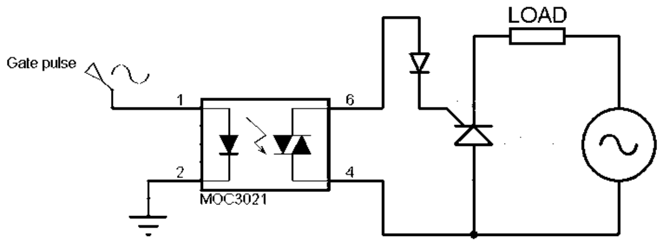


Fig. 10. Connection of a dedicated opto-coupler to single thyristor

B. *Thyristor protection*

The reverse recovery current generated in thyristors when they are reverse biased may result in unacceptably large over voltages because of series inductance. Hence snubber circuitry as in Fig. 11 needs to be installed.

Based on the assumption that the reverse recovery time t_{rr}=10 µs, equation (12) can be used to calculate the reverse recovery current for single thyristor,

$$I_{rr} = \left(\frac{di}{dt}\right) t_{rr} = \left(\frac{\sqrt{2}V_{LL}}{2L_c}\right) t_{rr} \tag{12}$$

Following this calculation the capacitance and the resistance values for the snubber circuit can be calculated from the formulae (13) and (14).

$$C_s = L_c \left(\frac{I_{rr}}{V_{LL}}\right)^2 \tag{13}$$

$$R_s = 1.3 \times \sqrt{2} \times \frac{V_{LL}}{I_{rr}} \tag{14}$$

Each thyristor leg is also provided with a fuse of ratings just beyond the rated current of the dc link to ensure further protection of the thyristors.

IV. Development as a Learning Tool

Being a learning tool, this design will have the provision to check the behaviour of the voltage and current parameterspreferably via connection to an oscilloscope at either side of each converter. It will also facilitate to observe the waveforms of the gate pulses for the converters as preferred and the effect on dc link voltage and current waveforms by variable firing angle.

Under the abnormal behaviour of the dc link, this model will facilitate to observe the effect of failure of one or more thyristors, misfiring of one or more thyristor and short circuit faults in the dc link.In spite, the effect of both ac harmonic filters and dc filter (choke) can be observed by switching the individual filter units.

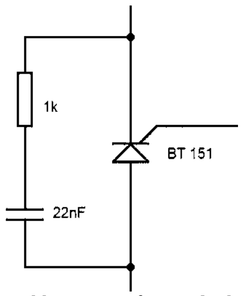


Fig. 11. Snubber circuit for single thyristor.

The final outcome of this model is expected to bring out a number of laboratory experiments under HVDC and power electronics for the undergraduates.

V. Conclusion

The design phase of the DC link for an existing power system simulator presented had the challenge to identify the optimum technology for each application for teaching purposes. The Graetz Bridge with six thyristors is used for the converters of the DC link. Alternative methods of generating the gate pulses for the converters were attempted to select the most appropriate way and a dedicated circuit has been developed using comparators and a programmable controller. Snubber circuits and optical isolation of gate pulse circuits have been adopted to ensure the protection of the converters.

Control of power flow has been achieved by allowing the rectifier to operate in the constant current mode and the inverter in the constant extinction angle mode with feedback control from the DC link. Four single tuned band-pass filters and a high pass filter are proposed to minimize the effect of harmonics in the ac sides of the converters and provide a part of reactive power requirement and, the dc side is provided with a choke.

A user friendly external interface is used in the model for simulating and observing the performance parameters of a HVDC link.

ACKNOWLEDGMENT

The heartiest gratitude of this paper presenters will go to all the staff members of the Department of Electrical Engineering Department, University of Moratuwa.

REFERENCES

[1].S. Singh, *Electric Power Generation, Transmission and Distribution*. New Delhi: Prentice-Hall of India Private Limited, 2006, pp. 282-305.

[2]N. Mohan, T. Undeland and W. Robbins, *Power electronics*. New York: Wiley, 1995.

[3]M. Zamani and M. Mohseni, 'Damped-Type Double Tuned Filters Design for HVDC Systems', *International Conference on Electrical Power Quality and Utilization*, pp. 1-3, 2007 [Online]. Available: http://ieeexplore.ieee.org/xpl/abstractMetrics.jsp?arnumber=4424205. [Accessed: 06- Nov- 2015]

[4]D. Khare, 'Reactive Power Compensation and Harmonic Filters for HVDC Classic', 2015.

[5]L. Grigsby, *Power Systems*, 3rd ed. New York: CRC Press Taylor and Francis Group, 2012, pp. 24-18.

[6]U. Patnaik, *Back to back SCR_interface by opto_coupler or pulse Transformer.avi*. 2010 [Online]. Available: https://www.youtube.com/watch?v=miyQHCq3HRs. [Accessed: 17- Nov- 2015]

[7]J. Lucas, *High Voltage Engineering*, 1st ed. Sri Lanka, 2001, pp. 184-204 [Online]. Available: http://www.elect.mrt.ac.lk/HV_Chap11.pdf. [Accessed: 02- Aug- 2015]

[8] Wikipedia, 'HVDC converter station', 2015. [Online]. Available: https://en.wikipedia.org/wiki/HVDC_converter_station#Reactive_Power. [Accessed: 24- Nov- 2015]