An Overview of HVDC Power Transmission System with Voltage Source Converter

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Abstract-A general platform is introduced to study thedynamics of power systems with high voltage dc (HVDC) transmission links. Small-signal stability, voltage stability, and interaction phenomena of power systems with both line-commutated-converter HVDC (LCC-HVDC) and voltage-source- converter HVDC (VSC-HVDC) are addressed using the proposed platform. In quest of high efficiency, power density and problems of bulk power transmission over long distance, requirement of full control over power transmission and growing interest to incorporate renewable energy source into the grid has led to develop a new era of high voltage direct current (HVDC) transmission system. The researchers have developed many new HVDC configurations and voltage source converter (VSC) based HVDC transmission is one of them. Their high efficiency, compact size, high reliability, short installation and commissioning period and low operating and maintenance cost make it suitable choice for HVDC transmission. The HVDC system with power converter acts as a backbone and provides high reliability with a long useful life to support the AC electrical system. The power conversion i.e. AC to DC or vice versa is achieved by controllable electronic switches in a 3-phase bridge configuration.The wide spread use of AC-DC converters for various applications has resulted in power quality pollution leading to failure of sensitive equipments, reduced efficiency, etc.

Keyword- *line-commutated-converter, voltage-source- converter high efficiency, compact size, high reliability,*

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I. Introduction

The industrial growth of a nation increases consumption of energy, particularly electrical energy. This leads to increase in the generation and transmission facilities to meet the increasing demand. Till the early seventies, the power demand doubled in every seven to ten years which requires considerable investment in the electric power sector.The depleting reserves of non-renewable sources and responsibility of supplying energy to the consumer at reasonable cost has led to establish more fossil fuel based thermal power plants at remote site location. Moreover, hydro power plants away from hundreds of kilometers from the load centers are the costliest option to fulfill the varying consumer's demand. The remote cited thermal power plant, costliest hydro power generation source and increasing interest towards sharing benefits of different energy sources have created interest to interconnect neighboring power systems and develop large power grids.Remote power generation and system interconnections have led to a research in the area of efficient power transmission at high power level. The increase in voltage level is not always feasible in AC transmission. The power flow in AC transmission depends on phase angle difference in voltage vector that varies with the load demand. The generation changes according to the load demand which alters frequency of the generator, thereby results control complexity in AC transmission. The problems of bulk power transmission over long distance, requirement of full control over power transmission and growing interest to incorporat renewable energy source into the grid has led to develop a new era of high voltage direct current (HVDC) transmission system .The HVDC system with power converter as a core component provides high reliability with a long useful life to support the AC electrical system as a backbone. The power conversion i.e. AC to DC or vice versa is achieved by controllable electronic switches in a 3-phase bridge configuration. More than 100 HVDC projects have been installed across the world as on date and this number is expected to grow in future due to expansion of renewable energy sources and advancement in solid-state converter technology.

II. Benefits of HVDC System

The HVDC system has number of technical, economic and environmental benefits that favors the HVDC transmission instead of AC transmission.

A. Technical Benefits

The DC-link makes possible to exchange power between the two asynchronous AC networks. The asynchronous interconnection via DC-link isolates interconnected part and can be used for any level of power quality control such as harmonic distortion, unbalance, flicker voltage etc. The asynchronous interconnection facilitates large number of AC system to interconnect across the world such as Japan and South America HVDC link which has different nominal frequency (50Hz and 60Hz) and link between eastern USA and western USA, having different voltage levels.

In long AC cable transmission, large amount of reactive power flows due to large cable capacitance which limits maximum possible power transmission over the given distance, whereas no technical limit of potential length in DC cable. Moreover, solid insulated DC cables are manufactured for high voltage level. Unlike AC transmission, DC transmission reduces number of cables for a desired power rating, thereby needs less repairing and way-leave requirement. Apart from economical design, DC cables are subjected to less stress of over current due to absence of any appreciable current in the core material. As the demand of HVDC projects using submarine cable increases, more cost effective design are being developed for example ABB built Nor Ned link, a longest submarine high voltage cable transmission with 580km in the world.A number of HVDC projects around the world e.g. USA, Canada, Brazil, China and India through overhead lines are found for long distance power crossing. The HVDC system does not require reactive power in DC transmission and doesn't provide short circuit current to the interconnected AC systems under fault condition.

The fast controllability is most desired feature of present transmission system due to increased concentration of renewable energy resources i.e. solar, wind etc. Due to intermittent nature of renewable sources, power flow pattern experiences more fluctuation in the grid. The HVDC provides fast, accurate and fully controllable option. Moreover, advancement of semiconductor technology and programming support has created enormous control possibilities in HVDC transmission.

To meet peak demand while optimizing the use of existing infrastructure, numbers of alternatives are available for AC transmission system to upgrade transmission capacity of existing lines. This can be achieved by increasing number of conductors per phase, voltage level, and replacement of conductor with better performance, line current maximization or conversion of AC lines to DC.

lines. Among them, conversion of AC line to DC line is considered as better option due to outstanding stability and controllability in HVDC system.

B. Economic and Environmental Benefits

HVDC transmission losses are lower than AC transmission of the same power capacity, although, installation cost of HVDC project is high. However, after a 'break even distance' i.e. 700-800km for overhead lines and 50km for underground cables, HVDC provides the lowest running cost. Figure 1.2 depicts cost evaluation between AC and DC transmission. Moreover, the DC cables i.e. buried or extruded polymer cable increase interest alternative to traditional cable due to economical and environmental reasons. Many AC networks are connected via DC-link through overhead line or cables, by mean of these links, existing generating plants operate more effectively i.e. giving extra generation at no investment. The interconnection between available generating plants gives efficient operation with obvious environmental benefits. The greatest environmental benefit is achieved by linking hydro generation and thermal generation sources. As the thermal power plants run more efficiently with constant demand and peak demand can easily be compensated by hydro power plants. The HVDC line with two conductor bundles is equivalent to double circuit AC line with six conductor bundles, therefore, it occupies less space and less virtual impact; collectively lesser environmental impact and provides facilities of underground cabling in urban areas. The HVDC interconnections are used for mutual support i.e. reserve sharing, and saving of generation capacity.The development of self-commutated switch i.e. IGBT, GTO permits maximum power transfer irrespective of AC voltage phase relationship, it also compensates required reactivepower to maintain AC bus voltage at the interconnected buses with fast and accurate control against any transient conditions. Moreover, HVDC is a vital solution for asynchronous AC interconnection. Hence, HVDC offers sustainable, efficient and reliable operation with economic and environment friendly features and considered as ultimate flexible transmission option for future transmission grid.

III. SYSTEM DESIGN

The voltage source converter (VSC) is the prime unit of a VSC based HVDC system, therefore, its design and performance evaluation is most important to have desired results. This chapter deals with design, modeling and control of VSC for back-to-back AC interconnection and long distanced transmission between two AC networks using HVDC system.

The functionality of VSC based HVDC system depends on proper selection of switch rating, interfacing reactor, and DC-link capacitor. The voltage source converter is designed with self-commutated IGBT switch which has combined features of MOSFETs and bipolar junction transistor (BJTs) switch. It has gate, driven like MOSFETs and voltage/current characteristics like BJTs, thereby IGBTs operate at very high current (>1000A) and switched at higher frequency more that 3 to 4 times as compared to GTOs. Therefore, the IGBT switch has high current handling capability and ease of controllability. However, HVDC converters can be switched up to 2 kHz frequency to make the switching loss within acceptable limit .

The DC-link capacitor acts as an energy buffer to stabilize DC-link voltage under normal as well as transient condition. The large value of capacitor may create harmonic distortion in input source whereas low value may cause instability in power transmission. Hence, proper selection of DC-link capacitor is a significant part in VSC designing [Mohan, 2003; Rashid, 1990]. The DC-link capacitor is designed based on number of factors such as power rating of VSC HVDC system, magnitude of DC link voltage, and recovery time under transient condition etc. The selection of interfacing inductor and DC-link capacitor depends on rating of point-of-common coupling (PCC) load and AC main voltage.

A. Design of Back-To-Back VSC Based Hvdc Power Transmission

Back-to-back (BTB) HVDC interconnections are used for power transfer between two independent neighboring AC systems via DC-link. The rectifier and inverter are located in same station having practically zero meter long transmission between them. The BTB configuration is used for number of reasons such as: To connect asynchronous high-voltage power systems with different frequencies.The VSC based HVDC system is composed of self-commutated switch, interfacing reactor, DC-link capacitor. The rectifier and inverter are connected back-to-back as shown in schematic diagram of Figure

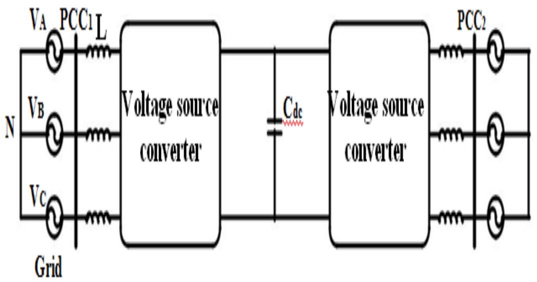

Figure: Schematic diagram of VSC based BTB HVDC system

- **Selection of VSC switch rating**

The proposed HVDC system is designed for rated voltage for 33kV, 100MW with 0.9 pf PCC load. Therefore,
Supply current = Apparent power/ (3×supply voltage)

Irms = VA/ (3×Vs) = P/ (3×pf×Vs)

The RMS value of supply current is calculated as 1.94kA for 100MW load. The crest factor is usually considered 2 or 3, therefore, peak load current (Ip) is calculated for crest factor value '2', as,

Ip = 3.88kA

Therefore, the current rating of IGBTs for VSC designing is considered as 4kA.

The voltage rating of IGBTs switch is calculated as, Vp = √2×Vrms

Considering the isolated transformer 33/2.1kV is used in between supply and the VSC, the peak voltage is calculated as 2.96kV. Considering the safety factor 2, the switch rating comes to be 5.96kV. Therefore, rating of IGBTs switch in VSC designing is selected as 6.5kV, 4kA. However, IGBT switch is available of the current rating 1.2kA [Lobsiger, et al., 2015], therefore to increase current rating of the valves, four parallel switches are connected in the designing of HVDC system.

- **Selection of Interfacing Inductor**

The rating of interfacing inductor (L) should be selected for limiting the 5^{th} harmonic current in conventional line commutated thyristor based HVDC system.This selection criteria is also applicable in VSC based HVDC system

The calculation of interfacing inductor is given as,

Base impedance Zbase = $(kV)^2$ / MVA== $(33)^2/100$ = 10.89

XL = 0.2*Zbase , L = XL / 2πf

The interfacing inductor is estimated 0.336H value

- **Selection of DC-link capacitor**

The system is designed for 100MW, 0.9pf PCC load. The total MVA rating of converter is 112MVA with 100MW active power load and 50Mvar reactive power load. By considering safety factor, MVA rating is considered as 120MVA. The VSC is rated for full reactive power of 50Mvar whereas 1.09% is used for active power rating. Extra 9% of active power (9MW) is compensated by DC-link capacitor voltage .It is desired to settle DC-link voltage within six cycles for 5% overshoot allowed under Transient condition. By considering all factors, DC-link capacitor is calculated as follows,

$E = P.\Delta t = (1/2). Cdc.\{(V^*dc)^2-(Vdc)^2\}$

The capacitor, Cdc is obtained as 1250mF.

B. Design Of Vsc Based Hvdc System With Transmission Line

Whenever the power has to be transmitted over long distance, HVDC transmission is the most economical option as compared to high voltage AC transmission. Two remote AC systems are coupled together via typically 300 to 3000km by overhead line or 10 to 800km by DC cable .The schematic diagram of VSC based HVDC system with long distance transmission line is shown in Figure 3.2. The two AC networks areconnected with 75km long transmission line for power balance. The interfacing reactor and DC-link capacitor plays significant role.

The interfacing inductor is selected to limit 5^{th} harmonic current as required inconventional thyristor based HVDC system.

Base impedance Zbase = $(kV)^2$ / MVA

XL = 0.2*Zbase

L = XL / 2πf

Interfacing inductor (L) is obtained 6.9mH.

- **Selection of DC-link capacitor**

For 100MW, 0.9 pf load, total system rating S = $\sqrt{P^2+Q^2}$ = 112MVA with 48.42MVar reactive power, by considering safety factor, total rating is assumed 120MVA. The system is designed with full reactive power whereas 1.09% is considered for active power. Extra 9% active power (9MW) is assumed for compensation provided by DC-link capacitor

[Hammad, *et al.*, 1990]. In this system, it is desired to settle the DC-link voltage within six cycles for5% maximum overshoot or undershoot allowed. Therefore, the value of DC-link capacitor is obtained as,

E = P.Δt = (1/2). Cdc. {(V*dc) ^{2}-(Vdc) ^{2}}(3.10) Substituting the values, P = 9MW, Δt = 6*20ms, Vdc = 180.5kV, V^*dc = 190kV in Eqs(3.10) the value of Cdc is estimated as 2040μF, therefore, capacitor for 2200μF is selected by considering practical value.

C. Modeling Of VSC Based Hvdc System

The system is controlled by pulse width modulation (PWM) technique, having constant pulse amplitude with modulating duty cycle. The duty cycle of VSC switch is decided by three variables, namely referenced DC-link voltage, 3-phase voltage and 3-phase current.The PWM technique based current multiplier technique is used to control VSC based HVDC system. This technique has two simple proportional and integral (PI) cascaded control loops, namely voltage control loop and current control loop.The controller output is influenced by controller gains and voltage error, obtained by comparing desired and measured quantity, thereby transmits controlled output in every sample time (T) to final output. The proportional controller quickly respond to change in error deviation, wherein integral controller eliminates offset error. The function of both controllers are discussed as below,

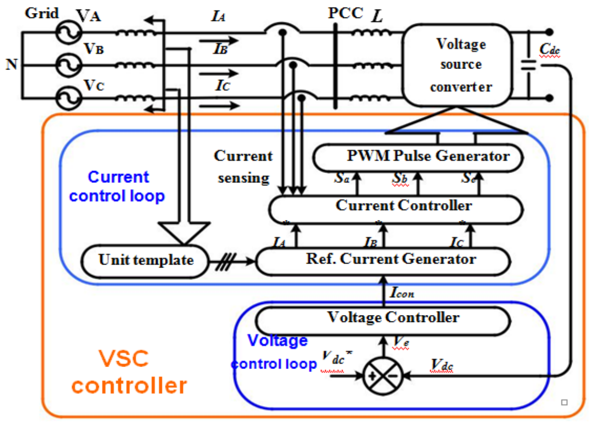

Figure: Schematic diagram of current multiplier approach

D. Performance Evaluation Of Vsc Based Hvdc System

The designed VSC based HVDC system is controlled with current multiplier approach. In the control scheme, voltage and current controller gains are tuned with Zeigler-Nichols approach. Since the transmission system is subjected with number of transient conditions such as load perturbation, non-linear load, voltage sag, unsymmetrical line fault at input AC mains.

Load perturbation conditions: Sudden decrease between 0.1 to 0.9 Pu in rated loadfor one half cycles to one minute or sudden increase of load between 1.1 to 1.8pu forone half cycle to one minute is considered as load perturbation condition.

Voltage sag: Voltage sag happens when RMS voltage decreases between 10 to 90% of nominal voltage for one half cycle to one minute.

Non-linear load condition: A load is considered non-linear if impedance changeswith the applied voltage. The changing impedance means that the current drawn bythe load will not be sinusoidal even when it is connected to a sinusoidal voltage.

Unsymmetrical fault: Those fault in the power system which gives unsymmetricalfault currents (unequal fault current in the line with unequal phase displacement) areconsidered as unsymmetrical fault.

The performance of the designed system is demonstrated under load perturbation, voltage sag, non-linear load condition, unsymmetrical fault i.e. tapped load fault for short duration at both point-of-common coupling in VSC based HVDC system. The both configurations i.e.BTB and long distance transmission are considered for performance evaluation in VSC based HVDC system.The sets of waveforms i.e. supply voltage (VA) and supply current (IA), DC link voltage (Vdc), load current (IAL) are used to show system performance under various transient conditions.

CONCLUSION

In this, VSC based HVDC system has been described to emphasize on need of power quality consideration under various transient conditions such as load perturbation, voltage sag, nonlinear load and unsymmetrical fault.A detailed investigation has been carried out in designing and control of VSC based HVDC system for two applications i.e. back-to-back as well as long distance power transmission. The choice of particular configurations depends on the utility requirements.

The modeling of the control scheme has been given and simulation model has been developed in MATLAB-Simulink environment. The results of performance simulation of VSC based HVDC systems have been presented with their detailed discussion. The VSC-HVDC system is found to have THDi higher than 5% under steady state as well as transient state conditions and do not meet the requirement of power quality standard IEEE 519. The system needs to feed with hybrid system such as multipulse converters for power quality improvement at points-of-common coupling.

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