Control Strategies For HVDC Converters: Optimization, Efficiency, And Performance

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Abstract- *The converters and their control strategies play an important role in converting, transmitting and improving the performance of high voltage direct current (HVDC) system. There are different types of converter and their control strategies being employed in the HVDC system such as line commutated converter, voltage source converter (VSC) etc. However, the existing converter controllers have still some limitations on certain deficiencies in certain aspects such as in weak AC grid or at high voltage and power level. Thus, an advanced converter control strategy is very much important in order to ensure optimal power transfer with minimal loss and stable voltage. This paper presents a comprehensive review of the advanced control strategies to address the problems and enhance the performance of the VSC based HVDC (VSC-HVDC) transmission system. A detailed study on the overview of VSC-HVDC and their converter classifications are investigated. The main contribution of this paper is to carry out the different types of VSC-HVDC control strategies in controlling voltage, current, power and the control parameters of the HVDC transmission system. This review also highlights several factors, challenges, and problems of the conventional VSC-HVDC controllers. Furthermore, the review provides some suggestions for the advanced control for the future research and development of the HVDC system.his paper represents a novel design and control architecture of the continuous stirred tank reactor (CSTR) based on its mathematical equivalent modeling of the physical system. The plant is formed analytically for the normal operating condition of CSTR. Then the transfer function model is obtained from the process. The analysis is made for the given process for the design of controller with Convectional PID (trial and error method), Ziegler Nichols method, Fuzzy logic method and Model Reference Adaptive method. The simulation is done using MATLAB software and the output of above four different methods was compared so that the Model Reference Adaptive Controller has given better result. This thesis also compares the various time domain specifications of different controllers.*

Keywords- Converter, voltage source converter, line commuted converter, control strategies, HVDC transmission

I. INTRODUCTION

High Voltage Direct Current (HVDC) transmission has emerged as a key technology for long-distance power transmission, interconnecting asynchronous AC grids, integrating renewable energy sources, and enhancing grid stability. HVDC converters serve as the backbone of these systems, converting AC power to DC for transmission and vice versa at the receiving end. Control strategies for HVDC converters are essential to regulate voltage, current, and power flow, ensuring efficient and stable operation.

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The introduction of HVDC systems involves discussing the significance of HVDC technology in modern power systems, emphasizing its advantages over conventional AC transmission, such as lower losses, increased controllability, and better integration of renewable energy sources. It also outlines the key components of HVDC systems, including converters, transformers, and control systems, highlighting their roles in power transmission and grid stabilization.

Furthermore, the introduction addresses the challenges associated with HVDC transmission, such as converter control complexity, grid integration issues, and dynamic response requirements. It sets the stage for the case study by emphasizing the importance of optimizing control strategies to address these challenges effectively. The introduction concludes by outlining the objectives and scope of the case study, which aims to analyze and optimize control strategies for HVDC converters to enhance efficiency, performance, and grid stability.

In high voltage direct current (HVDC) transmission system, converter becomes an interface between DC and AC networks where the conversion between the two signals takes place. The converter could act as a rectifier to convert from AC to DC signal, or an inverter to revert back from DC to an AC signal. Development of power electronics has innovated the converter technology that further improves the quality of the output signal and stability of HVDC system control. Ever since HVDC was first introduced, the converter used motor-generator set for electromechanical conversion that has a series connection on the DC side and a parallel connection on

AC side. In the 1940s, electronic or static type converter was built in the form of Line-Commutated Converter (LCC), which was manufactured with electronic switches to be turned on. The converter was comprised of a set of valves which is the actual component that did the conversion. Before the 1970s, the mercury arc valve was used in the LCC while after 1970s, thyristor valve was used. LCC was typically used when very high capacity and efficiency were required. However, the LCC type converter had a shortcoming of having Short Circuit Ratio (SCR) more than 2 that resulted in instability and poor efficiency. In 1997, Voltage Source Converter (VSC) was emerged and it was first commissioned in Sweden. VSC was designed with electronic switches to be turned on and off, unlike LCC that can only be turned on.

problems, especially during voltage drop or distorted. Its flexibility in controlling power makes it suitable to integrate with renewable energy networks. Unlike LCC type converter that has a limitation of SCR value more than 2, this VSC type converter does not have such negative point which means it can interface with the grid without the necessity of

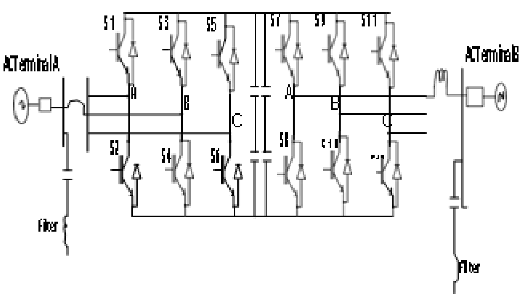


Fig1. The topology of a two terminal-HVDC transmission system

synchronous generators, for instance, offshore wind power plants. Furthermore, it also ensures continuous AC voltage regulation. With the VSC type converter, control of power flow can be reversible. Besides, the reactive power compensation is not required in its operation. In addition, power cables are lighter in weight that results in lower installation cost. Lastly, the VSC type converter also exhibits low order harmonics and requires less space at the converter station. VSC is incorporated with Pulse Width Modulation (PWM) technique based on the idea of solid state switches which has “gate-turn-on” and “gate-turn-off” features. PWM offers benefits such as fast switching rate even at high voltage and current rating. Though VSC based HVDC provides a significant contribution in power transmission system, the limitations of this converter have been reported, especially when the DC system is connected to a very weak AC grid. When a fault occurs in a HVDC transmission system interfacing with a very weak AC system, it is difficult to provide reactive power at the required rate This will cause severe voltage distortion and the converter will fail to operate correctly, hence gives more commutation failure and provides slow recovery of the system. To address the problems, many control strategies of VSC-HVDC transmission system have been explored. Furthermore, HVDC is designed to further enhance the controllability and stability of the system on various possible cases that might occur in the system. In essence, VSC-HVDC needs to be controlled in order to have a precise and accurate active power, reactive power and the output frequency of the inverter.

the AC signal from AC terminal A to DC signal. The DC voltage will then be transferred via a DC transmission line towards VSC2 which is another converter specifically an inverter that will regulate the DC link voltage and invert back the DC signal to AC signal. The parameters of the two AC networks i.e. AC terminal

A and AC terminal B could be different, for example, AC terminal A has 275 kV, 50 Hz AC sources while AC terminal B has 230 kV, 60 Hz AC system. This is one of the advantages of using HVDC transmission system as compared to HVAC. The converter that accommodates rectifier at sending end and inverter at the receiving end is comprised of IGBT switching valves. PWM technique is applied in these switching valves with a specific switching frequency, for instance, 1620 Hz. The basic VSC schematic diagram is shown in **Fig.2** which includes a six- pulse converter having six switching devices. The switching devices are configured in series or parallel in a high power converter. The equivalent circuit of VSC converter connected to a three-phase AC source is shown in **Fig. 3.** The relationship of voltage and current between the converter and AC source is expressed in (1) . The converter produces a three-phase output voltage either in a square shape or in a PWM shape at the necessary frequency . The output waveform is determined by the pulse modulation technique and the type of the circuit layout. The active and reactive power depends on converter configuration, either shunt-connected or series-connected. The formation of shunt-connected VSC is shown in **Fig. 4**

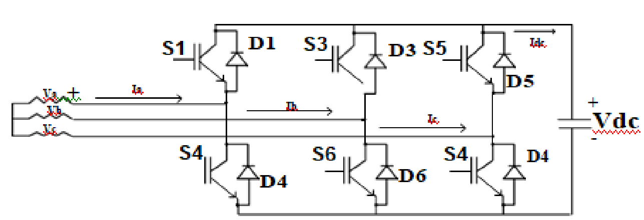


Fig2. VSC Schematic Diagram

OVERVIEW OF VSC-HVDC TRANSMISSION SYSTEM

The VSC uses transistors as the main component in its operation. The Insulated Gate Bipolar Transistor (IGBT) is the most commonly used transistor that combines the good features of both bipolar transistors and Metal Oxide Semiconductor Field Effect Transistors (MOSFETs). The IGBT switching - valves in VSC converter have a high input impedance of a MOSFET and exhibit lower on-state voltage drop and greater turn-off time than MOSFET. Furthermore, IGBT exhibits strong controllability, higher switching frequency and provides an output voltage at any preferred amplitude or phase angle. The topology of VSC HVDC transmission system is presented in Fig. 1. The AC terminal A is a sending end from the AC network while AC terminal B is a receiving end AC network. VSC1 is a converter specifically as a rectifier that will convert

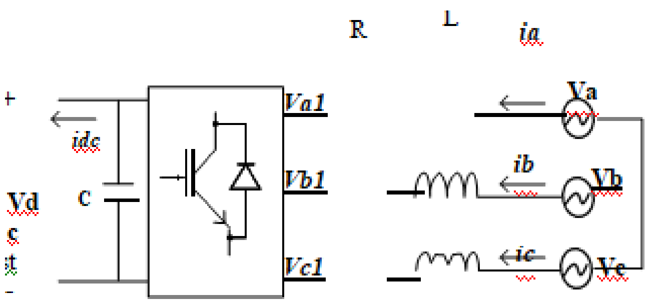


Fig3. The equivalent circuit of a VSC connected with AC Source

$$va=va1+iaR+j\omega Ldia/dt$$
$$vb=vb1+ibR+j\omega Ldib/dt \text{------------------} \quad (1)$$
$$vc=vc1+icR+j\omega Ldic/dt$$

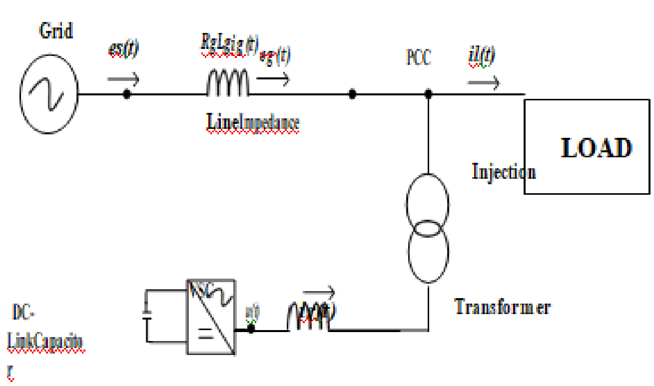


Fig4.Singlelinediagram ofShunt-connectedVSC

III. HVDC BASED VSC CLASSIFICATION

Many configurations of VSCs have already been developed and applied in numerous applications. VSC can be classified into several different configurations such as two level converter, three-level converter, modular multilevel converter (MMC) and hybrid VSC. However, the investigation is required to address the challenges of the existing converters as well as to invent the new technologies. The further research is still ongoing to search for new alternatives in order to develop a robust and the improved VSC type converter.

A. TWO LEVEL CONVERTER (6-PULSE BRIDGE)

Two level converter in a three phase system is also known as a six- pulse bridge. This converter consists of IGBTs with inverse parallel diodes and DC capacitors [36]–[38]. Every AC output phase voltage is operated within two discrete voltage levels with respect to the positive and negative terminals of DC voltage as shown in (5)

B. THREE LEVEL CONVERTER

Three level converter has the significant contribution in improving the harmonic performance of the converter. It utilizes three discrete voltage levels at every phase of the AC signal such as +½ Ud, 0 and -½ Ud, as shown in Fig. 6. The DC capacitor is divided into two areas where the diode valves are connected between the capacitor mid-point for one phase, the other two phases are at one- quarter and a three-quarter point between the two capacitors . The IGBTs are switched on in such way that first two, middle two and last two are switched on for obtaining positive output voltage (+½ Ud), zero output voltage, the negative output voltage (-½ Ud) respectively.

C. MODULAR MULTI-LEVEL CONVERTER (MMC)

Like a two-level converter, modular multi-level converter (MMC) is designed using six valves installed in three sub modules. Each valve is connected from one DC terminal to one AC terminal which is identical to the two-level converter. The difference is that each valve in MMC has a controllable voltage source and each valve has its own storage capacitor. Every sub-module (SM) is comprised of two series connected IGBTs across the capacitor where the common-point of them is connected to the AC voltage source.

Thus, the generated voltage from each SM could be either 0 or Usm (SM capacitor voltage). Consequently, the valve can produce stepped voltage waveforms that are very close to a sine-wave by connecting an appropriate number of SM in series. This kind of waveform will contain a very low level of harmonic distortion. The flow of current is maintained endlessly in all converter valves for the whole cycle in the MMC, thus there is no “ON-state” and “OFF state” like the other type of VSC converters. The DC current is divided equally into the three phases while the AC current is divided equally into upper and lower valves of each phase.

D. HYBRID VSC

This is an advanced type of VSC where it combines both two-level and MMC converters. which includes combination of soft-switched H- bridge converters, M2C cells and the H-bridge converters consisting of series IGBTs in order to generate required voltage rating at the fundamental frequency. The M2C cells are arranged such that it will provide a wave-shaping function, however, it only operates at part of the main line current, hence its rating is lower than the alternative arrangements. The main objectives of this combination are to reduce power loss and to achieve the high harmonic performance of the MMC while maintaining its compact design with efficient capability and controllability. Besides that, a triple harmonic modulation scheme can be added to the combination so it can enable voltage control for the purpose of real and reactive power regulation. This combination can also produce low distortion AC current and therefore AC filters may not be needed. In addition, if a DC fault occurs, enough voltage might have been produced to control the inductor current. Further research on enhancing the structure can be explored by employing a half bridge where losses might be reduced. Using half bridge means the number of conducting IGBTs is halved, so the design will be more compact as compared to full H-bridge.

ISSUES AND CHALLENGES

Even though VSC has been dominant to conventional LCC type converter, there are several shortcomings that need to be addressed. Firstly, grid interaction stability issue such as angle and voltage stability limitations of VSC-HVDC. Secondly, the limitation of the converter like the maximum current and voltage restrictions of the power converter. These limitations need to be considered in designing an efficient controller of VSC-HVDC system. Besides, the selection of controller parameters is also a critical aspect of a controller design as it will affect the system behaviour. Inappropriate parameter selection might lead to system instability. Moreover, there are many problems that could possibly occur when VSC-HVDC is interconnected to a weak AC network.

A. HIGH DYNAMIC OVERVOLTAGE

When there is an interruption in DC power transfer, reactive power absorption by converter will drop to zero. Then, the AC voltage will be increased due to the shunt capacitor and harmonic filter. This will require high insulation of equipment in the system, otherwise, this equipment will possibly be damaged because of this overvoltage.

B. VOLTAGE INSTABILITY

In this scenario, direct current will be increased in order to restore the system to scheduled power. Consequently, firing angle at inverter will also increase to maintain the commutation margin. Reactive power drawn by the inverter is increased, however reactive power produced by the shunt capacitor is low. This will cause AC voltage to
drop yielding towards voltage fall .

C. HARMONIC RESONANCE

Harmonic resonance might come from parallel resonance at shunt capacitor and harmonic filters, also when the AC system operates at lower harmonics. The conversion process at the converter station becomes more difficult with the increasing demand of capacity link concerning to the increasing short circuit capacity at the commutating bus. Since the converter produces harmonics in current on the AC side and harmonics in voltage on the DC side, harmonics generated by the DC link is also increased when the DC power transmission is increased. On top of that, the interaction between AC and DC in the converter station also generates small amounts of uncharacteristic harmonics even though an equidistant pulse firing scheme is in use. It becomes worse when these uncharacteristic harmonics are injected into poorly damped resonant networks which will make the operating condition of the HV DC/AC system more difficult. If there is a DC side series resonance at the fundamental frequency, the low order harmonic resonance at the AC side might create more severe problems.

D. VOLTAGE FLICKER

During switching between the shunt capacitor and reactor, and in rapid changing loads, voltage fluctuations could occur that would result in AC voltage flicker Besides, the inter-harmonics is caused by variation in loads that could be the cause of voltage flicker. In fact, handling with inter-harmonics can be more difficult than harmonics. The frequencies in inter-harmonics are not integer multiple of the fundamental frequency, and the magnitude of voltage waveform might fluctuate even in the condition of waveform distortions .

Equipment Damage: Voltage flicker can cause damage to sensitive equipment like computers, electronics, and machinery, leading to malfunctions or even permanent failure.

Reduced Equipment Lifespan: Continuous exposure to voltage flicker can shorten the lifespan of electrical equipment due to the stressit imposes on components.

Operational Disruptions: Flickering lights and equipment malfunctions can disrupt operations in industrial, commercial, and residential settings, leading to productivity losses and inconvenience.

Voltage Stability Issues: Voltage flicker can be an indicator of broader voltage stability issues within the power grid, potentially leading to cascading failures if not addressed promptly.

Regulatory Compliance: Utilities may be subject to regulations regarding acceptable levels of voltage flicker to ensure the quality and reliability of power supply to customers.

Customer Dissatisfaction: Persistent voltage flicker can result in customer complaints and dissatisfaction due to the inconvenience caused by frequent disruptions and equipment damage.

Safety Concerns: Voltage fluctuations can pose safety hazards, particularly in environments where precise control of electrical systemsis critical, such as hospitals or manufacturing facilities.

VSC HVDC BASED CONTROL METHODS : VOLTAGE CONTROLLER

This is the most basic control of VSC-HVDC system where it uses voltage control scheme. In addition, it has direct control of the reactive power controller and power angle controller. In this scheme, the phase-angle shift, controls the active power between VSC and the AC system. Power angle, is obtained from terminal voltage and current value. The desired power angle achieves an error which will be processed by the angle controller to become reference phase angle. The VSC voltage magnitude controls the reactive power. The reactive power also depends on the modulation index.

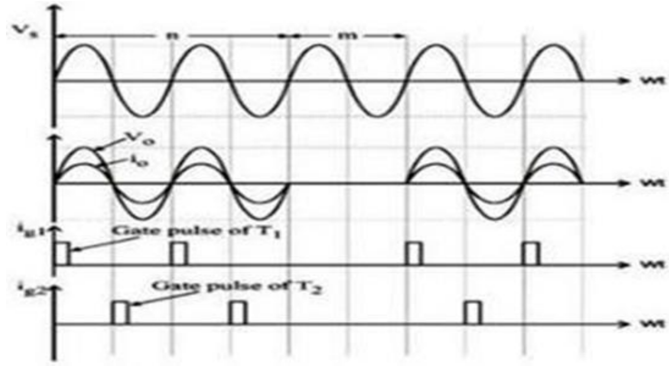


Fig 5. Gate Pulse Indicator

VECTOR CURRENT CONTROLLER :

This method is designed to overcome the problem encountered by the voltage controller that cannot control active and reactive power independently. It basically involves a transformation from three phase steady state into the d-q axis to control active power and reactive power separately. The separate active and reactive power control is possible in this method by a fast inner current control loop with d-q composition technique. The current in the inner current control loop is decoupled into d and q components using grid voltage as a phase reference.

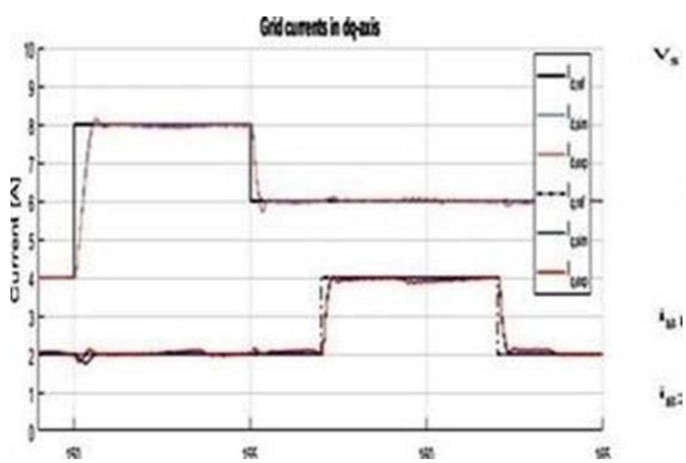


Fig 6. Vector Current Indicator

POWER SYNCHRONIZATION CONTROLLER :

Power Synchronization Controller (PSC) approach can be applied to integrate VSC-HVDC with weak AC network. The principle of PSC is the same as a synchronous machine in AC system that uses internal synchronization mechanism, hence it does not require any addition short circuit capacity of AC system . The VSC terminal gives voltage support to the weak AC system during the operation of a synchronous machine. fundamental idea of power-synchronization control of grid- connected VSCs is that VSCs synchronize with the ac systems through the active-power control instead of using a phase- locked loop (PLL), similar to the operation of a synchronous machine

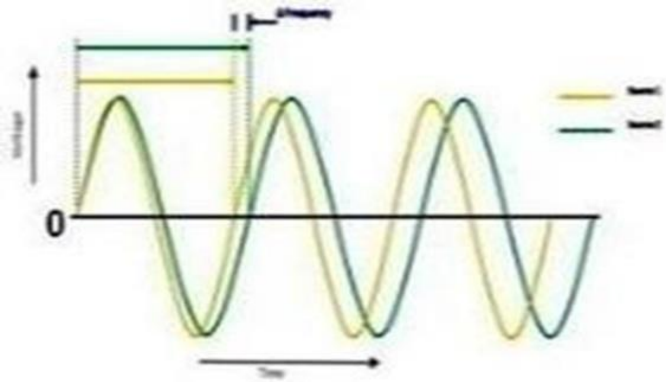


Fig 7. Power Synchronization Indicator

ABC FRAME CONTROLLER :

ABC controller method can be applied to MMC based HVDC transmission system that is interconnected to a very weak AC system as shown in The schematic diagram of the ABC frame controller is presented in Fig. In this method, VSC is regulated in ABC frame without PLL operation. The active power and reactive power are controlled exclusively at the point Of coupling (PCC). ABC phase reference current is determined from positive and negative a-b stationary frame sequence component voltage at PCC.

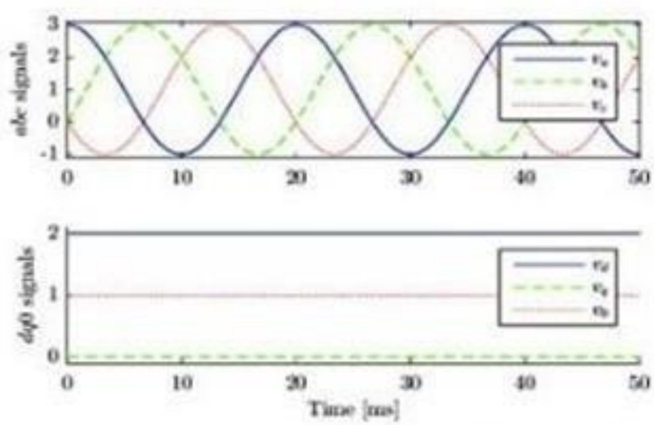


Fig 8. ABC Frame Indicator

VOLTAGE DROOP CONTROL :

The voltage droop control technique is employed in Multi terminal HVDC system, for instance, offshore wind farms and node or branch scheme as depicted Power source comes from wind farm grid merging into wind farm converter. Grid side converter on the load side will be controlled to maintain its DC voltage and to execute power-sharing. When a severe voltage fault arises in the AC grid, the fault current might drive the converter up to its current limit. Wind farm converter changes into voltage regulation mode while the grid source converter tries to extract maximum power without DC voltage regulation.

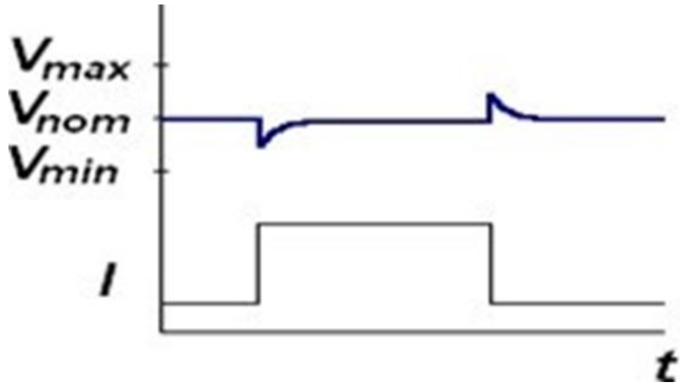


Fig 9. Voltage Drop Indicator

ADAPTIVE BACK STEPPING CONTROLLER:

Adaptive back stepping controller method can also be applied to offshore wind farm grids like voltage droop controller as explained in IV.F. The principle of adaptive back stepping controller is based on the DC cable dynamics where its objective is to maintain DC bus voltage at a rated value and DC voltage at constant value all time. On DC side, VSC acts a controlled current source. The system is said to be stable in overall when the regulation of local DC voltage on the DC side is stable. The construction of a DC transmission line.

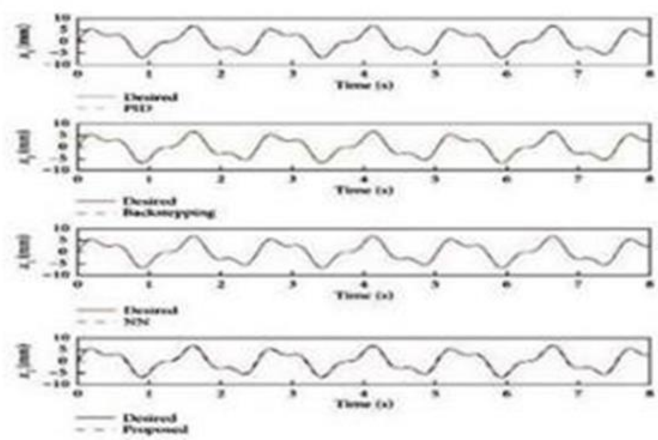
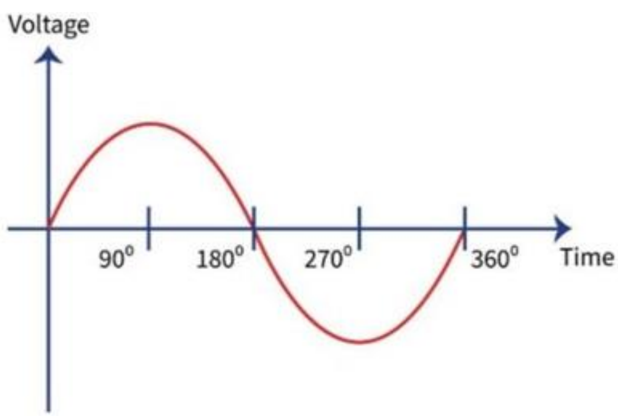


Fig 10. Adaptive Back Stepping Indicator

FLEXIBLE POWER CONTROL METHOD :

This method is suitable for Hybrid Multi-Infeed Direct Current (HMIDC) application in which the transmission system is designed using many DC links LCC and VSC type converters. The system configuration for flexible power control method The flexible method configuration In this configuration, there are many layers of control scheme as below;

- The active power and reactive power controller which are operated independently by the Inner vector-current controller.
- AC voltage and active power controllers.
- Intermediate adaptive current limiter to mitigate the problem of pre-setting current limit at power controller outputs.



PROPORTIONAL INTEGRAL (PI) DECOUPLED CONTROL :

This decoupled control on Proportional-Integral (PI) method is based on selection and optimization of the parameters in the PI compensators in different control loops of a VSC-HVDC transmission system.The control organization along with current controllers and outer- loop controllers. Reference values are produced by outer loop controllers in order to fasten the action of inner-loop current-controllers. These reference values are tracked by active and reactive currents controlled by the inner loop controllers via feed-forward decoupled control.

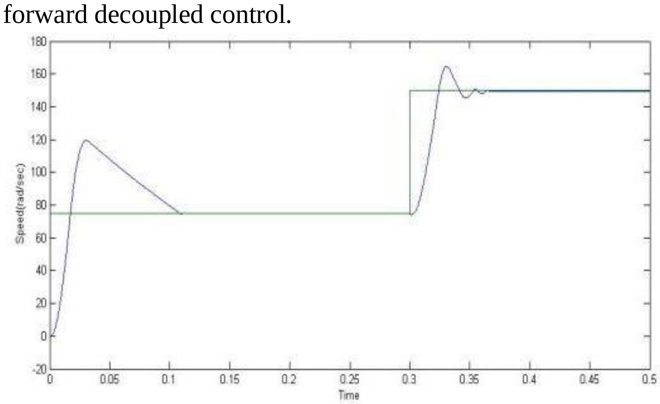


Fig 11. PI Indicator

CONCLUSIONS AND RECOMMENDATIONS

A comprehensive review of the different control strategies Of VSC based HVDC is carried out. From the discussion On the various controllers of VSC-HVDC in section IV, it Can be concluded that controller of HVDC transmission System is open or flexible that it is not merely depends on Protection scheme like a HVAC system. The design of HVDC is improved with the applications of the VSC and The appropriate selection of control parameters. The very

Basic of VSC-HVDC control is voltage controller method, However, the independent control of active and reactive Power cannot be achieved with this method. This has been Overcome by the VCC method, nevertheless, it cannot be Applied to the VSC-HVDC connected to weak AC Network. Thus, an advanced VCC is used to enhance the Outer loop control as well as PSC that eliminates the Dependency on PLL.

Hence, the synchronization of VSC-HVDC is improved When connected to a weak AC network. Other than Interfacing with weak AC system, VSC-HVDC can also be Applied in offshore wind farm application and voltage Droop control with the deployment of adaptive back Stepping controller. The adaptive back stepping controller Can reduce maximum voltage rise and minimum voltage Drop during a fault condition, thus voltage output is Restored with the reduced settling time. The fuzzy adaptive PI controller is suitable for passive network application. HMIDC consists of both LCC and VSC which enhances The power control flexibility. Apart from the design of the controller, an appropriate Selection of controller parameters is very important in Enhancing the stability of the VSC-HVDC transmission System. Considering this, different optimization algorithms Based PI controller is designed to determine the best PI Parameters as well as to improve the VSC-HVDC Performance. However, the cost of VSC becomes higher Because of the installation of these controllers. Furthermore, The probability to have commutation loss is high. VSC is Capable to handle the limited voltage and power levels. Therefore, it is recommended that further research on VSCHVDC performance at various levels of voltage and power Needs to be conducted.

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