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Advanced Control Strategies of VSC Based HVDC Transmission System: Issues and Potential Recommendations

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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 and voltage source converter (VSC). 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 paper also highlights several factors, challenges, and problems of the conventional VSC-HVDC controllers. Furthermore, this paper provides some suggestions for the advanced control for the future research and development of the HVDC system.

INDEX TERMS Converter, voltage source converter, line commuted converter, control strategies, HVDC transmission.

I. INTRODUCTION

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 [1], [2]. 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 [3]. In the 1940s, electronic or static type converter was built in the form of Line-Commutated Converter (LCC) [4], [5] 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 [6], [7]. However, the LCC type converter had a shortcoming of having Short Circuit Ratio (SCR) more than 2 that resulted in instability and poor efficiency [8], [9]. In 1997, Voltage Source Converter (VSC)

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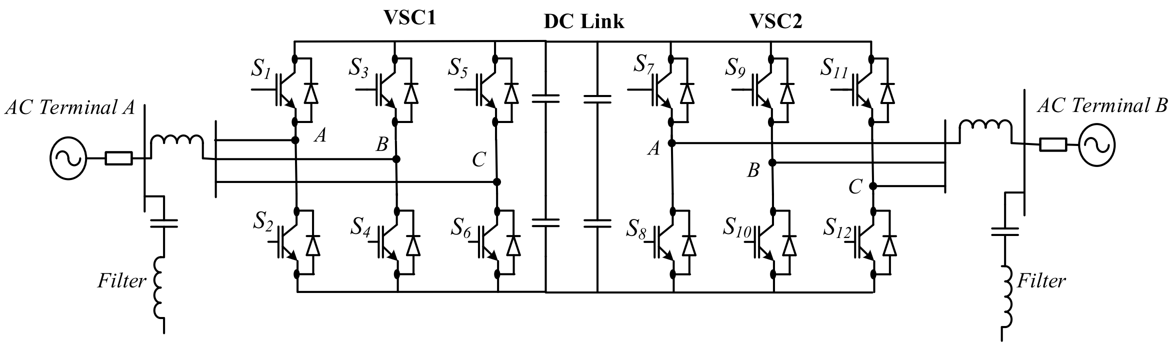

FIGURE 1. **The topology of a two terminal VSC-HVDC transmission system [3].**

was emerged and it was first commissioned in Sweden [10]. VSC was designed with electronic switches to be turned on and off, unlike LCC that can only be turned on [11].

To date, the VSC type converter has brought many benefits to the improvement of HVDC operation and stability. First of all, VSC can eliminate commutation failure 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 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 [12]–[15]. 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 [16].

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 [17], [18]. 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 [19]. 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.

This review has summarized each of the control strategies, with advantages and disadvantages explained in details in section IV. Before that, section II and III figure out the overview of VSC-HVDC control and development of VSC technology. Issues and challenges in the existing VSC based HVDC are later explained in section V. Finally, the review ends with the conclusion and recommendation in section VI.

II. 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 [20], [21]. 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 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 [22]. 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 [23]–[25].

The basic VSC schematic diagram is shown in Fig. 2 which includes a six-pulse converter having six switching devices [26], [27]. The switching devices are configured

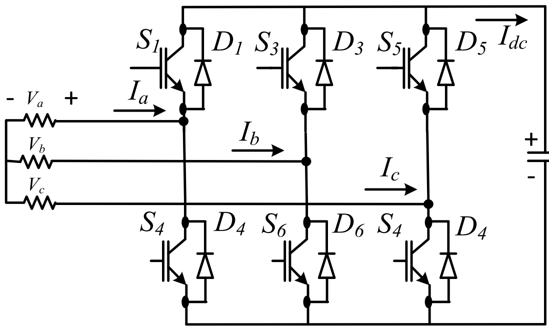

FIGURE 2. VSC Schematic Diagram [26].

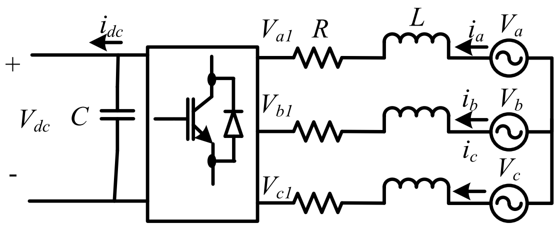

FIGURE 3. The equivalent circuit of a VSC connected with AC sources [22].

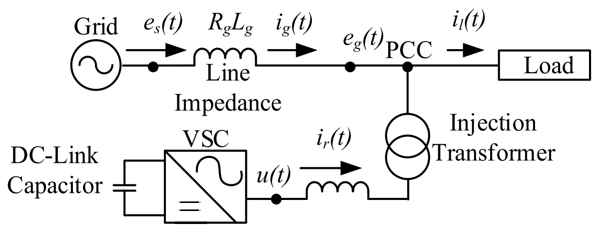

FIGURE 4. Single line diagram of shunt-connected VSC [29].

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) [22].

The converter produces a three-phase output voltage either in a square shape or in a PWM shape at the necessary frequency [28]. 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.

$$\begin{cases} v_a = v_{a1} + i_a R + j\omega L \dfrac{di_a}{dt} \\ v_b = v_{b1} + i_b R + j\omega L \dfrac{di_b}{dt} \\ v_c = v_{c1} + i_c R + j\omega L \dfrac{di_c}{dt} \end{cases} \tag{1}$$

When the output voltage amplitude is reduced below the supplied AC voltage, VSC converter generates reactive power. In contrast, when the converter output voltage leads the AC supply voltage, active power is supplied by VSC supplies. The real power of VSC is absorbed from the AC supply if the output voltage lags the AC supply voltage. The leading or lagging output voltage can be determined by controlling the phase angle between the voltages of the converter and the AC system.

The reactive power exchange between VSC and power system can be executed by controlling the output voltage value, while the active power exchange can be performed by a different VSC or an energy storage; for example, battery or a superconducting magnet. The exchange of the real power and reactive power between the VSC converter and power system is executed on an individual basis. In the series-connected configuration, the output voltage of the VSC is inserted in series with the AC line. The magnitude and phase of the voltage can be controlled by changing the magnitude and phase of the output voltage produced. VSC only produces reactive power to the AC power system if the inserted voltage is controlled with a quadrature relationship to the line current and a different VSC or energy storage device is not needed on the DC terminal. Multiplication of maximum output voltage and maximum line current will give the VA rating of the VSC. VSC will produce both active and reactive power if the injected voltage is controlled with four-quadrant manner (360 degree) to the line current and another VSC or energy storage device will not be required on the DC terminal for the power exchange. The ability to control the exchange of the active power and reactive power makes it possible for HVDC-VSC system not to use a rotating synchronous machine as it has resembled similar operation of such machine, giving an advantage of VSC type converter over the LCC type converter [28]–[30].

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 [10], [23], [28], [31]–[35]. 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 Fig. 5.

This type of VSC converter features high switching loss when it is being applied with PWM to minimize harmonic distortion of the converter. This switching loss comes from the successive IGBT switching on and off (typically twenty), hence the efficiency of the overall transmission is declined. Besides, a number of series connected IGBTs would

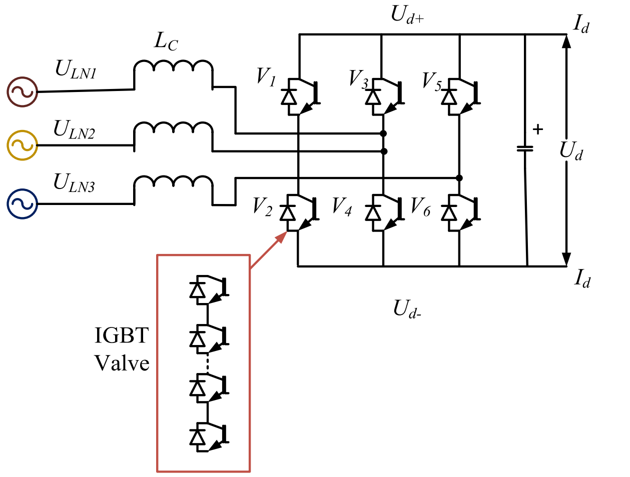

FIGURE 5. Three-phase, two-level voltage-source converter for HVDC [38].

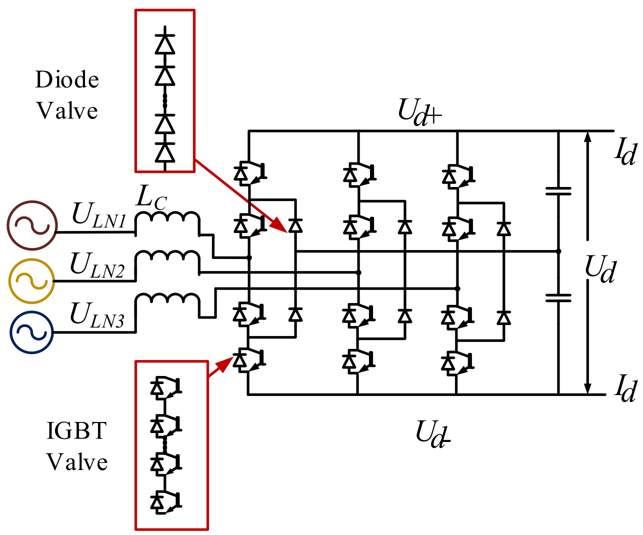

FIGURE 6. Three-phase, three-level, diode-clamped voltage-source converter for HVDC [38].

require very high operating voltage to be switched simultaneously, which may result in electromagnetic interference problems.

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 +1/2 Ud, 0 and −1/2 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 [38]–[40]. The IGBTs are switched on in such way that first two, middle two and last two are switched on for obtaining positive output voltage (+1/2 Ud), zero output voltage, the negative output voltage (−1/2 Ud) respectively.

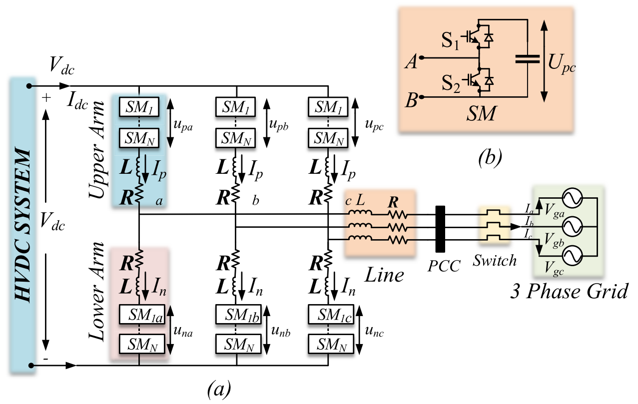

FIGURE 7. Three-phase MMC topology (a) MMC topology (b) Sub module topology [43].

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 [41]–[43]. 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. The configuration of MMC is shown in Fig. 7.

Either one of the two IGBTs in each SM can be turned on. During ON state, the IGBT will connect the capacitor into the circuit, while during the OFF state, IGBT will bypass the capacitor into the circuit.

Thus, the generated voltage from each SM could be either 0or U_{sm} (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 [44], [45]. 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. The relationship between the alternating and direct current on each valve is shown in (2) and (3) [41].

$$\text{Uppervalve}: I_v = \frac{I_d}{3} + \frac{I_{ac}}{2} \tag{2}$$

$$\text{Lowervalve}: I_v = \frac{I_d}{3} - \frac{I_{ac}}{2} \tag{3}$$

One of the advantages of having MMC in VSC-HVDC system is that it achieves an excellent harmonic performance without the need any filter and PWM technique [46], [47]. Furthermore, power loss is much lower than the two-level converter. Because of these strong points, MMC has become the most common type of VSC nowadays. However, a few

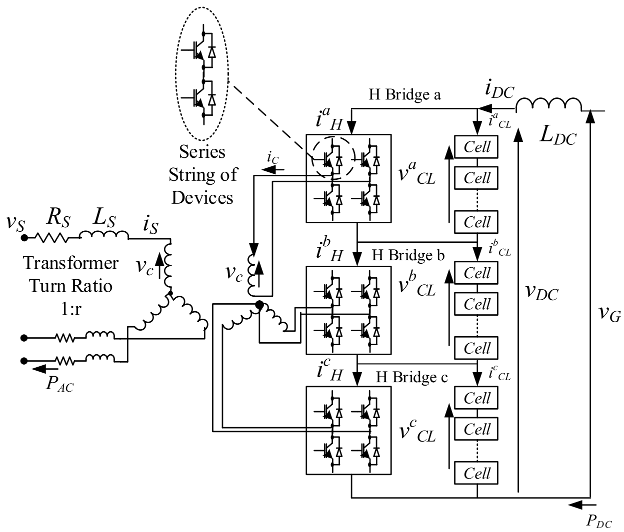

FIGURE 8. **Three-phase hybrid VSC topology [49].**

weaknesses are encountered, such as its control is more complex than a two-level converter. Also, it requires computation of power and high-speed communication between the central control and the valve. Besides that, its size is larger than a two-level converter because of the size of each SM in the capacitor, thus requiring more space in the substation [41].

D. HYBRID VSC

This is an advanced type of VSC where it combines both two-level and MMC converters [34], [48]. The configuration of a hybrid VSC is shown in Fig. 8. which includes a 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 [50], [51]. 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 [52]. 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. However, there is a possibility that the converter will not be able to block a DC fault [52].

IV. VSC BASED HVDC CONTROL METHODS

The effectiveness of grid interfaced VSC based HVDC system depends on the control strategy. The designs of this controller together with the correct selection of its parameters will have a substantial impact on the system stability. In the controller structure, each control loop has its own control rule and parameters.

A. 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, δ controls the active power between VSC and the AC system. Power angle, δ 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. The actual value of reactive power is called the reference reactive power which obtains an error. This error will be processed by the reactive power controller to become the magnitude of the modulating signal. Phase Locked Loop (PLL) will synchronize the output voltage of the inverter to the grid [53]–[56]. This is a simple and easy process to be employed. However, the outcome from both reactive power controllers and power angle controllers show that both active and reactive power is the function of power angle, δ which means active power and reactive power cannot be controlled independently [57]. Specifically, the control bandwidth of power angle controller is constrained by the grid frequency and a resonant peak and it cannot limit the current flowing into the converter, thus issuing problems to the system if the over current fault occurs.

B. VECTOR-CURRENT CONTROLLER (VCC)

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. The d and q components control the active and reactive power through a rectifier and inverter respectively. The control of d and q current components are executed within a Synchronous Reference Frame (SRF) and the synchronization is done by a PLL [20], [58]. Both rectifier and inverter have identical control schemes but there is no communication between them. The converter acts as a current source where the injected current will follow the current phasors. In a steady state condition, the three-phase quantities, a-b-c are transformed into two-phase quantities,

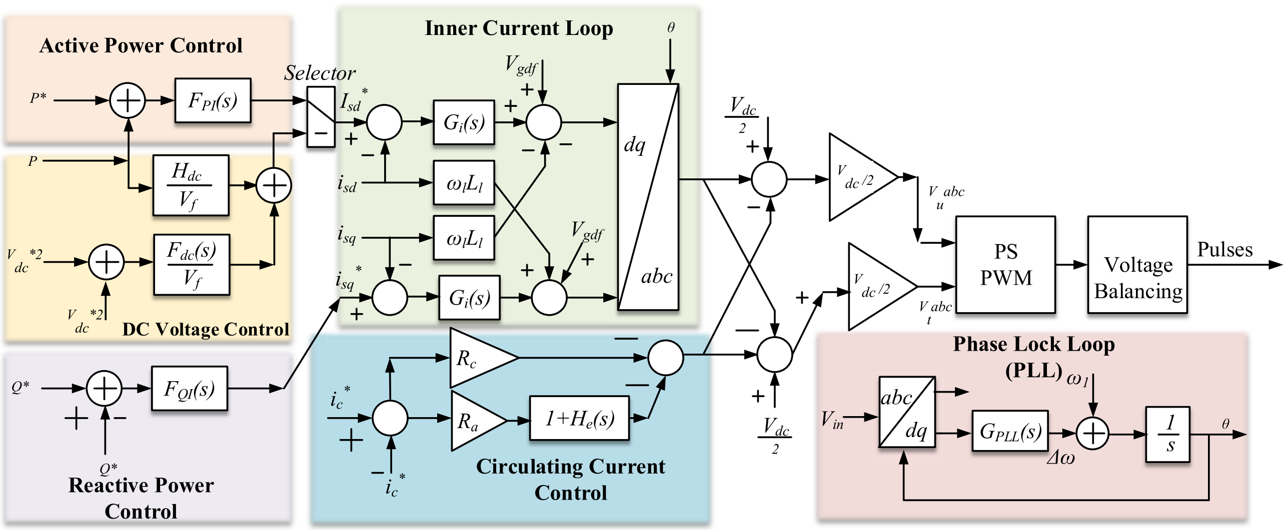

FIGURE 9. Vector current control (VCC) of MMC-HVDC [59].

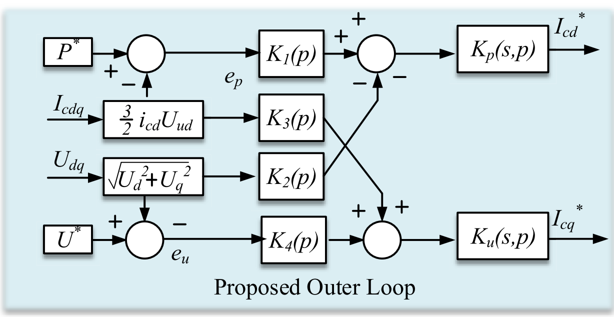

FIGURE 10. The control structure of advanced VCC [66].

$\alpha\beta$ and later is transformed into two axis block d-q [59], [60]. The configuration of VCC in MMC-HVDC system is shown in Fig. 9.

The independent active and reactive power controllability with the fast dynamic response is the main strength of the VCC method. Besides, VCC delivers better power quality where the converter is less affected by harmonics and grid disturbances. In addition, the current flowing into the converter can be limited naturally as it is current-control based technology. Moreover, VCC can provide protection against over current fault and can compensate for a line or grid harmonics. However, this method is not suitably applied to DC link connected to weak AC network ($2 < \text{SCR} < 3$) or a very weak grid AC network ($\text{SCR} < 2$), where it would deliver poor performance in a VSC-HVDC system [61], [62]. The interconnection will make the outer loop becomes unstable that results in poor performance due to high power demand. The low-frequency resonance can interconnect with the vector current control and affect the inner current control loop. This might limit the VSC control operation and performance. Besides, PLL dynamics might also affect the performance of VSC-HVDC even though its function is to achieve synchronization with the AC system when VSC is connected to it [63].

C. ADVANCED VECTOR CURRENT CONTROL

This method is an enhancement of the normal VCC method to be applied in VSC interfaced with weak AC signal. This controller considers the non-linearity of the system design that might affect the performance and efficiency. The approach is to enhance the outer loop in conventional VCC method discussed in IV.B. This enhanced outer loop allows superior regulation of the voltage and active power for operating VSC in the feasible range [64]–[66]. The advanced outer loop control structure of VCC is shown in Fig. 10. The outer loop control consists of extra four decoupling gains between the voltage value and power errors before the Proportional Integral (PI) operates. In addition, it also incorporates parameter-varying scheme so that it can overcome system non-linearity and achieve similar results. The goal of this outer loop is to improve the handling interaction between active power and voltage control. The d-axis and q-axis current outputs are shown in (4) and (5) and expressions of KU and KP are presented in (6) and (7) [67]–[72].

$$i^*_{cp} = K_P(s,p)(k_1(p)\,e_p + k_2(p)\,e_u) \tag{4}$$

$$\boldsymbol{i^*_{cd} = K_U(s,p)(k_3(p)\,e_p\, C\, k_4(p)\,e_u)} \tag{5}$$

where;

$k_1(p)$, $k_2(p)$, $k_3(p)$ and $k_4(p)$ = decoupling gains (proportional gains

$$K_U(s,p) = (k_{p-u}(p)\,s + k_{i-u}(p))/s \tag{6}$$

$$\boldsymbol{K_P(s,p) = (k_{p-p}(p)\,sC\,k_{i-p}(p))/s} \tag{7}$$

This method has made possible for VSC-HVDC to interact with weak or very weak AC grid where it can better

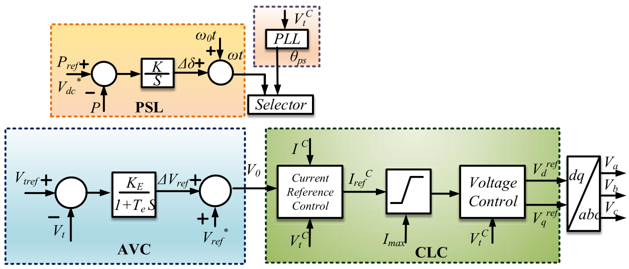

FIGURE 11. PSC based VSC-HVDC system [64].

handle high power demand as compared to conventional VCC controller. This is because it has been designed to address severe non-linearity, highly-coupled active power and outage interactions under both normal and fault conditions, thus injecting any value of active power to the converter within its possible range. The drawback of this advanced VCC is to ignore the asymmetrical fault and any sudden change during grid operation.

D. 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 [73], [74]. The VSC terminal gives voltage support to the weak AC system during the operation of a synchronous machine. The configuration of PSC is shown in Fig. 11. It uses a phase angle to control active power, and voltage value to control reactive power, identical to the power angle controller as explained in section IV.A. The difference is that it does not use a PLL to control the power synchronization.

This method upholds synchronism between VSC and AC system. The power control error is transformed to a frequency deviation to change the angle. After, the angle from the output signal ωt transforms the voltage reference v_c^{ref} from the d-q frame to the stationary frame of the converter. The law of power-synchronization control is shown in the following equation,

$$\frac{d\Delta\theta}{dt} = k_p(P_{ref} - P) \tag{8}$$

where,

$_{Pref}$ = The reference active powe
P = The output active power from VSC
k_p = The controller gain
$\Delta\theta$ = The controller output

The synchronization of VSC is achieved using $\Delta\theta$. The control of the transferred power is executed by correcting the output voltage phasor of the VSC. This method does not depend on PLL so it eliminates the possible instability caused by PLL when connected to a weak AC system. In addition, it does not have a pre-set current value which means it does not depend on an inner current loop like in VCC as explained in IV.B. The transient power transfer is determined by the interconnecting network. The weakness of this method is that if severe AC system fault occurs on the system, the controller needs to change its mode to current control mode to avoid over current on the converter valves. Furthermore, higher load angles is another challenge that VSC-HVDC could interface if it is interconnected with a weak AC system [76].

E. 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 Fig. 12. The schematic diagram of the ABC frame controller is presented in Fig. 13. 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.

The outer control loop is designed to deliver more reactive power to AC voltage at PCC. In addition, the design offers the maximum power exchange within the rating boundary of the converter in order to give fluent transition between weak and healthy AC networks. I_{refABC} is calculated from the inversion of Clark transformation [75]. By reducing active power during a fault condition, the average input active power and input reactive power can be exchanged with the AC grid and DC link, thus avoiding the ripple active power of the transformer. This method uses two separate controllers; one is for controlling active power and DC voltage as shown in Fig. 14; another one is for controlling reactive power and AC voltage as shown in Fig. 15.

In the active power or DC voltage controller, the P_{ref} output is used to reduce the power demand for keeping the DC voltage within the range. The limiter is used to prevent AC current from being conducted above the nominal value to ensure that the converter is in the safe process especially under a fault condition. Both limiters in Fig. 14 and Fig. 15 can be combined into one and it can be prioritized whether to select maximum active or reactive power during a fault condition. Since this method does not depend on the PLL operation in its control, there is no possibility of PLL problem like lack of synchronization when VSC-HVDC connected to weak AC network. This method also has a broader range in the current control loop, thus assuring fast output of reference current. In the d-q frame of Synchronous Rotating Machine (SRF), positive and negative sequence components are extracted so that the delay in the feedback currents is not required. Furthermore, adaptive filter is not required in the grid voltage frequency variation and harmonic distortion [30], [66], [77], [78].

F. VOLTAGE DROOP CONTROL

The voltage droop control technique is employed in Multi-terminal HVDC system, for instance, offshore wind farms as shown in Fig. 16 and node or branch scheme as depicted in Fig. 17. Power source comes from wind farm grid merging into wind farm converter. Grid side converter on

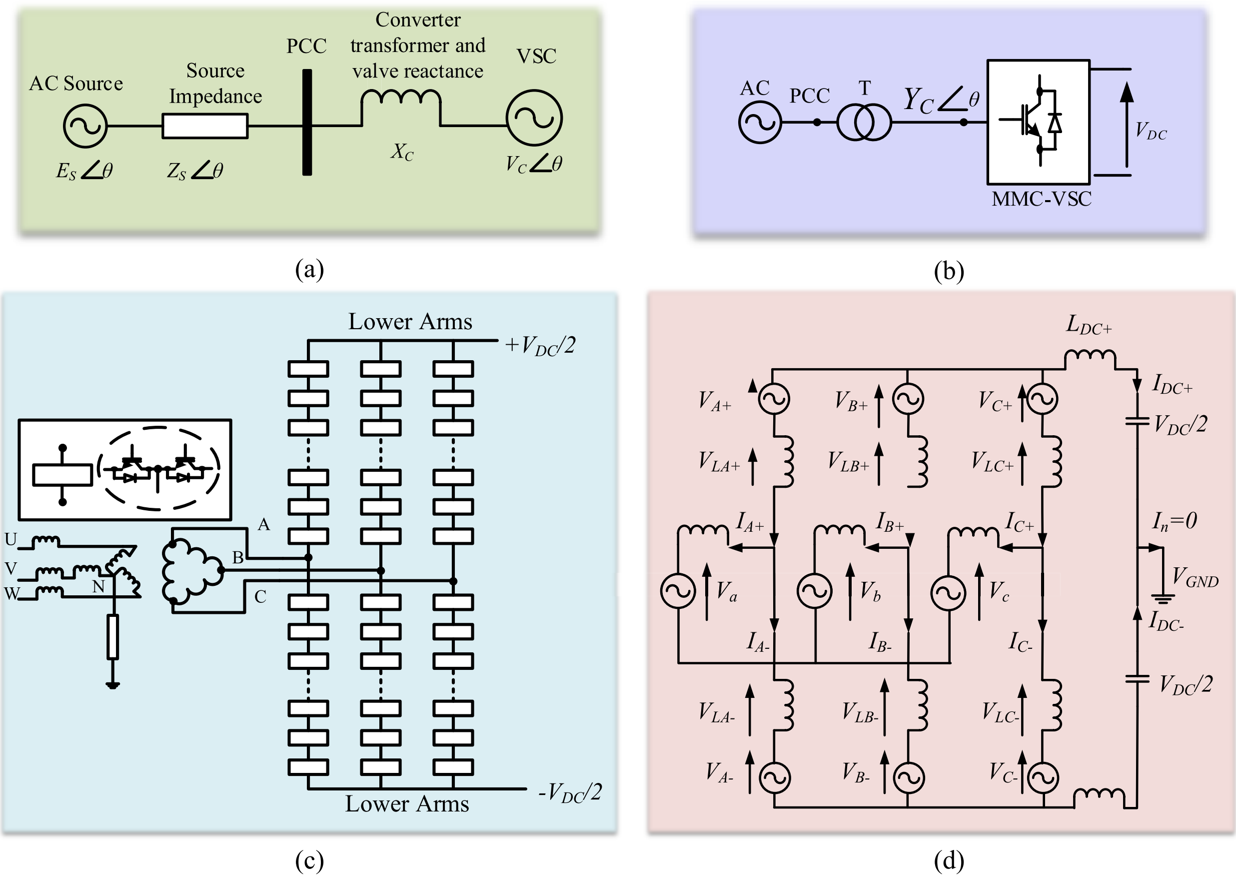

FIGURE 12. (a) Transmission system of VSC-MMC (b) Equivalent circuit of VSC-MMC converter with transmission system (c) half-bridge cells based MMC converter (d) equivalent circuit of MMC [73].

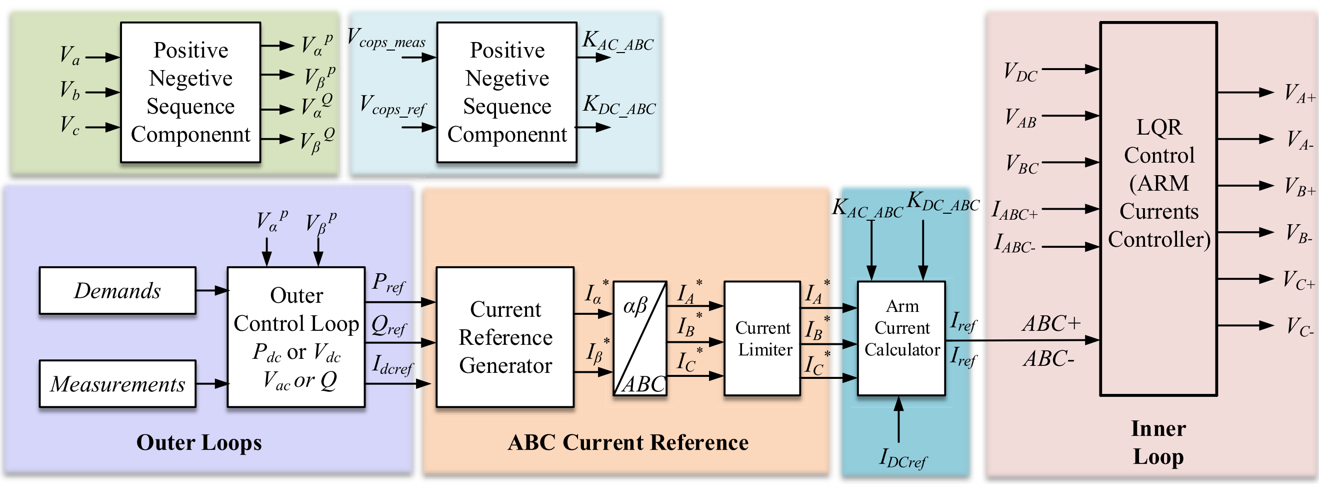

FIGURE 13. Schematic diagram of the ABC frame [75].

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 [9].

Voltage droop control is based on frequency response analysis [8], [9]. The performance specification takes into account the desired voltage error and the maximum control input

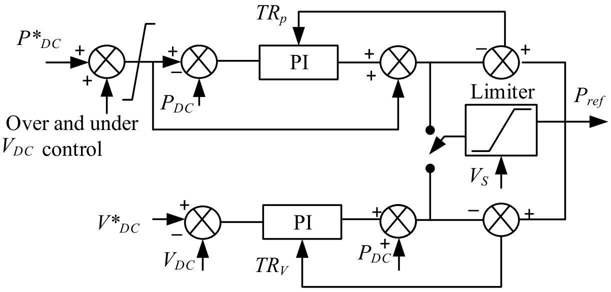

FIGURE 14. Control of active power and DC voltage [30].

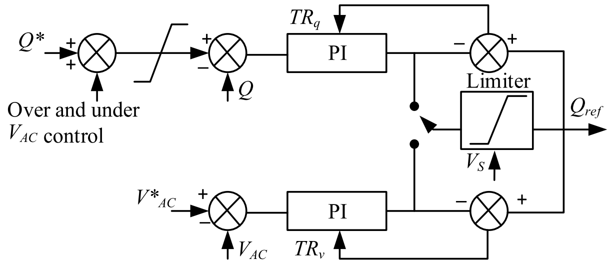

FIGURE 15. Control of reactive power and AC voltage [30].

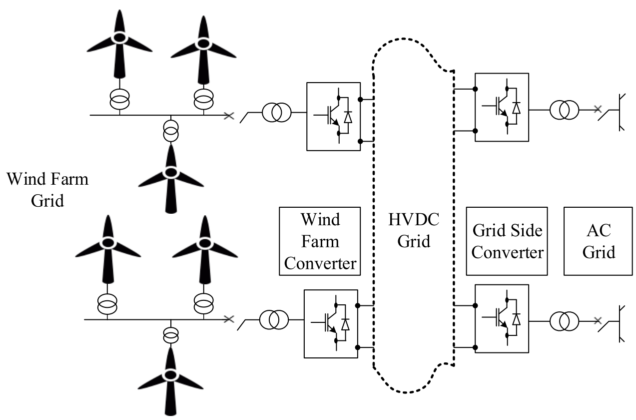

FIGURE 16. Typical HVDC multi-terminal network [9].

current for choosing the desired droop gains. The control scheme is shown in Fig. 18.

Droop parameters are selected based on the steady-state analysis. The distribution of power among different terminals is executed without communications. In each converter, there is two level of control being designed; level one is an inner loop that controls current while level two is an outer loop that regulates DC voltage. The outer loop is the one where the voltage droop control plays its role. It will provide a reference current, I_{ref}, hence deliver power to the inner loop. Control of this reference current is based on (9) involving droop gain, K_{droop}.

$$i^* = K_{droop}(E - E_0) \tag{9}$$

where E is the V_{dc}, E_0 is the reference and K_{droop} is the droop gain.

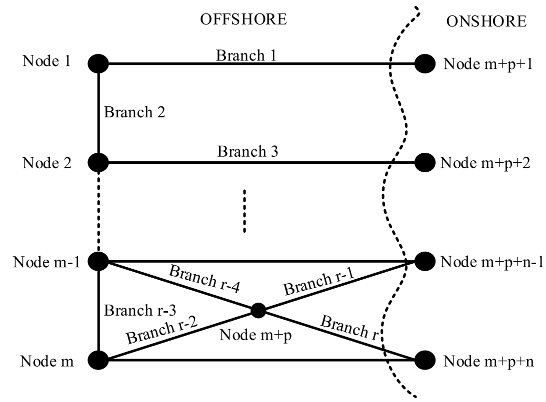

FIGURE 17. Node and branch scheme of a multi-terminal HVDC network [9].

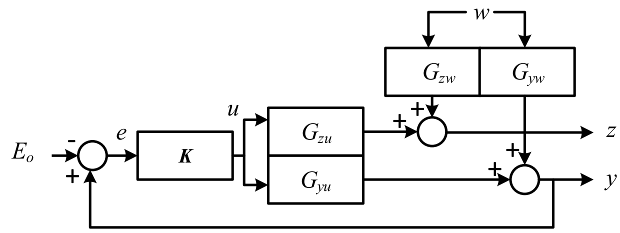

FIGURE 18. Droop control scheme in a multi-terminal grid [9].

Value of K_{droop} depends on the entire of the multi-terminal behavior both in normal and fault condition. It also takes into account the multivariable system theory that every local controller might affect the stability of the whole system and DC voltage in another terminal. For a stable operation, the value of K_{droop} must be above zero since droop control is synonymous with adding energy dissipation to the system. The relationship between K_{droop} and performance objectives is analyzed by the frequency response of the system. Frequency response shows a vector of sinusoidal signals of frequency, ω being changed by the system. The objectives of the performance specification are to reduce the effect of disturbance on DC voltage as well as to keep the control input within its range [9].

G. ADAPTIVE BACK STEPPING CONTROLLER

Adaptive back stepping controller method can also be applied to offshore wind farm grids [79] 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 [80]–[82]. The construction of a DC transmission line is shown in Fig. 19.

The controller might compensate for the current disturbance in capacitors of the DC side. DC cable model is designedinto a series of π sections, where every section

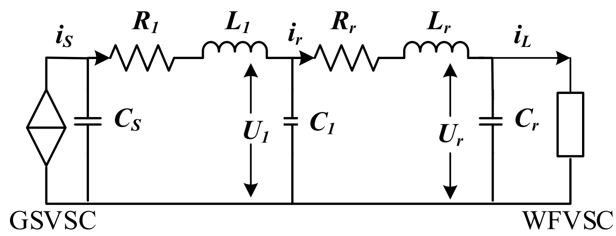

FIGURE 19. Simplified structure of the DC transmission line [79].

controls the preceding one to eliminate the accumulative error from previous steps. Errors accumulated come from all parameter uncertainties and state errors. The final control signal of VSC is determined by Inner current loop based on the measurement of voltage and current values.

Afterward, the internal states of the DC cable might be projected. Power equality between AC and DC links the inner current loop and DC side model. The voltage control law demonstrates that the active and reactive power flow at PCC is controlled in the d-axis and q-axis respectively, as shown in the following equations [84].

$$V_{Cd} = \frac{3e_{us}V_{Nd}}{2u_{cs}} + V_{Nd} + Li_{dref} - \omega Li_q + Ri_d + k_{dp}e_{id} + \theta_d \tag{10}$$

$$V_{Cq} = V_{Nq} + Li_{qref} - \omega Li_d + Ri_q + k_{qp}e_{iq} + \theta_q \tag{11}$$

The variation of DC voltage and the stabilization time might be reduced by this method under power change condition and a fault condition. The overshoot voltage will be reduced in both wind farm and grid side terminals, thus, the performance of existing DC voltage controller has been improved. However, this adaptive back-stepping method does not take into account the model uncertainties which could also affect the overall system performance. State observer might be utilized to estimate the internal states of the DC cable, for example, capacitor voltage and inductor current that cannot be measured directly [80], [84].

H. 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 is shown in Fig. 20.The flexible method configuration is shown in Fig. 21. 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.

When a fault occurs, active current reference will be altered with reference to the change of reactive current reference in order to restore the grid voltage. The output of the power control loops is denoted by i_{*d} and i_{*q}. Both current references are regulated by the adaptive current limiter, which is shown in the following equations,

$$i^*_{q1} = \begin{cases} i^*_{q1}, -i^*_{lim} < i^*_q < i^*_{lim} \\ i^*_{lim}, i^*_q \geq i^*_{lim} \\ -i^*_{lim}, i^*_q \leq -i^*_{lim} \end{cases} \tag{12}$$

$$i^*_{d1} = \begin{cases} i^*_d, i^*_{dlim} < i^*_d \leq \sqrt{i^{*2}_{lim} - i^{*2}_q} \\ \sqrt{i^{*2}_{lim} - i^{*2}_q}, \sqrt{i^{*2}_{lim} - i^{*2}_q} < i^*_d < \quad i^*_{\mathrm{lim}} \\ i^*_{lim}, i^*_d \geq i^*_{lim} \\ i^*_{dlim, i^*_d \leq i^*_{dlim}} \end{cases} \tag{13}$$

where i^*_{lim} is the VSC current limit, i^*_{dlim} is the lower boundary of active current from active power control loop. The operation of the adaptive current limiter is illustrated in Fig. 22.

Based on the AC voltage controller output, the reference value of active current is assigned. Under little fluctuations of grid voltage, the generated current references lay within the circle. Therefore, the system achieves a new stable operating point, M, where current references of i^*_{d1} and $i^*_q 1$ remain equal to i^*_d and i^*_q, respectively [83]. Under extreme voltage drop condition, huge instabilities occur between active power and AC voltage, which in turn rises the current signals i^*_d and i^*_q considerably. The adaptive current limiter operates to set the VSC current limit, i.e. $i^{*^2}_d + i^{*^2}_q = i^{*^2}_{lim}$. After, the reference value of active current i^*_{d1} is changed in such a way that the current reference vector is directed in clockwise direction along the current limit circle. Based on the condition of fault, the current reference vector inclines to hold a new stabile operating point N, or remains rotating until point D where the power capacity of VSC and current phase angle are employed for the reactive power support [83], [85].

The capability circle of the VSC for various AC voltages is shown in Fig. 23. At particular operation mode, the transmission of active power by the VSC-HVDC link is unidirectional. Therefore, the capability circle of the VSC is drawn in two quadrants. The capability circle will shrink in various pattern with variation in voltage drops. The steady-state operating point could maintain within the capability circle, for instance, point I in Fig. 23. For a voltage drop, the output power of VSC falls to the point, F, within a smaller circle. The current vector reference might meet its boundary instantly.

This method gives the possibility to have a stable voltage in the HMIDC systems through the flexible power control on the VSC-HVDC link. However, this method does not consider AC grid dynamics and load effect. Not many information on the impacts of the power capacity is considered, thus a quantitative method for voltage stability analysis is required for further study [83], [85].

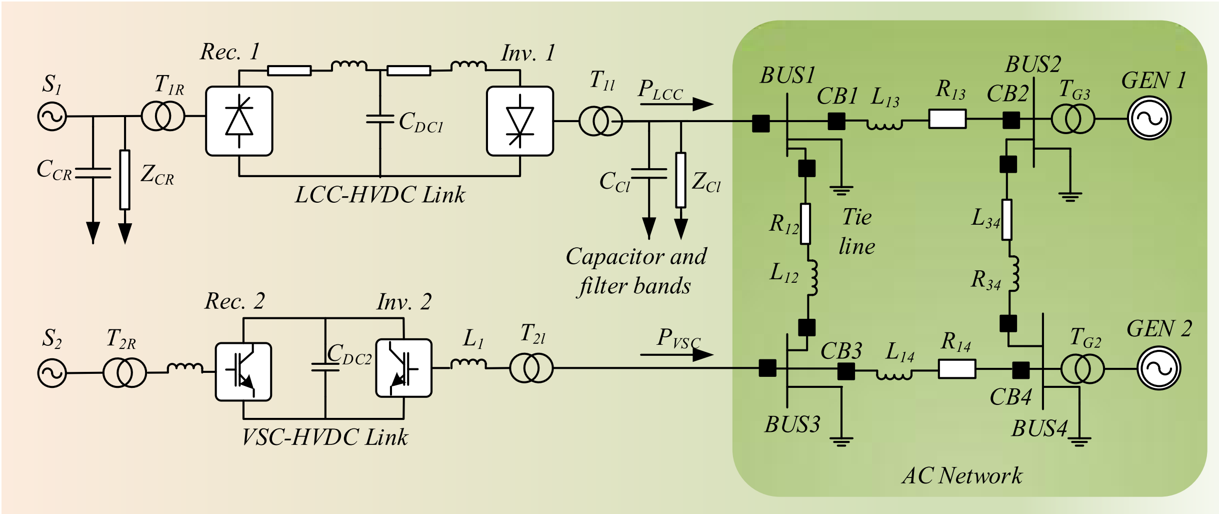

FIGURE 20. Simplified one-line diagram of the built HMIDC system [83].

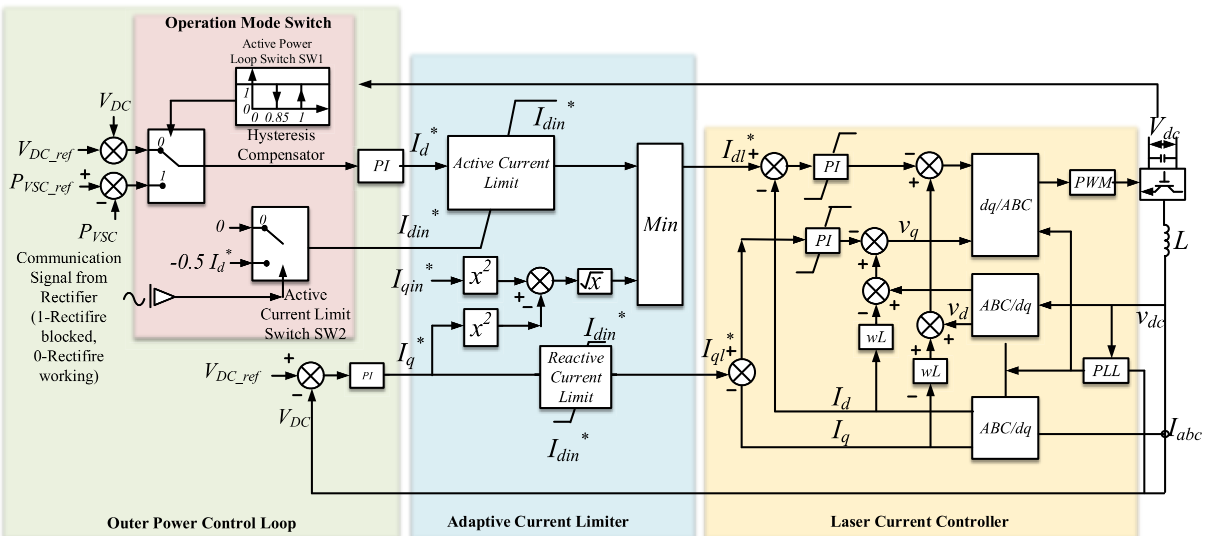

FIGURE 21. Flexible method configuration for HMIDC [83].

I. 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 [86]. The control organization along with current controllers and outer-loop controllers are shown in Fig. 24. 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. The real power is controlled by sending end converter or rectifier while the DC voltage is regulated by the receiving end converter or rectifier. The reactive power at the link ends is controlled distinctly by the respective converters [52], [87]. The transfer functions of four closed loop PI controllers including inner current, outer DC voltage, outer active power and outer reactive power control loops are shown in Fig. 25 26, 27 and 28 respectively. These four controllers must be integrated at each VSC.

The initial PI compensator parameters are obtained using frequency response design method from these four control loops. All these parameters become inputs to the optimization algorithm based on simplex method application. The aim of these controllers is to compare the objective function values at the N+1 vertices of a simplex. Then, the worst objective function is removed and accordingly a new vertex value is obtained. This process continues iteratively until the optimum point is found. The optimum PI compensators of the different VSC control systems supplying for the active network are obtained after this optimization. The dynamic behavior and

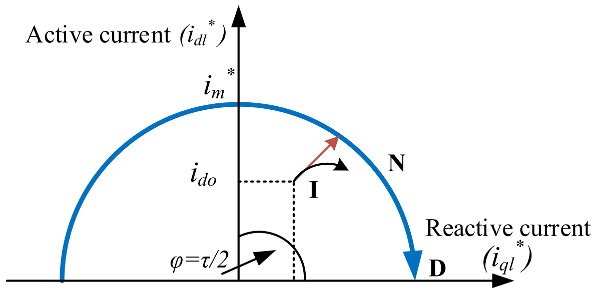

FIGURE 22. Current trajectory with the regulation of adaptive current limiter [83].

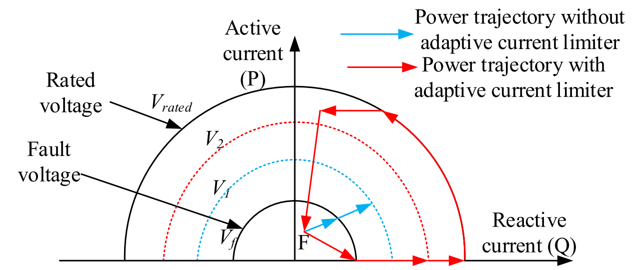

FIGURE 23. Capability curve of VSC under voltage drop [83].

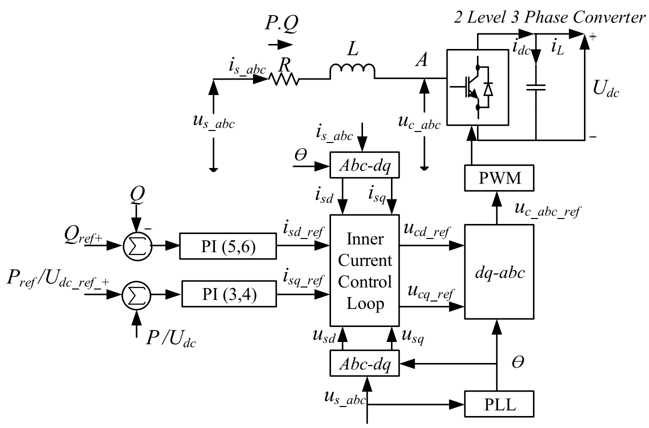

FIGURE 24. The diagram of the inner and outer controllers for VSC [87].

performance of the VSC-HVDC system are enhanced significantly with the optimum PI parameters. However, this method does not consider the power losses of the transformer, the grid filter and converter [52], [87], [88].

J. FUZZY ADAPTIVE PI CONTROLLER

This fuzzy adaptive PI controller can be applied to VSC-HVDC connected to passive AC network. The constant DC voltage and constant reactive power controls are used in rectifier side of VSC while the AC voltage control is used in inverter side of VSC [16], [88], [89]. The Fuzzy PI control for VSC-HVDC system is shown in Fig. 29.

The α-β coordinate axis controls the AC voltage and frequency, and hence a discrete mathematical model is developed. The principle of this method is to transform the three-phase output voltages intothe α-β frame which consequently

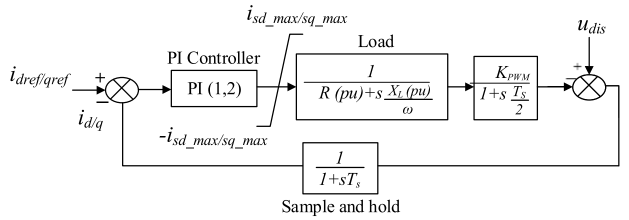

FIGURE 25. Inner current control loop [87].

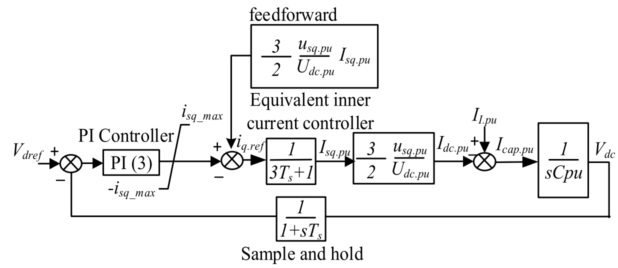

FIGURE 26. Outer DC Voltage control loop [87].

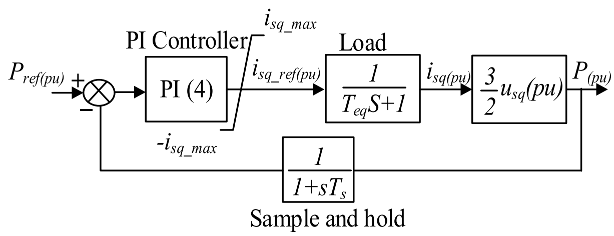

FIGURE 27. Outer active power control loop [87].

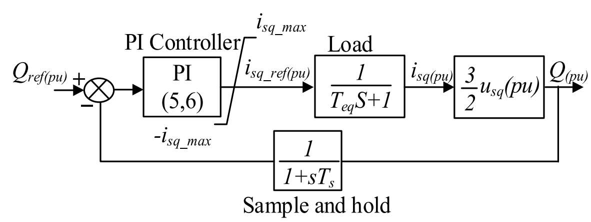

FIGURE 28. Outer reactive power control loop [87].

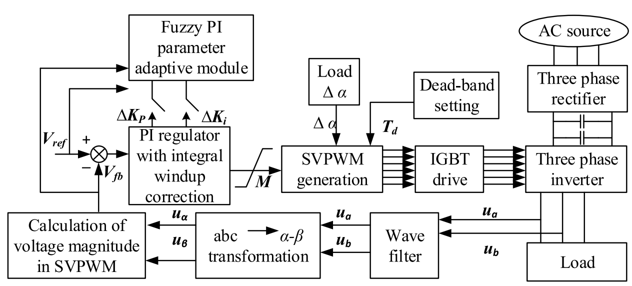

FIGURE 29. Fuzzy based PI control for VSC-HVDC system connected to a passive network [90].

produces a reference voltage vector. The AC voltage magnitude and frequency become controllable by altering this voltage vector. The extracted formulas are shown

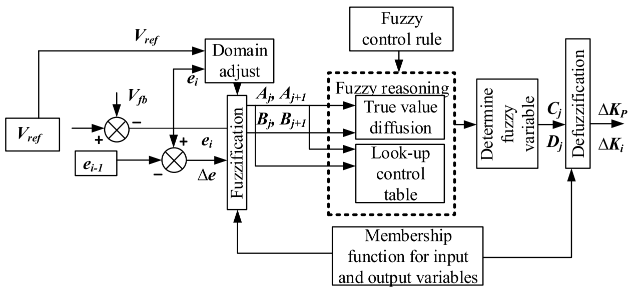

FIGURE 30. Structure of fuzzy adaptive controller [90].

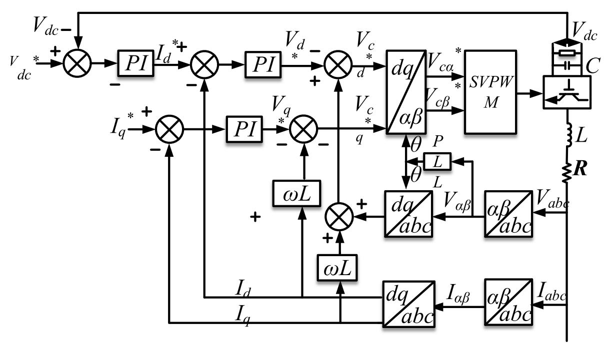

FIGURE 31. Decoupled dq-vector control scheme used for DC voltage control [92].

in (14) and (15).

$$v_\alpha = v_a \tag{14}$$

$$v_\beta = (2v_b + v_a)/\sqrt{3} \tag{15}$$

where $v_a = V_m sin\omega t$, $v_b = V_m \sin(\omega t - \frac{2\pi}{3})$, $v_c = V_m \sin(\omega t + \frac{2\pi}{3})$, $v_\alpha = V_m sin\omega t$, $v_\beta = V_m \sin(\omega t + \frac{\pi}{2})$

The main function of the fuzzy adaptive module is to make the complex parameters in the conventional PI controller to be auto-regulated and adapted automatically during the changing work conditions and system fluctuations when the system is running. This will ensure an effective control over the AC voltage. Both fuzzy inference and control process is developed using the binary system and the parameter values are processed by Digital Signal Processing (DSP). Fig. 30 presents a structure of the fuzzy adaptive controller. This method still keeps the advantage of conventional control on top of the adaptive control that it can adapt to the changes within the system and regulate the PI parameters automatically. However, the robustness of this method needs to be checked whether it can withstand the range of disturbances [16], [90], [91].

K. PI CONTROLLER OPTIMAL DISTURBANCE REJECTION

This method advances the conventional PI controller by considering AC input voltage fluctuation and load disturbances in VSC-HVDC system [92], [93]. The overall scheme of this controller is shown in Fig. 31.

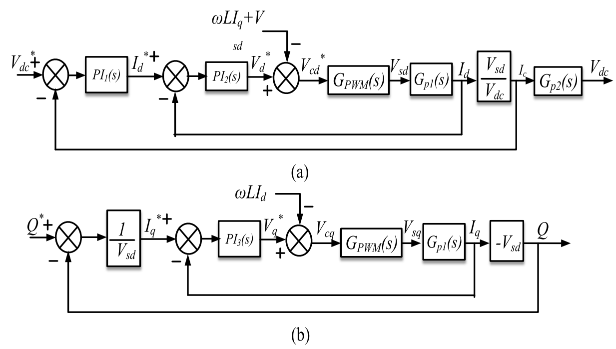

FIGURE 32. Block diagrams of control loops. (a) DC voltage control. (b) Reactive power control [93].

Two things are considered to implement this method. Firstly, it uses a decoupled d-q vector control scheme that uses a control algorithm which derives first-order-plus-time-delay (FOPTD) of the non-linear system as shown in (16) and (17) [93]. The system model and its controller operations in the rotating d-q frame are expressed from (18) and (21) [93].

$$p_{ac} = v_{sd} i_d + v_{sq} i_q \tag{16}$$

$$q_{ac} = -v_{sd} i_d + v_{sq} i_d \tag{17}$$

d-axis is aligned 90 degrees behind phase a, so the equation becomes,

$$p_{ac} = v_{sd} i_d \tag{18}$$

$$q_{ac} = -v_{sd} i_d \tag{19}$$

Power on the DC side is shown in (20),

$$P_{ac} = v_{dc} i_{dc} \tag{20}$$

Using the power balance equation for both the AC and DC side,

$$v_{dc} = \frac{i_d}{i_{dc}} v_{sd} \tag{21}$$

Secondly, the optimum PI-tuning parameters are achieved by using a non-linear optimization algorithm based on lessening the integral time absolute error (ITAE) performance index. The desired dynamic performance and zero steady-state error can be obtained via two PI controllers as shown in Fig. 32.

This method has some advantages. The real power and reactive power can be controlled independently. Also, this method improves the performance of existing DC voltage controller in comparison to the traditional PI controller. Furthermore, the usage of optimum tuning parameters is avoided because of the complex computation and time-consuming procedure. However, the method exhibits a few drawbacks. Firstly, the tuning approach of FOPTD yields quasi-optimal tuning parameters [92]. In addition, the simulations are not extended to a full HVDC system, hence the robustness of this method is yet to be proven. This method can also be applied to

TABLE 1. Comparative analysis of various control strategies.

No.	Control method	Operation	Advantages	Disadvantages	Ref.
1.	Voltage Controller	• Direct control over active power, reactive power and power angle.	• Simple and easy process.	• Active power and reactive power cannot be controlled independently. • Cannot limit the current flowing into the converter.	[53]–[57]
2.	Vector Current Controller	• Steady state operation into the d-q axis to control active power and reactive power separately.	• Fast dynamic response. • Delivers better power quality during harmonics and grid disturbances. • Provides protection against over current fault. • Can compensate grid harmonics.	• Achieves poor performance when it is applied to DC link connected to weak AC network.	[59]–[62]
3.	Advanced Vector Current Controller	• Outer loop control including four decoupling gains to incorporate parameter-varying scheme and overcome system non-linearity.	• Better handle capability to interact with weak or very weak AC grid.	• Ignores the asymmetrical fault and any sudden change during grid operation.	[64]–[72]
4.	Power Synchronization Controller	• Uses a phase angle to control active power, and voltage value to control reactive power, • Does not use PLL to control the power synchronization.	• Can uphold synchronism between VSC and AC system. • Eliminates the possible instability caused by PLL when connected to a weak AC system. • Does not need to have a pre-set current value and does not depend on an inner current loop	• Over current on the converter valves during the severe AC system fault occurrence. • High load angles when it is interconnected to a weak AC system.	[73], [74], [76]
5.	ABC Frame Controller	• VSC is regulated in ABC frame without PLL operation. • The active power and reactive power are controlled exclusively at the point of coupling (PCC).	• Achieves good synchronization when VSC-HVDC connected to weak AC network. • Fast output of reference current. • Feedback currents delay and adaptive filter are not required in the grid voltage frequency variation and harmonic distortion.	• Complex structure and operation to control active and reactive power.	[30], [66], [77], [78].
6.	Voltage Droop Control	• Selects the droop parameters based on the steady-state analysis. Inner loop controls current while an outer loop regulates DC voltage.	• Reduce the effect of DC voltage disturbances.	• Reference current control could diverge in any sudden change during grid operation.	[8], [9]
7.	Adaptive Back Stepping Controller	• Uses DC cable dynamics to maintain DC bus voltage at a rated value and DC voltage at constant value.	• Reduce the overshoot voltage in both wind farm and grid side terminals, thus, the performance of existing DC voltage controller has been improved.	• Does not take into account the model uncertainties which could affect the overall system performance.	[80]–[82], [84]
8.	Flexible Power Control Method	• Control the active power and reactive power independently. • Intermediate adaptive current limiter to address the pre-setting current problem.	• Stable voltage in the HMIDC systems through the flexible power control on the VSC-HVDC link.	• Does not consider AC grid dynamics and load effect.	[83], [85].
9.	Proportional Integral (PI) Decoupled Control	• Uses optimal parameters in the PI compensators in different control loops.	• Enhances the dynamic behaviour and performance significantly.	• Does not consider the power losses of the transformer, the grid filter and converter.	[52], [86], [87]
10.	Fuzzy Adaptive PI Controller	• Regulates the conventional PI controller parameter automatically during the variable operating conditions and system fluctuations. • Converts the three-phase output voltages into the α-β frame.	• Ensure an effective control over the AC voltage. • The adaptability to change within the system and regulate the PI parameters automatically.	• Poor robustness during disturbances.	[16], [88]–[91]

different control strategies, for instance, direct power control topologies etc. A detailed comparative study of all the control strategies is presented in Table 1.

V. 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 behavior. 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 [56], [65].

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 [12], [56], [63].

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 [94]–[96]. 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 [97], [98]. 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 [99]–[101].

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 [102]. 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 [103].

VI. 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 VSC-HVDC performance at various levels of voltage and power needs to be conducted.

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