Chapter 1

Introduction

1.1 General

Power generation facilities, transmission grids, and distribution networks are continually expanding to manage the rising demand while also striving to minimize the environmental impacts associated with non-renewable energy sources. In this endeavor, renewable energy such as wind, solar, and hydro energy plays a crucial role. High voltage direct current (HVDC) technology, which has been in use for over 70 years [1], is well-suited for transmitting significant renewable power over extended distances with minimal energy losses. The advent of HVDC has led to an increasing number of direct connections between various locations across the globe. These HVDC links effectively deliver power to consumers with efficiency and in accordance with demand, which enhances the security of power supply and reduces the sporadic nature of renewable energy sources.

The next logical progression involves connecting these individual HVDC links to enhance the network's dependability and controlability. A multi terminal HVDC (MTDC) grid is a good potential option to decrease the number of converter stations and transmission lines compared to point-to-point HVDC link. Moreover, the MTDC grid's flexible control capabilities, enabling the integration of multiple renewable energy sources (offshore wind farm, solar farm etc.) and loads, makes it an exceptionally competitive solution for enabling cross-border power transmission. This extensive DC grid network is well-positioned to provide reliable and economically feasible power transmission services while simultaneously enhancing the capacity of existing AC infrastructures through the integration of power electronics converter technologies.

Within HVDC system converter's techniques, voltage source converters (VSCs) technology is emerging as a better alternative option compared to traditional line commutated converters (LCCs) due to its distinctive features. These feature includes: 1) compact, scalable and flexible converter station layout; 2) high dynamic performance and improve AC system stability; 3) the ability to black-start and provide power to passive networks; 4) independent reactive and active power control; and 5) the ability to reverse power flow direction without DC voltage polarity reversal [2–4]. Hence, VSC based HVDC stands as a more fitting option for integrating extensive renewable energy resources and establishing MTDC grids. Notably,half bridge modular multilevel converters (HB-MMCs), a sub-type of VSC, have been adopted in numerous commercial HVDC initiatives (e.g., INELFE project, Nan'ao three-terminal project, and Zhoushan five-terminal project) due to their exceptional fault tolerant operation and steady state performance [5–7].

While VSC-based MTDC grids enhance the functionality and control ability of existing AC grids, the extensive expansion of such grids encounters several challenges. One primary hurdle is the absence of fast and dependable protections for DC grids. The absence of current zero-crossing events inherently complicates the interruption of DC current, differing from AC system's circuit breaker requirement. Despite certain manufacturers producing fast HVDC circuit-breakers, their elevated cost restricts their practical application [8, 9]. In contrast to AC systems, the low inductance in DC circuits results in a potentially rapid rate of change for both DC voltage and current during instances of DC short-circuits. A DC network lacks the ability to impede the voltage collapse that occurs following a DC fault throughout the network. Converters are incapable of offering voltage support during a DC fault, as they might promptly block themselves to protect against substantial DC fault currents. Unless the faulted DC circuits can be promptly and reliably isolated, AC currents will persistently feed into the DC fault from the AC side. Therefore, an ultra fast DC protection scheme is a need of the hour, which detects and isolate DC fault within the DC protection speed requirement. With the HVDC market's continuous expansion, focus must be directed towards comprehending the transient behaviors of both AC and DC grids subjected to a DC fault. Furthermore, exploring the influence of fast and reliable approaches to detecting, isolating and locating DC faults is essential for stability of AC/DC system.

From the AC system perspective, the integration of a VSC-HVDC network with the mainland AC grid presents several benefits: 1) enhancement of power system stability; 2) power system oscillations damping; 3) elimination of sub-synchronous resonance (SSR) phenomena and 5) suitable for offshore wind systems integration. Despite these advantages, there are critical concerns related to VSC-HVDC systems that demand immediate attention: 1) vulnerability to DC and AC short circuit currents; 2) effective short circuit ratio (ESCR) reduction of the AC grid, 4) impact of VSC converters control on protection schemes for HVAC systems.

Integrating MMC-HVDC technology into the existing mainland AC system comes with several challenges, as previously mentioned. One major concern for grid protection engineers is the assessment of how the control of voltage source converters impacts the existing protection equipment, particularly distance protection scheme. It is imperative to thoroughly investigate the effects of power electronic converters and their control strategies on the AC network and its protection scheme. The operation of converters and their associated controllers exhibits distinctive behavior during normal and abnormal scenarios, diverging significantly from conventional synchronous generators. Moreover, the rapid response times of MMC controllers lead to swift changes in system parameters, including the point of common coupling (PCC) voltage and line currents. In the event of a short-circuit fault on an AC transmission line, the MMC converter's ability to deliver power is constrained by its saturation threshold. This limit is influenced by the thermal capacities of the power electronics switches, which are typically designed to handle approximately 15-20 % more than the nominal current. Consequently, the MMC can generate fault currents with a magnitude of up to 1.2 per unit, imposing limitations on the fault level. This situation has repercussions for the conventional grid protection mechanism, which relies on the fault responses of traditional synchronous generators. Furthermore, the responses of the MMC converter to grid-side faults are notably different from those of a synchronous generator (SG), a crucial component of the power system. Connecting MMC-HVDC to AC transmission lines equipped with distance relays presents a challenge wherein faults occurring on the line might not be accurately detected by the distance relay at the intended location. This anomaly arises from the fast converter controller response in compliance with grid codes, particularly involving the injection of reactive currents. Consequently, this can result in either delayed activation or a complete lack of response from the distance relay. The implications of such delays or absence of relay action pose a significant risk to the entire power system.

Apart from protection challenges, there are some practical implementation limitation for accurate and robust fault location in MTDC and HVDC interfaced HVAC grid. The accurate fault location system is paramount to minimize power restoration time in the network. Specially in HVDC grid, where the high speed (few milliseconds) protection requirements in MTDC grid will lead to limited measurable post fault data and it poses a challenge for efficient fault localization. Out of the available fault location strategies in the literature, traveling wave (TW) based fault localization scheme align with the requirement of MTDC grid. But for accurate fault localization, the TW based scheme requires high sampling frequency measurement which increases computation burden on the protection and fault locator hardware and restricts its practical implementation due to communication and measurement standards requirements. Therefore, a low sampling frequency TW based protection and fault localization scheme is required for MTDC and HVDC interfaced HVAC grid which conforms to applicable communication and measurement standards.

1.2 Literature Survey

The thesis primarily focuses on developing novel algorithms for both primary and backup protection and fault localization of MTDC grid, TW based DC fault location algorithm compliant to IEC-61869 measurement standards, single ended TW based DC fault localization scheme and robust TW based wide area backup protection scheme (WABPS) for hybrid HVAC network interfaced with MMC based HVDC link. The upcoming subsections provide a comprehensive overview of the current state-of-the-art of the mentioned issues, concentrating on existing research and the corresponding issues and challenges linked with these problem.

1.2.1 Primary and backup protection for MTDC grid

Amid the optimism around the benefits of MTDC system, the protection of VSC-MTDC is still in its early research cycle and it faces grave challenges in the non-blocking operation of the MTDC grid under DC fault. In MTDC grid, a transient pole to ground fault can be cleared by temporarily blocking and restarting the entire VSC converter, while the converter has to be blocked again to clear the permanent DC fault [10]. Indeed, protective relaying has become the better solution with the advent of fast hybrid DC circuit breaker (HDCCB), and faulted lines can be isolated from healthy VSC-MTDC grid within several milliseconds. The protection relaying algorithm should detect the fault within the first milliseconds and the protection requirement of the DC grid is at least one order magnitude faster than a conventional HVAC system [11]. Similar to an HVAC protection system, a selective and time-sensitive primary and backup protection is crucial for fault resilient high voltage VSC-MTDC grid.

Various primary protection schemes for MMC based MTDC have been reported in the literature, such as DC differential protection for short distance MMC-MTDC, but it is generally not preferred for the protection of long-distance MMC-MTDC grid due to abnormal differential current introduced by the shunt capacitance discharge. However, some enhanced methods based on frequency-dependent models and Burgeon models [12,13] can compensate shunt capacitance discharge current, but its validation for industrial application is still difficult due to limited communication capabilities. Another MMC-MTDC protection scheme based on tripping AC side circuit breaker (CB) of the converter is proposed [10]. But the slow response of AC circuit breaker to the DC fault can potentially damage DC transmission lines as well as the MMC converter. Another DC side fault detection technique which uses undervoltage/overcurrent and rate of change of voltage/current are least sensitive towards high resistive faults [4]. Further communication based primary protection schemes such as harmonic current injection techniques are vulnerable to communication delays and failure [14]. For this reason, various local measurement protection schemes such as transverse differential current [15], low/high-frequency ratio [16], surge arrival time difference (SATD) between mode-0 and mode-1 [17], wavelet transform [18] are used in two-terminal MMC-HVDC and it can be extended to MMC-MTDC using boundary elements such as fault current limiting (FCL) reactor [19]. Generally, FCL reactors are recommended in the DC transmission line to limit the DC fault current and allow sufficient time for DC protection schemes to detect faults, but FCL reactors have a negative impact on DC grid stability [20]. Apart from that more widely used traveling wave (TW) based primary protection schemes rely on waveshape of TW. Mostly directional and distance protection based on polarity and arrival time (AT) of TW is used for DC fault detection and location respectively. Another pilot protection scheme using cosine similarity between TW at the two terminals is proposed for the MMC-HVDC system [21]. In general TW based primary protection can be implemented using single and two terminal methods [22, 23]. However, detection of second TW in single terminal technique is quite challenging due to TW attenuation in long transmission line as well as single terminal technique fails to detect close-in faults [24]. Furthermore, inaccuracies in TW arrival time detection leads to significant error in fault detection and location [25].

In a resilient protection system, a backup protection system responds to the fault in the system in case of primary protection system failure. A local classifier-based backup protection system is designed to detect primary protection failure using voltage signal from primary relay [26, 27] and its robustness is evaluated for the different operating conditions in [28]. Although the classifier-based backup protection is very fast it has several drawbacks such as the requirement of detailed system modelling, intensive training for different fault conditions, limited scalability, system topology dependence, and noise intolerant. To overcome the limitation of classifier based backup protection, a quickest change detection (QCD) based backup protection is designed for the MTDC system [29]. But the QCD-based backup protection scheme is quite sensitive to high impedance faults. Another backup protection scheme is proposed using TW frequency characteristics [30]. Based on the TW polarity and fault location lookup table (DC conductor parameter dependent) corresponding to TW frequency content, a remote backup protection scheme is formulated.

1.2.2 Primary protection and fault localization scheme for MTDC grid

Majorly, the MMC-MTDC transmission can be classified into two categories, half bridge MMC (HBMMC) and full bridge MMC (FBMMC) MTDC transmission system. The FBMMC-MTDC grid have the DC fault blocking as well as DC fault ride through capability which does not require blocking of FBMMC converter [31]. Whereas, the HBMMC-MTDC grid does not have the DC fault blocking capability, as the fault current will pass from the AC side to the DC side via freewheeling diode of HBMMC converter. And therefore, HBMMC-MTDC grid would need a separate DC protection relaying and DCCB unit to detect and isolate faulty DC transmission line [32]. The HBMMC-MTDC transmission system faces several challenges, and the most prominent one is the fast DC protection and fault localization unit for MTDC grid. The protection speed requirement of MTDC grid is comparatively faster than HVAC grid, and it should detect the fault within few millisecond (1 ms - 2 ms) [33]. With the advent of fast HDCCB, the DC protective relaying becomes an attractive solution to isolate the faulty DC transmission line from the rest of the healthy HBMMC-MTDC grid. Following the fast and selective DC fault isolation, its important to accurately locate the DC fault in the MTDC grid with the short data window during fault as it will allow faster system restoration, minimum power outage time and increased power system reliability.

The MTDC primary protection scheme published in the literature can be majorly classified as TW-based (using polarity feature [34] or TW arrival time (TWAT) feature [35, 36]), transient-based (time or frequency domain feature of the fault transient TW) [37, 38], current or voltage derivative-based [39], fault current limiter-based [40], artificial intelligence techniques-based [41], parameter identification-based [42] and VSC converter control-based [43] MTDC protection scheme. Out of these, the most common MTDC primary protection schemes are based on polarity (directional) feature of the TW [34], whereas the TWAT (distance) features [35] are generally used for offline fault localization. Broadly, both of the TW feature-based protection schemes for MTDC grid can be classified as single and double-ended fault detection scheme. The single-ended TW-based MTDC protection technique uses local voltage/current information, but it generally finds difficult to discriminate between internal and external fault without boundary elements or fault current limiters (FCL). Moreover, single-ended TW-based MTDC protection scheme find it difficult to discriminate between subsequent TW identification near local DC terminal end. There among, single-ended protection scheme based on the principle of rate of change of voltage (ROCOV), which also reflects TW change rate, is suggested [44]. But its application to flexible DC grid for high resistive fault is not guaranteed. Apart from single-ended TW-based MTDC protection schemes, there are several double-ended-TW based DC fault detection techniques which require communication channels between two ends of the protected zone [45]. There among, a TW-based double ended directional protection scheme is designed for MTDC grid using TW polarity feature extraction at protected zone terminals [34]. In principle, the TW polarity features can be used for directional MTDC protection, but it can not be used for DC fault localization in MTDC grid. Therefore the interest is shifting toward TWAT feature based protection scheme, which can be used for protection and real time DC fault localization scheme simultaneously.

The fault localization in MTDC grids can be majorly categorized as impedance-based [46], machine learning based [47, 48] and TWAT-based [49] DC fault localization scheme. In theory, the TWAT information can be simultaneously used for TW based real-time fault detection and localization in the MTDC grid. But due to the high sampling frequency and high computational efficiency requirement, the TWAT features are generally suggested for offline DC fault localization. The higher sampling frequency measurements (500 kHz - 1 MHz) are required in TWAT based fault location tool for accurate TWAT estimation (with accuracy up to 2 μs - 1 μs) for precise DC fault location. An offline TW based DC fault localization tool is designed using the fault incident TWAT information at the DC transmission line ends [49] for high sampling frequency measurement. Another TWAT based fault localization scheme suggested a TWAT difference based fault location principle for pole-to-ground fault and TW-based propagation path ratio for DC fault localization using 400 kHz sampling frequency measurement [50]. To improve the accuracy of TWAT based fault location technique, a predictor-corrector method is used to extract efficient TWAT for 200 kHz sampling frequency measurement [51].

1.2.3 TW based fault localization scheme

As with any transmission system, it is quite critical to have an accurate fault location system in the HVDC transmission line to quickly locate fault and dispatch repairing crew to the fault location with an effort to minimize the power outage time in the MTDC grid. Generally, MTDC converters are quite vulnerable to DC faults and therefore MTDC grids are operated with high-speed DC protection relaying units and hybrid DC circuit breakers (HDCCBs) to rapidly detect and trips DC faulty sections within time span of few milliseconds. With such limited measurable post fault data in the MTDC grid, it is quite difficult to design an accurate and efficient fault locator in the DC transmission line. Numerous HVDC/MTDC fault location techniques have been proposed in the literature, which can be broadly classified into TW analysis [52], fault signal analysis [53], and machine learning-based methods [47].

Lately, numerous methods for locating faults in DC transmission lines have emerged, primarily falling into three categories: frequency characteristics-based methods [54–57], time-domain-based methods [58–61], and traveling wave (TW) based methods [25, 47, 51, 62–70]. The fault location schemes based on frequency characteristics essentially depend on the precise extraction of fault-related features in the frequency domain. These features include the gap between adjacent peaks in the frequency spectrum [54], the frequency of TW reflections [55], and the natural frequency of TW [56]. To enhance the accuracy and reliability of fault location using frequency-based approaches, the bat algorithm is utilized for optimization, considering factors like time delay, characteristic frequency, and energy attenuation [57].

Time-domain-based fault location methods involve measuring voltage and current at opposite ends of the transmission line to determine the distributions of voltage and current along the entire line. Subsequently, fault location can be estimated using the wave equation and inherent characteristics at the fault point, such as the similarity of voltage signals [58–60]. Artificial Neural Networks are trained based on the similarity among voltage signals, forming a pattern for fault detection and localization,which significantly improve the fault location accuracy and robustness [61].

The TW-based fault location method relies on the arrival time of TW information and their propagation velocity to calculate distance to the fault from protection relay device. This TW-based approach can be applied to both AC and DC lines for pinpointing fault locations and offers advantages in terms of accuracy and the ability to handle various transmission line types, fault types, and system operation modes. Typically, this methodology is categorized into two types: single-ended and double-ended schemes. Double-ended methods, especially when combined with global positioning systems (GPS), are often considered more advantageous. In double-ended fault location schemes for multi terminal DC (MTDC) systems [62] and two-terminal HVDC systems with hybrid transmission lines [63], continuous wavelet transform (CWT) plays a significant role in detecting wave fronts. The TW propagation velocity is calibrated through repeated field tests and precise synchronization of measurements. Furthermore, the shortest path theory is developed to locate faults based on synchronized signals recorded at different line terminals, considering various DC network topologies [25]. An alternative method proposed for estimating fault locations in MTDC systems involves optically multiplexed sensors [47]. In this approach, distributed measurement points along overhead lines are fully synchronized to identify the faulty segment and precisely localize the fault point. Besides CWT, other tools for extracting fault-related features, such as the S transform [64], empirical mode decomposition (EMD) [65], and mathematical morphology (MM) [66], are also employed in fault location algorithms.

In contrast to double-ended methods, single-ended fault location schemes face challenges in accurately recognizing consecutive TW arrivals. Addressing the issue of false TW arrivals, some solutions have been proposed. One approach, described in [51], deals with the problem by considering TW front distortion. Another single-ended method is designed for locating faults in submarine cables, utilizing time-frequency domain reflectometry [67]. This method involves analyzing the fault signal based on similarity measures such as tangent distance and Euclidean distance to handle confusion points in wave head detection. Additionally, it employs a support vector machine to identify the faulty segment in hybrid transmission lines and decomposes local information using discrete wavelet transform (DWT) to determine TW arrival times for fault location [68]. Schweitzer Engineering Laboratories has extensively studied the single-ended fault location method for its application in HVDC lines [69]. This method utilizes both voltage and current signals to differentiate between incident TW and reflected TWs. TW arrival times are determined using a differentiator smoother and an interpolation-based estimator. Furthermore, the Bergeron time-domain fault location method incorporates TW theory and introduces a self-adaptive band-pass filter to calibrate velocity [70]. Time tags are adjusted with a zero-time reference, allowing for the calculation of time differences between TW arrivals at two ends, which can then be used for fault location.

The TW-based fault location principle has led to the development of several fault location schemes, incorporating learning theory [71, 72] and active pulse injection [73, 74]. While the use of learning theory can address challenges in TW-based fault location, such as TW attenuation, overlap of TW surges, and high impedance faults, it typically relies on a substantial amount of training data to ensure accurate fault location performance. Furthermore, considering the changing operation modes and uncertainties in system parameters, the feasibility and effectiveness of learning theory-based methods warrant further research. In contrast to passive TW-based fault location methods, active fault location schemes take advantage of the controllability of MMC to inject TW pulses [73] and DC voltage perturbations [74] into the transmission line without the need for additional equipment. It has been demonstrated that active TW-based fault location exhibits excellent robustness against variations in fault impedance and subsequent TW identification challenges [73, 74].

To solve successive TW arrival time estimation issue, a single ended TW based fault localization scheme using first incident aerial (alpha) and ground model TW is used to locate earth fault [17,75]. It uses the TW arrival time difference between aerial and ground mode TW to locate fault only, eliminating the need of identifying second or reflected TW which is a challenging task for single ended TW. But it is only applicable for earth fault and it can not be used to locate pole-pole fault due to unavailability of ground mode TW in pole-pole fault in MTDC transmission system.

1.2.4 Wide area backup protection for HVAC network interfacing MMC based HVDC link

For secured and resilient distance protection of HVAC transmission line, a backup (zone 2 and zone 3) protection is used with pertinent time delay in conjunction with instantaneous primary protection (zone 1). The backup zone of the distance protection schemes are generally more prone to system stressed conditions such as load encroachment, power swing and voltage instability, and which is further aggravated by the MMC converter interfaced HVDC link. To solve this issue, a two criteria approach is used to discriminate system stressed conditions from symmetrical fault for secured backup protection element [76]. But it did not considered the effects of PE converter based HVDC link on backup protection zone. The fast control dynamics of MMC converter in HVDC transmission line will severely effect the conventional distance relay operation. Therefore, an accurate impedance measurement based backup protection scheme is formulated to avoid miss-coordinated zone identification in distance relaying scheme [77]. But its study is only limited to reactive power control of VSC converter and lacks detailed discussions on its effect on backup protection scheme. Another fast communication assisted distance protection for HVAC line emanating from MMC-HVDC station is proposed by [78]. Its protection criteria is based on polarity direction factor and comparison of measured and projected reference impedance at the relay location. Its main limitations are communication dependence, delayed response for primary protection of some high resistive symmetrical fault and it also lacks study of converter control on backup protection scheme.

In summary, the protection of HVAC transmission line interfacing with MMC based HVDC link can be broadly classified into adaptive protection-based [79], robust control-based [80, 81], differential protection-based [82], integrated AC/DC protection [83–85], wide area phasor measurement unit (PMU)-based [86, 87], signal processing [88], traveling wave (TW)-based [89–91], generalized differential equations-based [92] and machine learning based protection scheme [87]. Out of these, the PMU-based wide area protection is the most widely suggested backup protection scheme for HVAC transmission line. For secured relaying operation, the conventional distance relay is supervised using wide area deep neural network (DNN) based tool to prevent relay maloperation under system stressed conditions [87]. Although the DNN based wide area backup protection scheme (WABPS) is resilient to high impedance, noise contaminated signal, but it has shortcoming such as limited scalability, system topology dependence, intensive training and detailed system modelling requirement. Another secured adaptive protection scheme is formulated using phase angle of the faulted current loop to determine pure fault impedance for correct relay zone identification [79]. But it might not work satisfactorily for noise contaminated voltage signal due to poor performance of conventional signal processing technique. To overcome this issue, a robust control based MMC converter unit is suggested for hybrid AC/DC system to avoid conventional distance relay malopeartion [80]. The performance of robust control based protection scheme is validated for low fault resistance only and it might not work satisfactorily for high fault impedance.

The TW principle is generally used for fault localization and researchers have also suggested TW based primary protection for HVAC transmission line recently [91]. Apart from the TW-based primary protection, very few researchers have also explored the TW-based wide area protection and fault localization schemes for HVAC transmission line [93–95]. It have mostly explored the suitability of IEC-61850 communication protocol for TW-based WABPS using high sampling frequency measurements (up to 500 kHz), but it have not studied its suitability for backup protection of MMC converter interfaced HVAC grid under low sampling frequency measurement (50 kHz). Moreover, the offshore wind farm integrated HVAC system requires overhead transmission line and submarine cables, but very few TW-based protection schemes are developed for mixed or hybrid overhead transmission line and cable system. The TW based fault localization scheme for hybrid transmission line is derived using wavelet transform technique in [96], but it did not studied and developed a robust protection scheme for HVAC system,using mixed overhead transmission line and cables system, interfacing HVDC link.

1.3 Motivation

With extension of point-to-point HVDC transmission system to multi terminal HVDC grid, its protection scheme is still at its early stage and it faces several challenges such as non-blocking operation of MTDC converter under DC fault, fast DC protection relaying requirement and non-availability of zero-crossing point in DC current for DC circuit breaker operation. Moreover, MMC converter based HVDC interfaced HVAC grid might lead to maloperation of the conventional distance relay and compromises selectivity and reliability of the distance protection scheme. From the above-mentioned literature review, the motivation behind this work are summarized below -

1. The traveling wave principle has been generally investigated for the primary protection and fault localization scheme for MTDC grid, however its application to the backup protection of MTDC grid is seldom explored. An integrated TWAT based primary and backup protection scheme is required which could also be extended to DC fault localization.

2. The MTDC protection scheme based on TWAT principle demands high sampling frequency (500 kHz - 1 MHz) to ensure fast fault detection and accurate fault localization, but its practical implementation faces limitations due to the IEC-61869 measurement standard requirement, which caps the maximum sampling frequency at 96 kHz.

3. The conventional single ended TW based MTDC fault localization scheme finds it difficult to discriminate first and subsequent TW for close-in fault. Some of the single ended TW based fault localization scheme uses aerial and ground mode TW to locate pole-to-ground fault to effectively locate close-in fault, but it fails to locate pole-to-pole fault.

4. The effect of MMC converter based HVDC link on the conventional backup protection scheme (distance relaying principle) for the AC transmission line is very

significant and TWAT principle based distance protection scheme is very rarely explored for WABPS of the AC grid using IEC-61850 communication protocol. In literature, very few research article have explored the protection of mixed cable and overhead transmission line in HVAC network.

1.4 Research Objective

The main research objective of the thesis are -

1. To develop a TW based primary and backup protection scheme for the MTDC grid, which can also be used for TWAT based fault localization.

2. To design and validate novel TWAT based primary protection and fault localization scheme for MTDC grid compliant to IEC-61869-9 measurement standard.

3. To develop a novel single ended TWAT based fault localization scheme for the MTDC grid which is resilient to locate close-in pole-pole and pole-ground fault near the DC terminal.

4. To develop a TWAT based wide area backup protection scheme for the mixed cable and overhead transmission line in HVAC grid interfaced with MMC converter based HVDC link.

1.5 Overview of major contribution

The major contribution of the thesis can be summarized as below -

1. The primary protection speed requirement for the HVDC grid is much faster as compared to the conventional HVAC grid. In this chapter, a traveling wave-based primary and backup protection scheme is proposed for the multi terminal HVDC transmission system using the morphological un-decimated wavelet decomposition signal processing technique. Depending on the polarity and arrival time information of the first incident traveling wave at both DC transmission line terminals, the fault is identified to be either in the internal zone, forward external zone, or backward external zone of the DC transmission line. Each DC transmission line is covered by

its own internal zone as well as forward and backward external zone of its neighboring line. The internal zone fault identification of the protection scheme sends the primary relay trip signals to associated hybrid DC circuit breakers. But if the primary protection relay fails, then the neighboring DC substation protection system identifies the fault either in forward external or backward external zone. Then it sends a remote backup trip signal to the DC circuit breaker in the forward or backward external direction with a coordinated time delay for backup protection of the DC transmission line.

2. TW based protection and fault localization requires high sampling frequency measurements (500 kHz - 1 MHz) and are non-compliant to the IEC 61869-9 measurement standards, which allows maximum sampling frequency of 96 kHz for DC application. In this chapter, a novel low sampling frequency (50 kHz) TW based primary protection and real-time DC fault localization technique for MTDC grid is proposed, which is compliant with the aforementioned measurement standard. In the proposed MTDC protection scheme, a TWAT is estimated under low sampling frequency measurement using cascaded combination of modified mathematical morphology gradient (MMG), sobel operator and linear regression tool. Subsequently, the TWAT information at both DC link terminals is communicated via dedicated communication channel compliant to IEC-61850-9-2 standard. And if the TWAT difference between DC terminals is less than the TW propagation threshold for the protected DC line, then a DC trip signal is issued to the associated hybrid DC circuit breaker (HDCCB). For fast power system restoration, the same TWAT information is also used for real-time fault localization in the faulted DC line, which is also compliant with IEC 61869-9 measurement standards. Finally, the practical feasibility of the proposed algorithm is demonstrated through control hardware-in-loop testing with real-time digital simulation setup and TI TMS320F28379d digital signal processor card.

3. A novel single ended TW based DC fault localization scheme is designed for the MTDC transmission system which utilizes the frequency domain characteristics of the only first incident TW, and overcomes the challenges posed by the conventional single ended TW based protection to detect close-in fault. It employs sliding matrix

pencil method (SMPM) to accurately estimate TWAT of the 500 kHz and 50 kHz (using down sampler and 2^{nd} order Butterworth filter) sampled voltage signal. The performance of proposed fault localization scheme is validated against different fault types, fault location, fault resistance and measurement noise in PSCAD/EMTDC offline simulation setup.

4. A robust and secured TW based WABPS for mixed cable and overhead transmission line in HVAC grid interfacing MMC converter based HVDC grid is developed. A modified fast successive matrix pencil algorithm (SMPA) is used to estimate TWAT at digital fault recorder (DFR) installed at AC buses, which sends the fault induced TWAT information to the centralized graph theory based wide area real time fault localization tool for secured backup protection of the AC transmission system. The validation of proposed WABPS scheme is performed against different fault location, fault types, fault resistance and MMC converter control effects.

1.6 Organization of the thesis

The organization of thesis is outlined as follows -

- **Chapter 1** presents the introduction of thesis. It includes the literature survey for the proposed research work, which helps to identify subsequent research gap and formulate research ideas or objectives. After that, overview of the thesis and organization of thesis structure is outlined.

- **Chapter 2** develops a TW based primary and backup protection scheme for the MMC-MTDC transmission system using MUDW signal processing technique. The polarity and arrival time information of the first incident TW at DC terminal ends is used to create three different zone (internal, forward external and backward external zone) which is used to formulate primary and backup protection scheme for DC transmission line.

- **Chapter 3** presents a low sampling frequency TW based primary protection and fault localization scheme for MTDC grid which is compliant to IEC-61869-9 measurement standard. The practical feasibility of the proposed scheme is also validated with hardware in loop (HIL) setup compromising of real time digital simulator and IED prototype using TI TMS320F28379D digital signal processing board.

- **Chapter 4** develops a single ended TW based fault localization scheme for the MTDC transmission system which uses first incident TWAT for high and low sampling frequency (derived from high sampling frequency signal using downsampler and low pass butterworth filter) aerial mode signal. The proposed scheme overcomes the shortcoming of conventional single ended TW fault localization to locate close-in fault to the DC terminal.

- **Chapter 5** suggests a TW based WABPS for mixed cable and overhead AC transmission line in HVAC grid interfacing MMC converter based HVDC linke using IEC-61850 GOOSE message protocol.

1.7 Summary

This chapter introduces the work carried out in this thesis. At first, the problem statement is outlined followed by literature survey highlighting the existing works and issues and challenges associated with them. The motivation behind the thesis work is presented followed by the framed objectives of the thesis. Then, brief overview of thesis is presented with the major contributions from the research work. Lastly, the organization of thesis in different chapters is presented.