Chapter 1

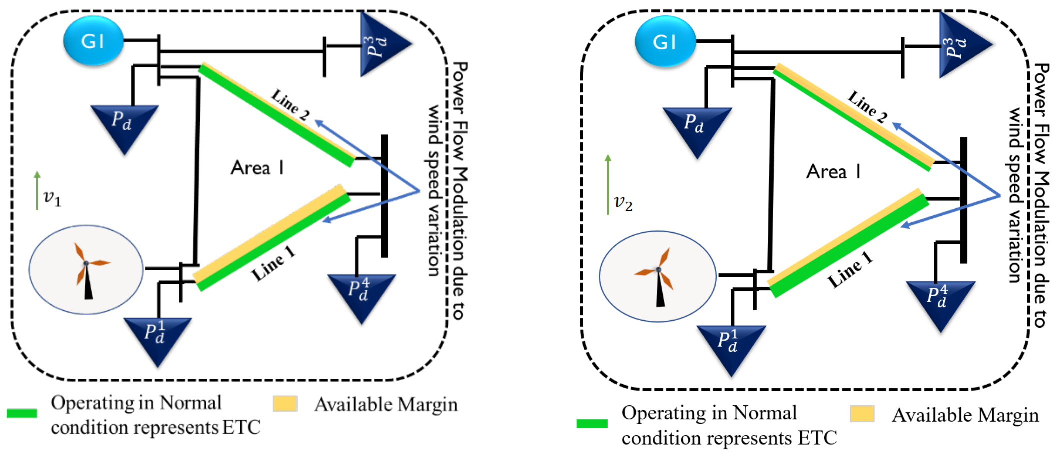
INTRODUCTION AND LITERATURE REVIEW

This chapter articulates a brief overview of the prevailing power sector scenario at both local and global levels. It lays the foundation for the research conducted and reported in this thesis. This chapter, starting from a brief background and prevailing situation, furthers by delineating the literature review, research gap, motivation, thesis organization, and concluding remark.

1.1 A BRIEF BACKGROUND AND PREVAILING SITUATION.

Power systems monitoring, analysis, and control have always been the prime focus of power grid operators. Changing technologies brought about nascent tools (Phasor Measurement Units), which enhanced the capability of system operators in monitoring the vitals (i.e., voltage, current, active, and reactive power) of the system [1]. The task of the system operators and analysts became complicated with the inception of deregulation and open access. The deregulation introduced in the power sector aimed to enhance fair competition between market participants and provide economic benefit to the consumers. It revolutionized the energy market, transforming the vertically integrated and centrally controlled power system into a decentralized system where the power utilities' role was disaggregated and horizontally integrated [2]. During these restructuring processes, transmission open-access was also conceptualized and introduced in the power system. Open access provided the provisions for any legit independent power producer to inject Power into the grid and use the existing transmission facility while adhering to the grid standards and protocols. Deregulation, coupled with open access, brought about changes in the consumers' favor by advocating a healthy and competitive environment and complicated system operators' tasks.

The awareness of the system status (i.e., situational awareness) has always been a critical factor in power system security assessment, monitoring, and control. Various indices and metrics have been propounded and proposed in the literature to monitor the system's health during dynamic and static environments. Contingency Analysis has long been in practice to assess the system performance and prepare for adverse situations when subjected to critical contingencies. The generation capacity assessment through generation adequacy and transmission capacity assessment through transmission capability assessment has been used for transmission expansion and planning [3]. Due to the changing scenario, the generation is shifting from conventional sources to non-conventional sources of Power both at transmission level (several MW's to GW's) and distribution level (KW's to MW). As a result, the power flow through the lines is continuously changing. The transforming scenario has been inked in Figure 1.1, where variation in power-flows could be attributed to the intermittent renewable sources.

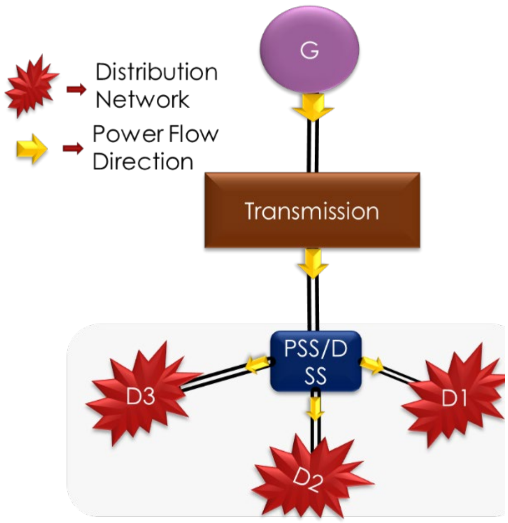


(a) Power system operating at lower wind velocity v_1

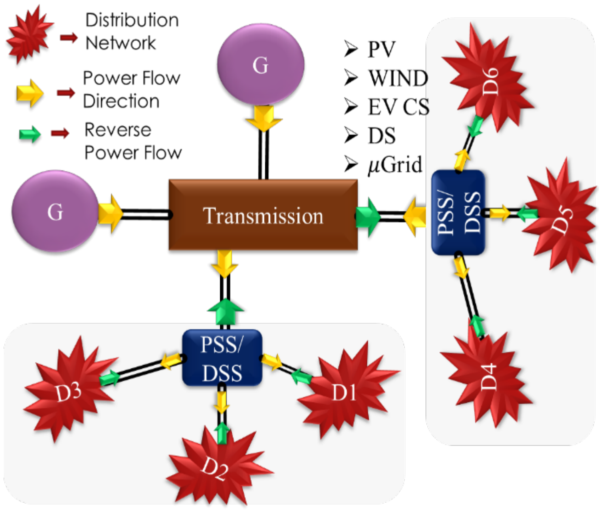
(b) Power System operating at higher wind velocity v_2

Figure 1.1 Schematic representation of power flow variation due to renewable source.

In such a scenario, assessing the transmission line's power flow capability in real/near-real-time becomes vital for providing the system operators adequate information on reliable power flow that could be permitted through the line, thus establishing the ATC assessment as an essential factor. Further, with increased penetration of distributed generation at distribution levels and the introduction of prosumer technology, the possibility of power being fed back to the transmission grid from the distribution network arises and increases (illustrated in Figure 1.2)[4]. These new developments have further mandated developing new frameworks for integrated analysis of transmission and distribution systems [5]. Also, reducing the carbon footprint across the globe has stimulated the governments to shift the modes of transportation from conventional (petroleum/diesel-based) to Electric Vehicles (EV) (Figure 1.3).

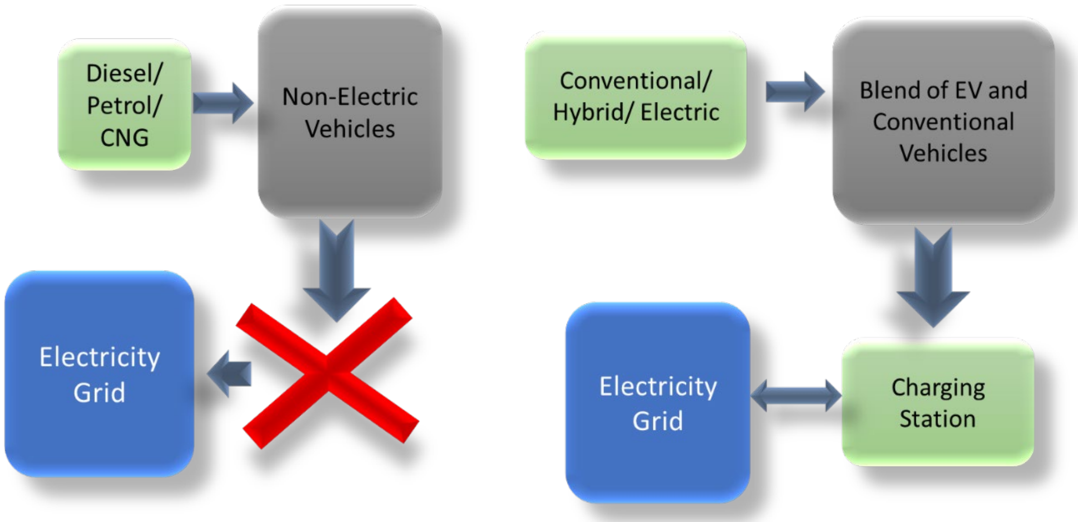


(a) Conventional T&D System



(b) Modern T&D System

Figure 1.2 Changing scenario of T&D systems.



(a) Conventional System of Transportation

(b) Modern System of Transformation

Figure 1.3 Restructuring of Transportation Sector And its impact on power grids.

The electric vehicle capable of acting as VPP (Virtual Power Plants) would be having the capability to modulate the power flow in active distribution networks. Thus, a need to analyze the available distribution capability of the system arises [6]. Further, the deployment of active devices with communication capabilities could empower them to participate in an energy trading mechanism through the bidding process [7]. Such tools could be enabled by utilizing the nascent blockchain technology [8]. Blockchain is a kind of distributed ledger which could be used for value as well as information exchange. It is an immutable, distributed, secure technology that eliminates intermediaries and could be utilized by the network peers to transact, communicate, and trade.

1.2 LITERATURE REVIEW

In this section, detailed literature for different aspects of the work reported in this thesis has been reviewed. The various aspects covered have been schematically shown in Figure 1.4.

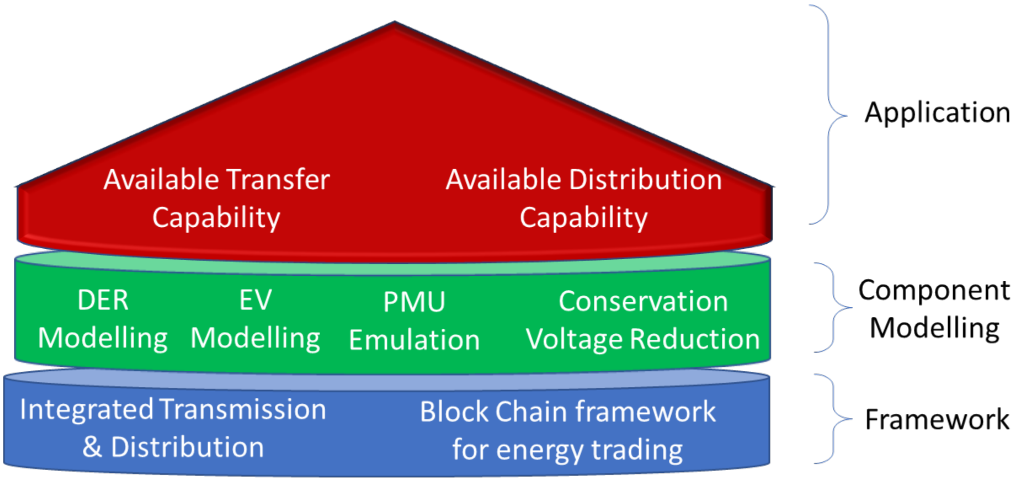
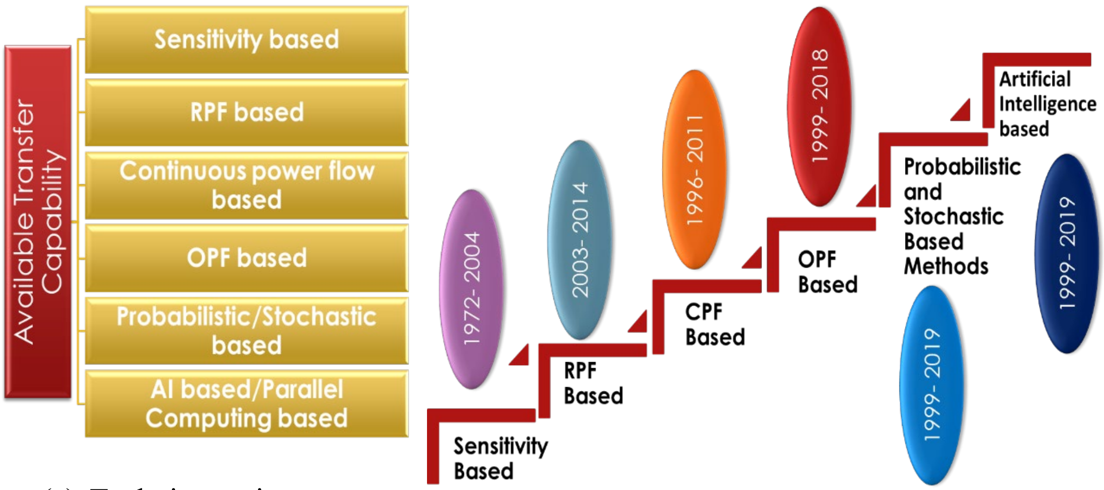


Figure 1.4 Schematic representation of various aspects for which the existing literature review has been given.

1.2.1 Available Transfer Capability

The recent changes in the power system structure have led to much more complexity in its operation. The deregulation resulted in the reorganization of the vertically integrated energy sector into a decentralized sector where generation, transmission, and distribution were not owned by a single entity but differently owned and controlled by several entities. The open-access granted free access to existing transmission facilities to any individual with the appropriate license to inject/draw power at any point into the system [9][10]. The open-access and deregulation made the system's operation difficult as the power drawl and injection became open for all. Thus ATC estimation and enhancement became a vital factor both from commercial and power system operation points of view. Federal Electric

Energy Regulatory Commission (FERC) order 888 and 889 ensures that the transmission owners provide comparable services to all the customers and they post/obtain pertinent information from OASIS (Open Access Same Time Information System) [11]. With these changes, the ISO (independent system operator's) responsibility increased; besides maintaining the system integrity by monitoring the power transactions, the system operator is additionally burdened with maintaining transmission system reliability in real-time. This will require a proper evaluation of the ATC of the system. The ATC estimation in a deregulated environment has been reported in several works [12]–[14]. In broad, the different techniques developed for ATC assessment could be broadly classified into six major categories, as shown in Figure 1.5. (a), while the year wise occurrence of articles reported using different techniques has been shown in Figure 1.5. (b). The sensitivity-based [15]–[21] methods (linear approximation methods) primarily utilize the power transfer distribution factors for computing the system's ATC.



(a) Technique wise classification for ATC assessment

(b) Reported articles in different years.

Figure 1.5 Different methods for ATC assessment.

The sensitivity-based methods comprise DC power flow-based (DCPF) and AC power flow-based (ACPF) techniques. Both these formulations (DC/AC power flow) produce similar results except in the complicated situation of low X/R ratio and significant change in system losses and voltage. Comparatively, the ACPF flow-based method is much slower than DCPF. Still, it is more general as it incorporates the active and reactive power consideration in the solution. The drawback of using sensitivity-based methods lies in the fact that the sensitivity factors are determined for a particular scenario; thus, the ATC value determined using these values might not be adequate if the system's operating point is substantially shifted.

Researchers have also investigated RPF-based techniques for the ATC assessment [22]–[28]. In RPF, power flow is repeatedly calculated along the operating points' sequence with a given transfer direction; however, it is vulnerable to singularity associated with the Jacobian matrix in the periphery of the saddle-node bifurcation point; thus, the process may be subjected to divergence. The drawback of RPF has been overcome by the Continuation Power Flow (CPF) based methods [29]–[35]. CPF uses the predictor-corrector method for tracing the P-V curve. The use of Flexible AC Transmission System (FACTS) devices can modulate the power flow through the line and hence be utilized for ATC Enhancement [36]–[43].

The optimal values of FACTS device control parameters can be determined by exploiting optimization-based algorithms. The Optimal-Power Flow-based (OPF) techniques have also been used for ATC assessment [44]–[48]. In the determination of ATC using OPF methods, ATC is formulated as an OPF problem. Unlike conventional power-flow techniques, OPF problems are formulated as an optimization problem in which various optimization techniques could be employed to obtain a solution. Pattern

Search Optimization discussed in [49] has been utilized as a solution technique in work presented in this thesis.

Uncertainty in the various system parameters is a significant concern in determining the ATC of the system. Therefore, probabilistic and stochastic methods that account for the system's uncertainty during ATC assessment [50]–[58] have been proposed in the literature. The uncertainties considered during ATC modeling with uncertainty are the component availability modeling, modeling uncertain renewable sources, and uncertainty modeling in loads. The limitations of the probabilistic approaches are the computation time and large amount of ATC data required for the accurate evaluation of ATC.

The Artificial Intelligence (AI) based methods have also been investigated from the perspective of ATC assessment [59]–[67]. AI-based methods have also been utilized for developing contingency analysis techniques [68], [69]. A methodology for online static security assessment has been presented in [70]. The major issue of employing an AI-based technique is that a large number of data set is required for training the ANN and are prone to over-fitting and underfitting. Further, in power system applications, the number of input features grows with the increase in the size of the system; therefore, adequate feature reduction techniques are needed to be employed for dimensionality reduction [71]

Although a lot of methods have been proposed in the literature, little work has been done for developing techniques that would use the real-time data streaming from the synchrophasor measurement devices for the estimation of the ATC. The development of such a technique would require the availability of PMU data corresponding to different probable scenarios to which the power system may be subjected during practical operation. In [72], measurement-dependent injection distribution factors (MDIDF) based method in which synchrophasor measurements have been utilized for ATC estimation.

Phasor Measurement Unit (PMU) is being integrated into the power system for enabling enhanced monitoring and control of the network, and many works are being done which investigate the applicability of PMU in broad areas of power system monitoring and control [73]–[78]. PMU are enablers for real-time and near real-time analysis of the power system. Wide-scale research activities are being done on enhancing the power system operation and control while using the measurements obtained from the Phasor Measurement Units [79]–[81]. The accuracy and nature of data required for proper monitoring and control of power systems depend on the nature of the application for which the data is required. Thus characteristics and nature of data required vary from application to application. Depending upon the nature of data requirements, the power system can be categorically divided into four categories given in Table 1.1. Data requirements with the objective of Static Security Analysis do not impose stringency on the accuracy, latency, and availability of the measured data.

Table 1.1 CLASSIFICATION DEPENDING ON NATURE OF APPLICATION

	Type 1	Type 2	Type 3	Type 4
Low Latency	Critical	Fairly Important	Not Very Important	Somewhat Important
Reliability/ Availability	Critical	Somewhat Important	Fairly Important	Not Very Important
Data Accuracy	Critical	Somewhat Important	Critical	Not Very Important
Time Alignment	Critical	Critical	Not Very Important	Somewhat Important
Message Rate	Critical	Somewhat Important	Critical	Somewhat Important
Sample Application	Out of step Protection	State Estimation	Disturbance Analysis	Real-Time Monitoring

Thus techniques intending to emulate PMU should exploit these factors into their algorithms. The measurement-based technique provides a snapshot of the system in terms of the measured variables. Many works are being done regarding emulation of Phasor Measurement Units both in Hardware and software. These works are intended to imitate the dynamic behavior of PMU. The OpenPMU technology platforms provide the design of crucial components for the fabrication of PMU from a hardware perspective by the researchers with a viewpoint of enabling the new developments to be tested by the researchers in an online environment [82]. Digital Signal Processing based PMU unit is presented in [83] using a one pulse per second GPS signal and Recursive Discrete Fourier Transform algorithm. The evaluation of the dynamic behavior of PMU and their analysis is done in [84]. The backbone for enabling PMU based monitoring and control is the interconnecting communication network through which the data sharing/communication for wide-area monitoring and control is accomplished. In [85], the authors discuss the experience of design and implementation of intranet telecommunication framework for phasor measurement units. In existing techniques, PMU emulation have been done from the perspective of dynamic studies in the power system, whereas emulation of PMU exclusively from static security analysis point of view has not been done.

1.2.2 Integrated Transmission and Distribution

Co-simulation platforms for integrated analysis of T&D systems are being developed for assessing the impacts of probable phenomenons at DN on TN and vice-versa. In [86] authors presented an architecture for transmission and distribution integrated monitoring and analysis system and employed the developed method for analyzing higher penetration of DER's (distributed energy resource) at DN levels. In [87], authors investigated the economic aspect of (integrated transmission & distribution (ITD) and presented a two-stage optimization problem for analyzing T&D economic models using transmission constrained residual supply curve along with aggregated residual demand curve. The impact of ADN on the risk analysis of transmission system has been assessed in [88], where the risk indices are derived using an iterative calculation between T&D. Network equivalent models have also been utilized to integrate the T&D system into a common electrical model [89].

In [90], the authors presented a master-slave splitting based global power flow method for integrated analysis of the T&D system. Authors have proposed heterogeneous decomposition for coordinated economic dispatch of coupled T&D systems in [91]. A decoupled co-simulation approach [92] whereby existing transmission and distribution simulators are linked through FNCS (framework for network co-simulation), a middleware framework, to assess the dynamic behaviors of ITD networks. Co-simulation has been achieved through federation, in which each process runs on its own simulator, with FNCS facilitating the data exchange and clock synchronization between the simulators. Three sequence models for transmission systems and three-phase models for distribution networks are utilized, and an integrated T&D power flow and dynamic simulation have been proposed in [93]. The method was capable of handling both unbalanced, balanced, and mixed scenarios of ITD. Attempts at developing OPF (optimal power flow) solutions for ITD operation have also been made in [94], whereby heterogeneous decomposition algorithms inspired by heterogeneous T&D characteristics have been proposed to solve the T&D OPF in a distributed manner. The methods for estimating the flexibility in active and reactive power exchange at the TSODSO interface have also been presented in [95], where authors have suggested optimization-based methods for estimation of the flexibility. Methodologies for emulating the inter-dependency of T&D systems are being developed for assessing the impacts of phenomenons taking place at DS on TS and vice-versa. In [96], the authors presented an architecture for developing integrated monitoring and analysis of T&D system and used it for impact assessment of higher penetration of DG at DS level.

Distributed energy resources modeling involves the modeling of uncertainties [97]–[102] linked with the inherent nature of the renewable source. For instance, the modeling methodologies model wind power forecast, using the Weibull-distribution, and the solar-based DER uses the beta distribution. Different modeling methodologies utilizing Monte-Carlo based, Markov-chain Monte Carlo based, and other probabilistic methods have been delineated in the literature. The probabilistic modeling of ATC considering the wind energy variability has been inked in [53], [54], [103]–[105].

A detailed review of different techniques for modeling EV could be found in [106]. A data mining model was developed to investigate the characteristics of electric vehicle charging demand in a geographical area [107]. A Fuzzy-Based model aggregates these characteristics and estimates the potential relative risk level of EVs charging demand among different geographical areas independent of their actual corresponding distribution networks. In [108], historical EV charging demand is first determined using the Markovian analysis of EV driving patterns and charging demand. A mathematical model for the optimal sizing of EV charging stations has been developed in [109], where the minimization of the total cost associated with EV charging stations to be planned as the objective function and solved by a modified primal-dual interior-point algorithm (MPDIPA) has been given. A reconfiguration strategy for an active distribution network with electric vehicles has been done in [110].

1.2.3 Conservation Voltage Reduction (CVR)

CVR isn't a new technology; it has been employed by several utilities during the decade 1980-90 to reduce their yearly energy consumption and peak power demand through the reduction in the substation voltage [111]. In 1973 [112], the American Electric Power System (AEP) and Public Service Commission of New York have for the first time established their first implementation of CVR. Subsequently, many utilities, namely:- Dominion Virginia Power [113], BC Hydro [114], Hydro Quebec (HQ) [115]. Bonneville Power Administration (BPA) [116], Southern California Edison (SCE) [117], and Northwest Energy Efficiency Alliance (NEEA) have deployed CVR and achieved significant energy savings due to voltage reduction [118]. The interest in utilizing CVR based schemes has increased these days rapidly due to the implementation of energy policy structures and the emergence of smart grids. United States has recently deployed CVR technology to all distribution feeders and obtained about a 3.04% reduction in energy consumption annually [116]. The CVR technology was widely investigated by other nations also. Australia, Ireland has obtained 2.5% and 1.7% energy saving by reduction of 1% of voltage respectively [119], [120].

CVR strives to operate the DN at the lower permissible limit of voltage deviation to facilitate demand reduction [121]. In distribution networks, mostly the loads are voltage-dependent; thus, feeder load demand can be controlled by varying voltage profile [122]. In [120] have studied the CVR effect on voltage stability of the transmission system, and the study reveals that voltage stability margin can be increased with the integrated operation of CVR. The literature for load models could be found in [123] a method has been proposed considering the practical aspects of user-end behavior.

1.2.4 Available Distribution Capability

The Available Distribution Capability or Total Supply Capability can be considered as a distribution level version of Available Transfer Capability. In literature, methods have been proposed for assessing the available distribution capability [124] or total supply capability [96], [125]. There have been a few advances in ADC assessment techniques, mainly because the distribution networks are generally radial and unidirectional power flow (directed from the source node to load nodes) took place. Nevertheless, with changing scenarios where consumers are transforming to prosumers along with the prevalence of EVCS (Electric Vehicle Charging Stations) in the network, the significance of ADC assessment and monitoring would increase manifolds.

1.2.5 Blockchain

In the era of wide-scale emphasis on renewable integration, the prosumers have ample opportunity to participate and reap the benefits of decentralized distributed generation through active participation in the energy markets. The prevalence of active sources ($DERS$ and EV as VPP) would significantly impact the overall load profile of the ADN [126]. The inherent nature of renewable sources (uncertain generation) in amalgamation with the complex behavior of EV as VPP complicates the technological as well as commercial aspects of power system operation and control.

Considering the blockchain-based energy trading in ADN, the impact on the overall aggregated load profile, available distribution capability, and load-ability of the system is assessed. In the blockchain, distributed protocols are utilized for energy transactions between the load and generating nodes. Blockchain technology empowers the peers to transact digital value and information without the requirement of any third party mediation; such features of blockchain are bound to enhance its applicability [8]. The likely changes in the modes of transformation to (EV/HEV) from conventional fuel-based systems would also necessitate the promulgation of blockchain technology for the control and management of transactive energy [127].

Blockchain technology propounded by Satoshi Nakamoto [128], is a form of distributed ledger which offers the features of immutability, security, and privacy. The double-spending problem encountered while exchanging the digital value could also be avoided using blockchain. Double spending refers to the phenomenon in which the same digital currency could be used for more than one purchase. Several techniques have been delineated in the literature that promulgates the deployment of blockchain-based methods for energy trade in the power sector. Blockchain-based distributed coalition formation for peer to peer energy trade among different microgrids have been presented in [129]. Blockchain consortium has been utilized to develop a localized peer-to-peer electricity trading for plug-in-hybrid electric vehicles in smart grids [130]. A survey on blockchain from the perspective of game theory could be found in [131]. Authors in [132] have addressed the technical aspects concerned with the power flow constraints along with considering energy as a trading commodity and presented a blockchain model for managing ancillary services of micro-grids.

1.3 RESEARCH GAP AND MOTIVATION

The research gap that has been identified during the literature review has been schematically shown in Figure 1.6. Mainly for the area have been identified: -

- Monitoring and control: - There have been many methods reported in the literature for offline analysis of ATC of the system. But techniques utilizing the real-time measurement data streaming in from synchrophasor measurement devices are yet to be developed.

- Integrated Transmission and Distribution: - The methods for integrated analysis of transmission and distribution from the quasi-static perspective that could be utilized for assessing the ATC/ADC effect were to be developed.
- Active Distribution Network and Active Distribution System: - Methodologies for assessing the effect of large-scale integration of DER’s and EV as Virtual Power Plants (VPP’s) needed to be developed.
- Blockchain-based energy: - In literature, Blockchain-based mechanisms have been proposed for their application in the power sector, but techniques for analyzing the effect of blockchain-based energy transaction on active distribution systems with respect to aggregated load profile and available distribution capabilities had to be developed.

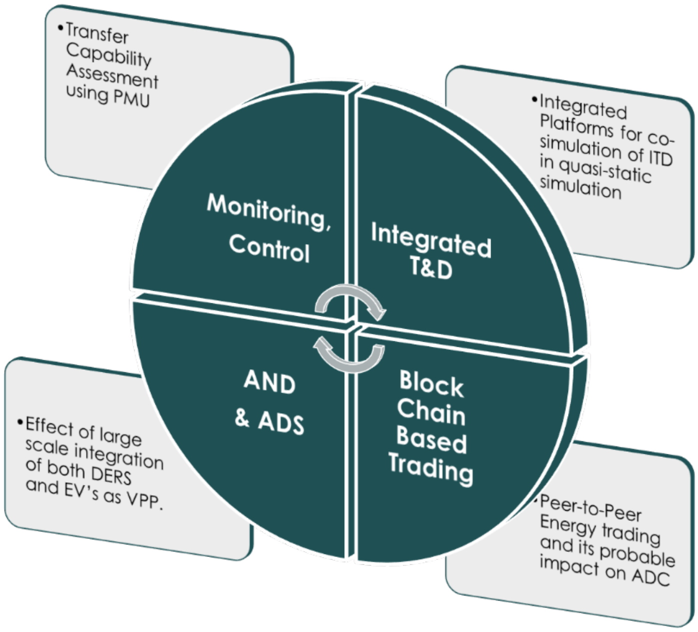


Figure 1.6 Schematic representation of different sections identified during literature review as research gap to be tackled.

Motivated from the gaps in the changing paradigm of power systems monitoring, operation, and control, in this thesis, attempts have been made to advance/develop methods and techniques in the field of Integrated Transmission and Distribution systems' analysis, monitoring, and control while emphasizing on ATC/ADC assessment and enhancement.

1.4 THESIS ORGANIZATION

The thesis has been segregated into eight different chapters, starting with a brief introduction, literature review, and research gap in the first chapter; the subsequent chapters to follow primarily discuss: -

- **Chapter 2: -** Offline ATC Assessment and Enhancement Methodology
- **Chapter 3: -** PMU Emulation and near-real-time load forecasting.
- **Chapter 4: -** Real-time ATC estimator and its authentication using RTDS.
- **Chapter 5: -** Multi-agent system based framework for integrated analysis of transmission and distribution system.
- **Chapter 6: -** Aggregated effect of the ADS on ATC considering Electric Vehicle and Micro-Grid as components of ADS.
- **Chapter 7: -** Energy transaction using blockchain, with its probable impact on aggregated load profile and available distribution capability.

Finally, the last chapter concludes the work along with a brief overview for further research and future scope.

1.5 CONCLUSION

This chapter introduces the problem along with an in-depth literature review of various aspects touched through the work reported in this thesis, followed by the research gap and motivation. At the end of this chapter, a brief sequential organization of the various topics covered has been delineated. The next chapter would be providing the base for offline ATC assessment along with the methodologies for obtaining optimal strategy for ATC enhancement.