Chapter 1

Introduction

This chapter presents a short overview of the worldwide electricity demand growth and keen interest in utilizing renewable resources locally and globally. Section 1.2 presents the motivation behind the work done in this thesis and followed by literature survey. Moreover, this chapter will outline all objectives, and will conclude with the organization of this thesis.

1.1 Background

In current scenario, electricity is one of the most influential factor for sustainable development of society. It has become such a part of modern life that one cannot think of a world without it. The energy in modern societies provides comfort, well-being, security and leisure to the society. This has led to rapid increase in energy demand across the world.

Fig. 1.1 depicts the global energy consumption from 2011 to 2018 [1]. Global energy consumption in 2018 increased at nearly twice the average rate of growth since 2010, driven by a robust global economy and higher heating and cooling needs in some parts of the world. Demand for all fuels increased, led by natural gas, even as solar and wind posted double digit growth. Higher electricity demand was responsible for over half of the growth in energy needs. Energy efficiency saw lacklustre improvement. As a result of higher energy consumption, CO2 emissions rose 1.7% last year and hit a new record.

Energy consumption worldwide grew by 2.3% in 2018 as seen Table 1.1 , nearly twice the average rate of growth since 2010, driven by a robust global economy as well as

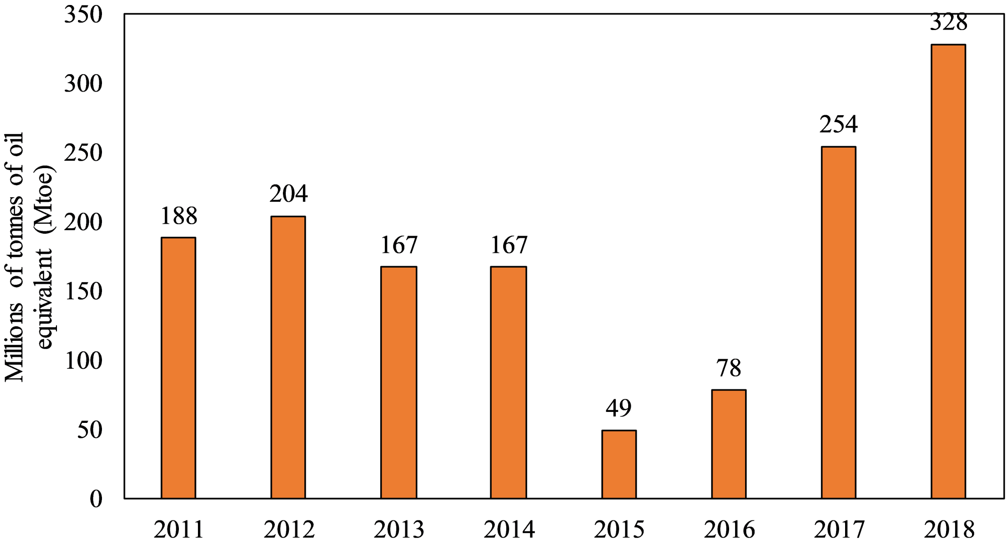

Figure 1.1: Annual change in global primary energy demand, 2011−2018

Table 1.1: Energy consumption worldwide in 2018

	Total Primary Energy Demand (Mtoe)	Growth Rate (%)
	2018	2017-2018
United States	2227	3.7%
China	3155	3.5%
India	933	4.0%
Europe	2010	0.2%
Rest of the World	5568	1.8%
WORLD	14301	2.3%

higher heating and cooling needs in some parts of the world. Among all countries, India consumed more energy in the year 2018, which is about 4% more than in the year 2017 as seen Table 1.1

The biggest gains came from natural gas, which emerged as the fuel of choice last year, accounting for nearly 45% of the increase in total energy demand. Demand for all fuels rose, with fossil fuels meeting nearly 70% of the growth for the second year running. Renewables grew at double-digit pace, but still not fast enough to meet the increase in demand for electricity around the world.

As a result of higher energy consumption, global energy-related CO_2 emissions increased to 33.1 Gt CO_2 , up 1.7%. Coal-fired power generation continues to be the single

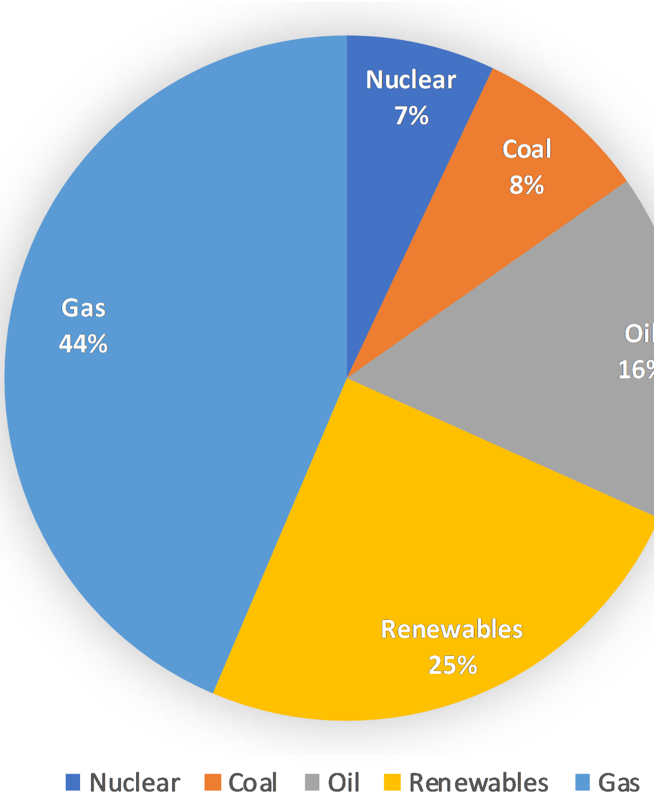

Figure 1.2: Global primary energy demand met by various sources in percentage,2018

largest emitter, accounting for 30% of all energy-related carbon dioxide emissions.

Fig. 1.2 portrays the global primary energy demand met by various sources in percentage in 2018. As seen in Fig. 1.2 the major share of the energy demand consumed today in the societies comes from conventional energy sources (e.g. fuel-wise, coal-based and nuclear power). Only a small part of the energy produced in the world comes from renewables, often called unconventional energy sources. For example; country like India, [1] as of end July 2017, the total installed capacity in the country stood at 330.15 GW. Out of which, share of fuel—wise, coal-based capacity about 60 percent, while renewable, hydro and gas sources accounted for 18 percent, 14 percent, 8 percent respectively as shown in Fig. 1.3.

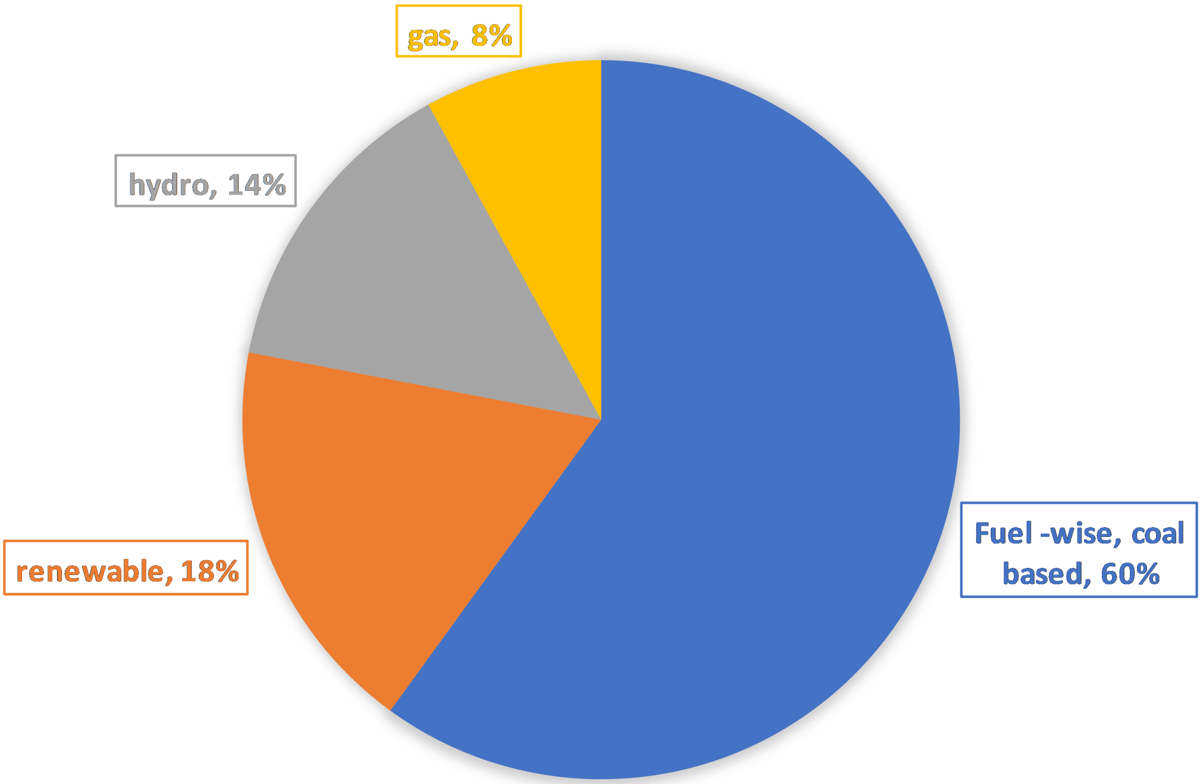

Figure 1.3: Total installed capacity in the India

Due to the three key factors, namely environmental concerns, technological innovation and government new policies, the integration of RESs has been tremendously increasing all over the world. The years 2010-2019 will have seen \$2.6 trillion invested in renewable energy capacity (excluding large hydro), more than treble the amount invested in the previous decade. Solar is set to have attracted the most in 2010-2019, at \$1.3 trillion, with wind securing \$1 trillion and biomass and waste-to-energy \$115 billion as depicted in Fig. 1.4 [2]. Fig. 1.5 shows the amount invested in renewable energy capacity in the top 20 markets up to the end of the first half of 2019 (it does not include an estimate for the second half of this year). All of them have spent more than \$14 billion on renewables excluding large hydro. The runaway leader in the 2010s has been China, with investment of \$758 billion, nearly 31% of the global total, with the U.S. second on \$356 billion, or 14%.

Renewable energy development in India [3], as of July 2017, the total renewable energy capacity was 58.9 GW, surpassing that of hydro-power which cumulatively stood at 44.6

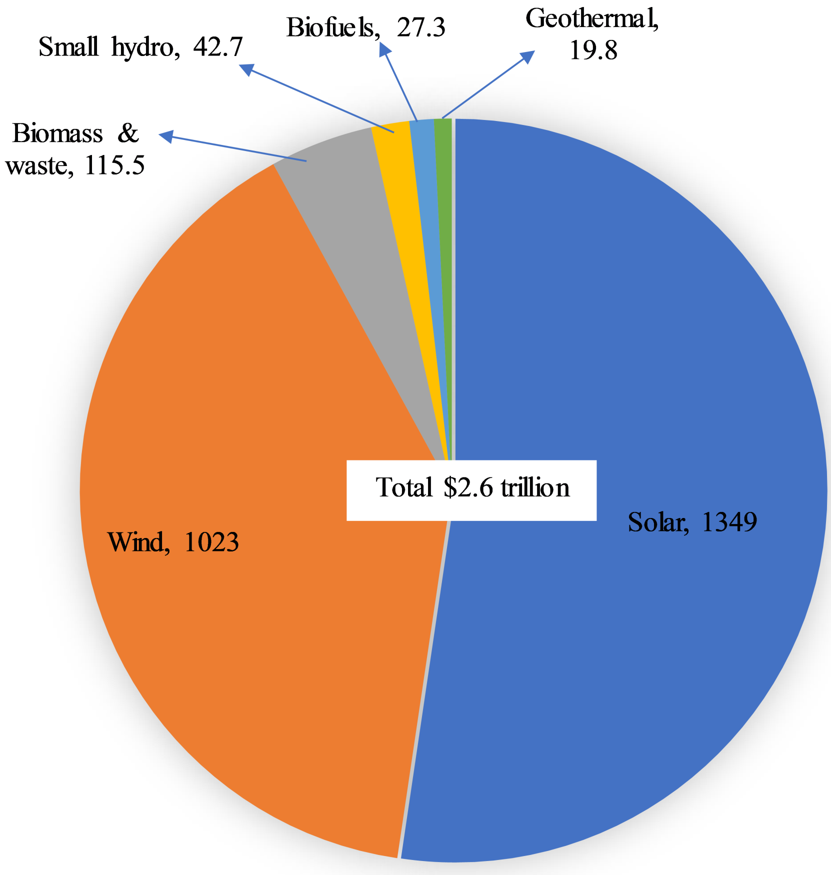

Figure 1.4: Renewable Energy Capacity Investment over the Decade, 2010-2019, $BN

GW. The share of renewable energy in the overall installed capacity also rose from about 14 percent in March 2016 to 16 percent in April 2017, and further to 17.8 per cent in July 2017. This rapid growth was enabled by the alignment of policies with the changing business environment. Moreover, the governments constant pursuit to resolve the inherent restraining factors such as distribution companies payments, grid connectivity challenges and power offtake issues have lowered the risk and improved investor interest in the sector, resulting in record capacity additions. On other side, the availability of advanced DER technologies and their diminishing trend of costs, along with the complicated nature of building new transmission lines, the increasing demand for greater reliability of supply, among others, has encouraged significant investment in RESs.

However, large-scale integration of RES-based DGs often poses a number of technical challenges in the system from the stability, reliability and power quality perspectives. This is because integrating RESs introduces significant operational variability and uncertainty to the distribution system, making operation, planning and control rather complicated.

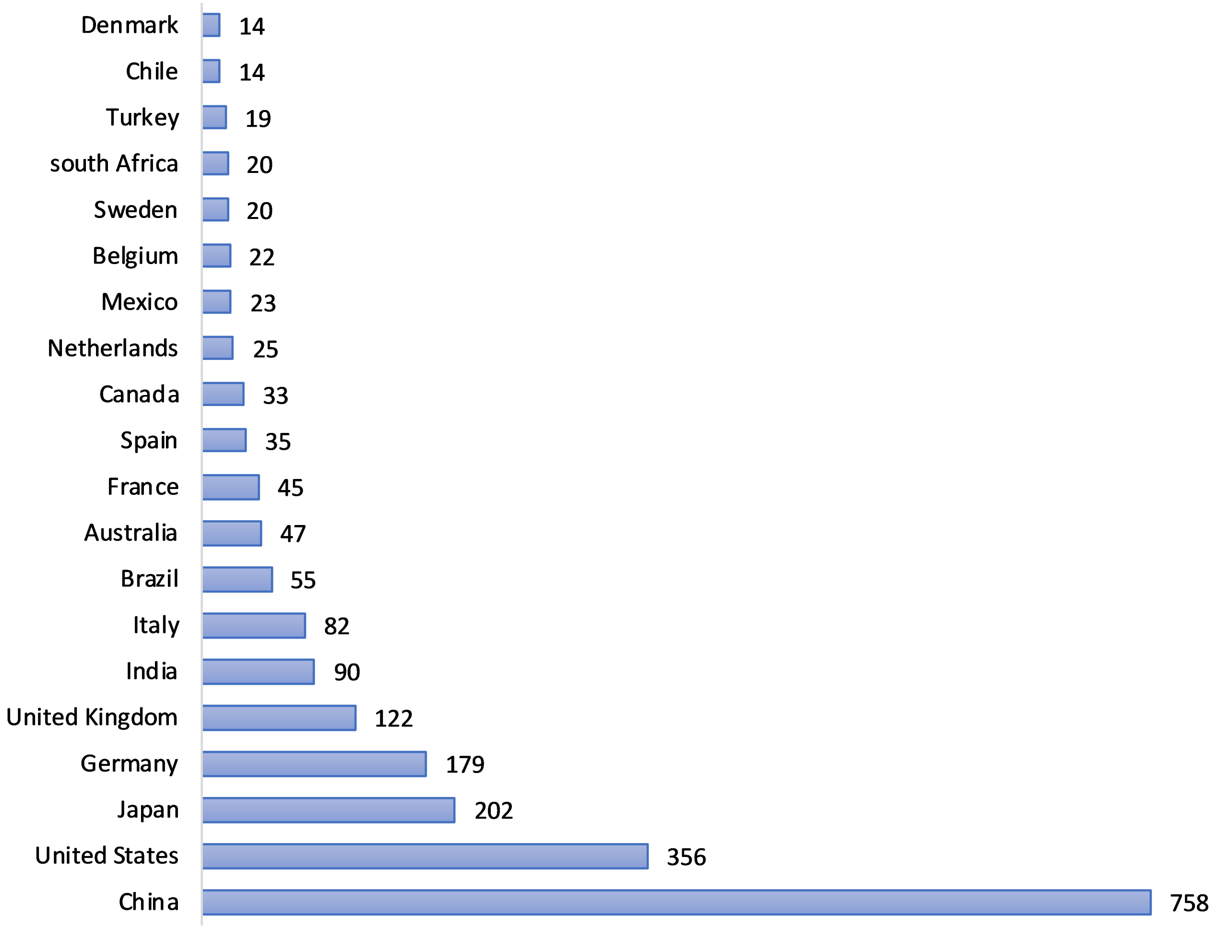

Figure 1.5: Renewable Energy Capacity Investment from 2010 To 1h 2019, Top 20 Countries, $BN]

Hence, such a high-level integration effort is likely to be supported by certain smart-grid technologies and concepts that have the capability to enhance the flexibility of the entire distribution systems. BESSs can play a vital role in integrating variable energy sources. In addition, distribution network reconfiguration, volt-VAR control and power electronics based converters can be very important because they can considerably enhance the flexibility of the system, increase the energy savings and maintain the voltage profiles, thereby increasing chances of accommodating large-scale RES power.

1.2 Research motivation and Problem Statement

As demonstrated in the background, RESs make a crucial part of the solution for environmental sustainability; hence, they will play an important role in power systems.

However, large-scale penetration of RESs will necessarily involve a process of adapting and changing the existing infrastructure because of their intrinsic characteristics, such as intermittency and variability.

The arbitrary allocation of DER units in the system may lead to an uncertain increase in the feeders power flows, resulting in network congestion and increased losses in the network. Therefore, DER allocation should be carefully planned to maximize the system efficiency. The high proliferation of DER and their integration to distribution systems can adversely impact on feeders voltage profile, due to reverse power flow. Besides, the intermittent nature of renewable energy sources such as wind, solar and uncertain behaviour of the load can cause voltage variation in distribution systems. The conventional voltage and reactive power control strategies in distribution systems are expected to face numerous challenges. When DER units are interconnected to a distribution system, they can significantly change the system voltage profile and interfere with the conventional local control strategies of OLTC, VR and SCBs. This interference leads to overvoltage, under voltage, increasing in system losses and excessive wear and tear of voltage control devices. Therefore, to mitigate voltage and reactive power control issues and facilitate a seamless integration for large penetration of distributed generation, DER units need to coordinate with traditional utility voltage and reactive power control devices.

On the other side, VVC and DNR are the promising techniques utilized by DSOs to enhance distribution system performance (e.g., good voltage profile, mitigation of maximum voltage rise and voltage drop limits, enhance system reliability, loss reduction, peak demand reduction and energy savings). To perform VVC operation, traditional devices such as OLTC, VRs, and SCBs have been employed. However, these devices are constrained by limited number of operations. Moreover, these devices may not be capable to handle the sudden voltage violations because of slow response and large delay time. The voltage fluctuations may result from various disturbances such as intermittence in power output from DERs such as PV and wind generation, change in network configuration, and load demand (especially in the case of flexible loads). Hence, there is a need of fast acting voltage regulation device such as SIs and SOP along with traditional VVC devices to encounter these issues. However, without proper coordination, these devices may cause a detrimental impact on distribution operations and network assets.

The installation of SOP and BESS along with RESs has become one of the most viable solutions to facilitate the increased penetration of DER resources as well as increased controllability and flexibility to the operation of distribution systems. BESS has a capability to level the mismatch between variable power generation and demand by store energy during periods of low electricity demand (price) or high RES power production, and then release it during periods of peak demand and low-RES production. In addition, SOPs has ability to control active power flow between adjacent feeders, reactive power compensation, and voltage regulation in a distribution system. Therefore, in addition to their technical support to the system, SOP and BESSs bring substantial benefits for end-users and DG owners through reliability and power quality improvement as well as cost reduction. Besides, they are being developed and applied in power grids to cope with a number of issues such as smoothing the energy output from RESs and improving the stability of the electrical system. SOP and BESSs also increase savings during peak hours and minimize the impact of intermittent generation sources, leading to a more efficient management of the integrated system. Despite the high capital costs, their deployment in distribution systems is in the upward trend. Cost-cutting and the strong need of integrating RES-based DGs is expected to push the demand for the simultaneous deployment of SOP and BESSs in distribution network systems. In other words, distributed BESSs and SOPs will increase dramatically in the years to come. Hence, proper planning and operation of such systems is crucial for enhancing the performance of distribution system.

1.3 Literature survey

1.3.1 Distribution Network Reconfiguration and Service Restoration

1.3.1.1 Distribution Network reconfiguration

Network reconfiguration in distribution systems is realized by changing the open/close status of normally closed (sectionalized) and normally opened (tie) switches dynamically to obtain a new radial topology of the distribution network on the premise of the switching time limits according to the dynamic load variation over a specic period of time. It is a well-established technique for the reduction of network losses, load balancing, and restoring the power supply of the outage area in distribution networks. DNR can be used for system planning as well as real-time control and operation.

In literature, existing approaches for solving distribution network reconfiguration can be classified as three categories namely, heuristic techiques [4] [11], metaheuristic based methods [12] [16] and mixed-integer programming methods [17] [21].

Merlin and Back [4] reported a initial work about network reconfiguration problem based on branch-and-bound type heuristic technique. In this method, initially all network switches (i.e. sectionalized and tie switches) are closed to obtain a meshed network. Then, network switches are opened one at a time until a new radial structure is reached, and the switch selected to open at each time minimized the losses of the resulting network. This work has been the basis for all other network reconfiguration studies that have followed. However, there are several major drawbacks of the methodology including the assumption of purely active loads represented by current sources, neglecting voltage angles and network constraints. In order to avoid aforementioned drawbacks, optimum flow based approach was proposed by Shirmohammadi and Hong [5]. In this approach, initially closed all network switches to obtain a meshed network. Then opened one-by-one another by determining the optimum flow pattern in the network. Goswami and Basu [6] proposed a sequential switch opening method based on the concept of optimum flow pattern. In this method, optimum flow pattern assuming that only one switch was closed each time to form one loop, and improved configurations were obtained by successively conducting single-loop switch exchange until no further improvements are obtained. Branch-exchange type heuristic algorithm was proposed by Civanlar and Grainger [7]. In this method, loss reduction can be achieved only if there is a significant voltage difference across the normally open tie switch and if the loads on the higher voltage side of the tie-switch are transferred to the other side. This conclusion is quite significant because the number of switches that need to be studied can be greatly reduced. Fan et al. [8] described an analytical and a systematic understanding about the single-loop optimization approach. Each time a loop is selected, and the best switch to be opened is determined by finding the minimum loss increment associated with a particular switch in the loop. The evaluation procedure starts from the original open switch and then goes up in one direction toward the source node by one switch at a time until the minimum loss increment is reached. Lately, a large number of literatures have been published to present their contributions on improving existing methods for solving network reconfiguration problems.

In the view of optimization-based methods, network reconfiguration is a mixed-binary nonlinear optimization problem where binary variables represent the switch states and continuous variables model the electric network. However, even for a distribution system of moderate size the number of switching options is so large that conducting load-flow studies for all the possible options is computationally inefficient and impractical as a real-time feeder reconfiguration strategy. As a result, during the past decades, numerous approaches have been proposed to solve reconfiguration problems. Genetic algorithms (GAs) was first applied to the network reconfiguration problem for loss minimization by Nara et al. [12]. GA mimic the process of natural selection and genetics are popular artificial intelligence techniques. In this algorithm, the genetic strings are defined to represent the arc (branch) numbers and the switch position on each arc, and fitness function was used to represent the power loss. The main disadvantage of this algorithm is the length of string is proportional increase to the number of the switches. A refined GA was proposed by Zhu [13], where a real number of codifications were employed instead of binary codification to represent the open switches in the network. Rao et al. [14] was employed a new Harmony search algorithm (HSA) to solve network reconfiguration problem, which is developed by mimicking the process of searching for better harmony in musical performance. The significant terms used in HSA include harmony memory (HM), harmony memory size (HMS), harmony memory considering and its performance was well compared with GA and tabu search approaches. Compared to heuristic methods, meta-heuristics or artificial intelligence techniques are well suited for solving mixed-binary optimization problems and are more likely to achieve solutions that are near the global optimal. However, these methods are generally not repeatable and may require several executions to obtain the best solution. Recently, a large number of literatures have been published to present their contributions on improving population-based algorithm for solving network reconfiguration problems. The improvements include new codification methods, adaptive operators, and changes in fitness functions.

Mixed-integer programming-based methods can acquire global optimal solutions but is much more complex method than the other two methods. Further it requires commercial numerical solvers to obtain a solution. However, with the assistance of advanced high-performance computers, mixed-integer programming methods are becoming more popular for solving network reconfiguration problems. Ramos et al. [22] linearized the

Table 1.2: Network reconfiguration solution technique and its objective

ref	Published year	Network reconfiguration solution method	Objective function
[9]	2013	minimum-current neighbour-chain updating methods	Loss minimization
[10]	2012	circular minimum-branch-current and circular- neighbour-chain updating technique	Loss minimization
[11]	2014	single-loop branch-exchange heuristic algorithm	Loss minimization
[15]	2016	shufed frog leaping algorithm (SFLA)	Reduction of voltage drops and voltage sags
[21]	2015	mixed-integer linear master -slave problem	Loss minimization
[23]	2017	mixed-integer linear programming	Overall cost minimization
[16]	2013	non-dominated sorting genetic algorithm-II	minimization of economic and environmental cost
[24]	2014	fuzzy-ACO approach	loss reduction, voltage prole improvement, and increase in the feeder load balancing.
[25]	2016	adaptive cuckoo search	loss reduction, voltage stability enhancement
[26]	2014	GA- improved switch-exchange method (ISEM)	loss reduction
[27]	2013	Improved Multi-Objective Harmony Search	power losses reduction and voltage prole improvement
[28]	2014	Fireworks algorithm	Minimization of power losses and voltage deviation
[20]	2016	mixed-integer linear programming	Minimization of power losses and service restoration
[29]	2009	sequential switch opening method	Minimization of power losses and service restoration

problem and then solved the linearized optimization problem using mixed-integer linear programming, however the solution does not represent losses exactly. In order to overcome such a drawback, Romero-Ramos et al. [17] presented a nonlinear formulation using a nonconventional group of variables to be solved using a mixed-integer nonlinear optimizer. Khodr et al. [18] also employed an exact model of losses in a Benders decomposition solution approach. However, the optimization problem models in [17] and [18] are both non convex so there is no assurance of convergence to the global optimal solution. Thus, Jabr et al. [19] presented an exact mixed-integer conic programming model using convex continuous relaxation, so the solution obtained was guaranteed to be globally optimal. Further, Table 1.2 presents the summary of recent techniques for solving the network reconfiguration problem.

Although many approaches have been proposed to solve the reconfiguration problem, one of the main remaining challenges with network topology optimization is the required computational time and resources. DNR is a complicated non-convex optimization problem with binary decision variables and operational constraints. Heuristic approaches have been shown to perform most quickly with satisfying approximations, but they are still not efficient enough when dealing with large-scale networks with thousands of buses. The occurrence of intermittent renewable energy, uncertain load demands for charging electric vehicles and more complicated demand responses have changed the traditional static network into a highly dynamic one. It is necessary to more frequently reconfigure the network in response to changes that occur in the grid. Thus, a highly efficient and effective approach to reconfigure distribution feeders to improve system operation is highly desired.

1.3.1.2 Service restoration

The main motive of service restoration is to restore the de-energized loads (i.e. affected due to abnormal or faulty conditions) by transferring to healthy distribution feeders without violating the system constraints via network reconfiguration while satisfying the following requirements [29]. i)Maximum restoration of de-energized loads. ii) Final distribution network remain in radial structure. iii) Minimum number of switching operations. iv) No violation of line ampacities.

Shirmohammadi and dariush [30] describes the principle and the execution of a heuristic methodology to restore service to the isolated portions of a distribution system via network reconfiguration. This methodology also determines a minimum possible number of switching operations needed to restore service to network branches that are isolated due to forced or scheduled outages. Singh et al. [29], suggested a sequential switch opening method for minimum loss feeder reconfiguration and further this method was extended for service restoration. A switching index based approach was proposed by Lin et. al. [31] and further, this method extended for service restoration. [32] proposed a fast and effective multi-tier service restoration algorithm using graph theory techniques and information from three-phase power flow analysis has been designed to meet important service restoration plan requirements and the algorithm supports fault scenarios where the entire outage area cannot be serviced. A hybrid multi-objective quick service restoration technique was proposed by [33]. In this technique, a network connectivity method and Genetic Algorithm (GA) has been employed for quick service restoration. Coordinated operation of OLTC tap position and remotely controlled switches has been conducted for service restoration considering voltage regulation [34]. During the service restoration process,the permissible limits of voltage of feeder buses may violate due to sudden change in genearion/load. Hence, suitable control actions should be taken to overcome such issues.

1.3.2 Volt-VAR Control and Conservation Voltage Reduction

1.3.2.1 Volt-VAR Control (VVC):

VVC is a control strategy to manage the voltage magnitude within the safe voltage limits and reactive power flow throughout the distribution network in order to achieve efficient operation of distribution network.

Recently, several papers have been published on Volt-VAR optimization (VVO) [35] [44] . Kumar et al., [35] were adopted particle swarm optimization (PSO) to determine optimal setting of VVC devices considering wind energy for energy savings. Padilha-Feltrin et al., [36] employed a Non-dominated Sorting Genetic Algorithm- II for simultaneously optimization of energy savings and peak load relief in distribution system. Daratha et al., [37] employed optimal coordination of OLTCs and static VAR compensators for minimization of the total line losses and number of switching in OLTCs and SVCs. Ahmadi et al. [38] proposed a deterministic optimization based approach to reduce the total active power loss and node voltage deviation. Liang et al., [39] employed fuzzy optimization approach to solve the VVO. Paudya et al., [40] presented optimal operation of distribution system with the objective of minimizing energy drawn from substation with reduced switching number of taps and capacitors. Mokgonyana [41] employed modified particle swarm optimisation algorithm for optimal volt/var control in distribution networks. Madureira et al, [42] employed evolutionary particle swarm optimization (EPSO) for optimal coordination of coordinated voltage control scheme. Li et al., [45] proposed coordinated VVC scheme based on soft open point (SOP) for minimization of operation costs and voltage profile improvement of active distribution systems. Niknam [46] has proposed a Chaotic Improved Honey Bee Mating Optimization (CIHBMO) to determine the active power dispatch of DGs, reactive power dispatch of capacitors and tap positions of transformers. Somma et. al., [43] performed a simultaneously optimize the economic and environmental aspects by optimal scheduling of distributed energy resources. Niknam et al, [47] proposed Modified Teaching-Learning-Algorithm (MTLA) to solve stochastic multiple objective VVC for minimization of losses, voltage deviations, energy costs, and emissions of DGs and grid. However, from [35]- [47], reactive power capability of the smart inverter has not been addressed for voltage control.

Smith et al., [48] introduced a smart inverter control scheme for high penetration of PV on Distribution Systems. Calderaro et al., [49] suggested optimal decentralized voltage control approach based on network sensitivity and active/reactive power regulation. Jahangiri et al., [50] have implemented a voltage control loop within PV inverters, which maintains the voltage within permissible limits by absorbing or supplying reactive power. However, in ref. [50] coordination of VVC devices and PV inverters has not been addressed for voltage regulation. Xu et al. [51] performed a multi-time scale coordination of VVC devices and PV smart inverters for power loss minimization. Similarly, Zhang et al., [52] performed a three-stage robust inverter-based VVC scheme for minimization of energy loss and voltage regulation. Singh et al., [53] estimated the energy saving by coordination of VVC devices and solar PV inverter. Ziadi et al., [54] employed PSO for optimal scheduling of DGs, tap transformers, and controllable loads in smart distribution system. Farag et al., [55] proposed cooperative operation of transformer tap changer (LTC) and DGs for minimization of voltage deviation and number of taps. Kabir et al., [56] suggested coordinated control of PV inverters and battery energy storage to maintain voltage in the permissible limits. Similarly, Liu et al., [57] proposed a coordinated control of distributed energy storage system with VVC devices to maintain voltage in the permissible limits. Bagheri et al., [58] conducted a benefit assessment of VVC schemes in distribution systems by using Advanced Metering Infrastructures (AMI) data. Murty et al., [59] has proposed a hybrid optimization for optimal coordination and management of distribution networked assets. Chen et al., [44] performed optimal scheduling of reactive power of photovoltaic inverters, OLTCs, and switch states of shunt capacitors in distribution system for minimization of loss and voltage deviation.

1.3.2.2 Conservation Voltage reduction (CVR)

CVR is a viable technique employed by utilities for peak demand reduction and energy savings. The main principle of CVR is to achieve energy savings by decreasing the voltage level in distribution feeder, ensuring the nodal voltages within acceptable limits and without affecting the performance of voltage sensitive customers [60]. According to American National Standards Institute (ANSI), the allowable range of voltages at the distribution transformer secondary terminals can be set as ± 5% of the nominal value.

CVR technique can be perform in different time periods namely, short-term period and long-term period. In short term period CVR, voltage reduction is done during peak hours. Whereas, in long-term period the voltage reduction is done for permanently [61] [62] [63]. It is found that CVR technique contribute significant savings in both energy and power demand . Traditionally, load tap changer (LTC), line drop compensation (LDC) [61] , voltage spread reduction (VSR) [64] , capacitor-based reduction [65] and home voltage reduction (HVR) [64] approaches have been employed for implementing CVR in distribution system. These approaches also called as open-loop approaches, which are simple to implement, since it does not require to deploy monitoring and communication infrastructure. However, these approaches have major shortcomings: (i) lack of observability on customer voltages, the extent to which voltages can be reduces is limited to conservative values; (ii) as they are based on fixed local rules, they do not adapt to network or drastic load changes (e.g., network reconfiguration) and; (iii) the decentralised operation of different devices in the network can present miscoordinations or at the very least, result in a suboptimal operation. In order to avoid aforementioned drawbacks, a closed-loop CVR approach has been employed [66] [67] [68], where Supervisory Control and Data Acquisition (SCADA) and advanced metering infrastructure (AMI) plays a vital role.

Studies reported in [61]- [68] rely on controlling legacy voltage regulating devices but do not include the impact of integration of DERs. Besides, recently an amendment was made to the DER interconnection standard (i.e. IEEE standard 1547 -2018 [69]), in which DER inverters are allowed to participate in distribution feeder voltage regulation. Ref. [70] reveals the advantages of coordinated operation of CVR and Demand Response techniques in the presence of DERs. Optimal power flow-Based CVR Operation in PV-rich distribution networks has been proposed in [71]. Ref. [72] reveal the advantages of the coordinated use of photovoltaic (PV) inverters with legacy voltage regulating devices to increase the energy savings in distribution systems.

The existing reported studies in CVR operation usually coordinate legacy voltage regulating devices with PV inverter, while coordinating multiple DERs including battery energy storage is rarely considered, which can better explore the benefits of coordinated operation. Thus, appropriate approach is desired to maximize the benefits of CVR operation incorporating the high penetration of DERs.

1.3.3 Distributed Energy Resources allocation

With the pressure of environmental concerns, the utilities are shifting from conventional generation to renewable sources generation. This has lead to distributed energy resources (DER) integration in the distribution systems. Basic definition of DER has been provided by Acermann et al. [73].Moreover, Marwali et al. [74] have discussed the technological advances in power electronics devices, small scale generators and battery storage devices. These technologies have given momentum to integration of DER into distribution networks. However, random location and sizing of DER in the distribution system may results in an increase in real power losses and may also deteriorate voltage profile.

Several methods have been proposed for the optimal placement of DER in the distribution systems to minimize losses and also improve the voltage profile of the system. An analytical approach based on the exact power loss formula for optimal allocation of single DER was presented by Acharya et.al [75] for minimization of real power loss in a primary distribution network, Hung et.al [76] [77] proposed an analytical method to determine the location and sizes of DER for both single and multiple DER allocations in a distribution systems. An analytical method has presented by wang and Nehrir [78] to determine the location of optimally placed DG in radial as well as meshed networks in order to minimize real power losses. However, in this method the optimal sizing of DER was not achieved. Celli et al. [79] proposed a multi-objective evolutionary algorithm with an objective of minimizing cost of energy losses, network upgrading and service interruptions for sizing and sitting of DER in the distribution systems.

Lee and Park [80] have proposed an Kalman filter algorithm for determining the optimal locations of DERs and their sizes in order to minimize the total power loss of the system. Their work [81] have recently been extended to introduce a new factor called optimal locator index (OLI) to determine the optimal locations. A multi-objective mixed integer formulation and its solution by GA has been proposed by Shaaban et al. [82] considering the uncertainty and variability associated with the intermittent nature of renewable energy resources and also loads. Naik et al. [83] suggested a new analytical method (AM) to determine the optimal sitting and sizes of DERs to minimise the power losses. Ameli et al. [84] applied an Multi-objective particle swarm optimization to determine the optimal locations and sizes of DG considering operational and economic aspects. Elsaiah et al. [85] proposed a novel power flow solution method and also analytical method for optimal allocation of multiple DERs in distribution system for loss reduction. Comparison of different loss sensitivity methods for single DER placement has been presented by Murthy and Kumar [86]. A thumb rule called 2/3 rule was developed by Willis [87] for optimal DER placement with uniformly distributed load. Muttaq et al. [88] proposed an analytical approach based on algebraic equations for uniformly distributed loads to determine the optimal operation, size and location of the DG in order to achieve required levels of network voltage.Deepak et al. [89] proposed a new algorithm called as cat swarm optimization, for optimal allocation of DGs to achieve reliability in the distribution networks. Esmaili [90], who used application of GAMS to solve a nonlinear programming (NLP) for optimal DER placement. Optimal location of DER based on exact loss formula and optimal sizing of DER by GA was proposed by Shukla et al. [91] for reduction of real power losses. Particle swarm optimisation (PSO), and gravitational search algorithm (GSA) was applied by Tan et al. [92] to solve the optimal placement and size of multi-DER units in the distribution system for real power loss reduction. Georgilakis et al. [93] presented a thorough description of the state-of the- art models and optimization methods applied to the optimal DER placement problem, analyzing and classifying current and future research trends. Naveen et al. [94] have proposed an approach for the multiple-DER planning solved by using constriction factor based PSO.

In the last two decades, several DER planning schemes in ADN have been proposed. In [95], [96]- [99] authors have presented the significance of simultaneously planning of RES and BES. In [95], cooperative planning model of DERs in active distribution systems has been proposed, where reducing costs, enhancing reliability, and promoting clean energy have taken as objectives. In, [96] a multi-stage planning framework has been proposed for simultaneously allocation of RES and BES. In [97], energy storage has been deployed for maximum utilization of RES in ADN. Benefits of coordinated allocation and scheduling of BES system in the high PV penetrated distribution system has been presented in [98]. In [99], optimal DER placement problem has been solved by genetic algorithm (GA) considering the uncertainties of the RES and load. However ref. [95], [96]- [99] , does not considered the benefits of DNR, CVR techniques and soft open points (SOPs) devices in planning of DER.

In order to improve the controllability and flexibility to the operation of ADN, Ref. [100], [101] [102] [103] [104] [105] [106] [107] [108]- [109] incorporates the DNR, CVR, smart inverter and SOPs techniques in planning problem. Ref [100] presented the benefits of CVR operation in the planning of BES in high penetrated RES. Optimal planning model of BES in ADN considering SOP, DNR and reactive power capability of DER has been proposed in [101]. Similarly, in [102] coordinated methodology for allocation of DERs, capacitor banks and SOPs has been proposed. Ref [103] demonstrated the role of oversizing of utility-owned renewable DG smart inverter considering VVC devices. Ref. [104] proposed the various schemes based on photovoltaic smart inverter control for substantial benefits in facilitating the increasing integration of RES. Ref [105] presented the benefits of DNR operation in the planning of BES with high penetrated RES. In [106], reveals the significance of DNR and demand side management while DER planning in active distribution network. Ref [107] demonstrated the significance of CVR operation in the formulation of planning problem. Similarly, ref [108] implementation of CVR operation in planning of DGs and BES simultaneously. Ref [109] reported the importance of the VVC devices such as OLTC, SCB, and SVC, while DERs planning in ADN. Studies in references [100], [101] [102] [104] [105] [106] [107] [108]- [109] reveals the significance of DNR and CVR techniques in planning of DER. However, combined impact of DNR and CVR techniques considering advanced power electronics based devices such as smart inverter and SOPs have not been considered in these studies. Further, Table 1.3 presents the summary of recent DER planning techniques. Thus, a highly efficient and effective approach for optimal coordination of the DER planning and their scheduling in conjunction with advanced techniques is highly desired to enhance performance of distribution systems.

Table 1.3: Summary of DER planning studies

Reference	Published year	Decision variables	Static /Dynamic	Uncertainty	VDLM	RES	BES	SI	loss	Reliability	Emission	DNR	CVR	Formulation	Solution Method/ solver
[110]	2009	Size, location	S	N	Y	N	N	N	y	N	N	N	N	MINLP	GA
[111]	2012	Size, location, type	D	Y	N	Y	N	N	Y	Y	N	N	N	MINLP	GA
[112]	2012	Size, location	S	N	N	N	N	N	Y	N	N	N	N	MINLP	GA/PSO
[99]	2013	Size, location	S	Y	N	Y	N	N	Y	N	N	N	N	MINLP	GA
[95]	2019	Size, location, type	S	Y	N	Y	Y	N	Y	Y	Y	N	N	MINLP	PSO
[97]	2018	Size, location	S	Y	N	Y	Y	N	Y	N	N	N	N	MINLP	(MOALO
[23]	2017	Size, location, type	D	Y	N	Y	Y	N	Y	Y	Y	Y	N	MILP	MILP solver
[101]	2018	Size, location	S	Y	N	Y	Y	Y	Y	N	N	Y	N	MISCOP	MOSEK solver
[98]	2018	Size, location	S	N	N	Y	Y	N	Y	N	N	N	N	MINLP	GA
[102]	2018	Size, location, type	S	Y	N	Y	N	Y	Y	N	N	N	N	MINLP	GA
[106]	2018	Size, location,type	D	Y	N	Y	N	Y	Y	N	N	Y	N	MINLP	DEA
[113]	2015	Size, location, type	D	Y	N	Y	N	N	Y	N	N	N	N	MILP	CPLEX
[114]	2018	Size, location, type	S	Y	N	Y	N	N	Y	Y	Y	N	N	MILP	CPLEX
[109]	2019	Size, location, type	S	Y	N	Y	Y	N	Y	Y	N	N	N	MISCOP	CPLEX
[115]	2019	Size, location	D	Y	N	Y	N	Y	Y	N	N	N	N	MILP	CPLEX
[116]	2018	—	S	N	N	Y	Y	Y	Y	N	N	N	N	MINLP	GA
[96]	2019	Size location	D	Y	N	Y	Y	N	Y	N	Y	N	N	MICP	CPLEX
[117]	2014	Size location	S	N	Y	Y	N	N	Y	N	N	N	N	MINLP	Analytical method
[103]	2019	Size	S	Y	N	Y	N	Y	Y	N	N	N	N	NLP	KINTRO

*Y means considered, N means not considered

1.4 Research objectives

The main objective of this research is to develop an integrated approach for planning, operation and control of DER in conjunction with volt-VAR control devices to enhance performance of distribution system. In order to accomplish this goal, the present work is further sectionalized in the following objectives

1. To investigate the combined impact of DNR and VVC operation on level of energy demand reduction and service restoration in the distribution system considering DERs.
2. To develop appropriate optimization models and methods for optimal operation of active distribution systems considering DNR and soft open point (SOP) in presence of high penetration of variable energy sources.
3. To investigate the impact of coordinated operation of conventional VVC devices and advanced devices (e.g. smart inverter and soft open point) on energy demand reduction as well as mitigation of voltage violation in high penetrated DER distribution system.
4. To develop appropriate methodologies for real-time control and optimization of distribution grids with massive integration of DERs.
5. To develop appropriate optimization models and methods for DER (e.g. wind, solar, BESS) planning and operation in distribution systems with conjunction of advanced technologies.

1.5 Organization of the thesis

The remainder of this thesis is organized as follows:

Chapter 1 is the introductory chapter of the thesis. It begins with the background of the thesis, followed by literature survey. Then, the research motivations and the problem definition are provided. Finally, the chapter concludes with outlining the structure of the thesis.

Chapter 2 presents an efficient and optimal approach for combined operation of DNR and VVC techniques. To achieve the optimal solution, modified binary grey wolf optimization (MBGWO) algorithm has been proposed. In the proposed approach, a centralised as well as local control schemes have been employed for optimal operation of distribution network such that no system constraints are violated. Besides, proposed method has been employed for service restoration considering voltage regulation and peak demand reduction under faulty condition. Finally, the effect of proposed method on both balanced and unbalanced distribution system has been presented along with remarkable conclusions

Chapter 3 presents a time series model of coordinated VVC scheme to minimize the energy demand including operating cost in distribution system considering DNR. Besides, soft open point (SOP) a flexible power electronic device has been introduced in the VVC scheme. Instead of simply opening/closing normally-open points, SOP devices are capable to control load transfer and optimize network voltage profile by providing fast, dynamic and continuous real/ reactive power flow control between feeders. Furthermore, technical-economical-environmental benefits of proposed coordinated scheme has been presented..

Chapter 4 introduces a hierarchical coordinated multi objective optimization model for the effective operation of ADN in presence of high penetrated photovoltaic based DER. The proposed model determines the optimal network configuration that achieves two objectives: 1) Minimizing the total operating cost and 2) Minimizing the total voltage deviation. Besides, the significance of battery energy storage (BES) on total operating cost and voltage deviation has also been presented.

Chapter 5 introduces real-time hierarchical coordinated voltage control of smart inverters for active distribution network with high PV penetration. Besides, the impact of advanced flexible power electronic devices such as PV smart inverter and soft open point (SOP) on energy consumption and losses have been presented. Furthermore, developed real-time co-simulation platform for operation and control of DER in the distribution system using MATLAB and Real Time Digital Simulator (RTDS).

Chapter 6 presents a new two-layer coordinated optimization framework for planning and operation of DERs and SOP in active distribution network (ADN). In order to solve the planning and operation of DERs in distribution system, a co-simulation platform has been developed using MATLAB and General Algebraic Modeling System (GAMS) tools. Besides, an integrated long-term planning model for DER has been presented that addresses the economic, operational, and environmental issues of DER. Furthermore, combined impact of DNR and VVC techniques in conjunction to smart inverter and SOPs on DERs planning has been presented.

Chapter 7 presents a summary of the main findings and conclusions gained from this research as well as potential improvements and future work that can follow the work presented in this Thesis.