CHAPTER 1

INTRODUCTION

1.1 Preamble

Nowadays, electricity has become the prime catalyst and indispensable power for the faster development and growth of any nation. Moreover, proliferation in smart grid technologies, green energy initiatives, and the 21st century's energy policy to improve the system efficiency have made an incredible impact on the electrical power sector. Therefore, power utilities and grid planners have to rethink in the purview of the smart grid and energy efficiency for better solutions and quality of service [1]. Further, information and communication technology-enabled smart grid solutions are offering great opportunities to resolve the distribution operational problems quickly and secured manner [2].

On the other side, a large amount of power from distributed energy resources (DER) (a major part of solar photovoltaic (PV) and wind energy) is being injected into the grid at various points of the electric power network through various initiatives and programs globally. The government of India has also planned to deploy 100 gega watts (GW) grid-connected solar power up to 2021-22 under the flagship of *National Solar Mission* [3]. The above capacity will come through grid-connected rooftop solar PV and medium & large-scale grid-connected solar power. About forty percentage, i.e., 40,000 megawatts (MW), is targeted from rooftop solar PV, which covers mainly institutional sector, commercial sector, industrial sector and housing. Rest will come (about sixty percentage, i.e., 60,000 MW) from medium and large-scale grid-connected solar power, including solar park projects and other schemes. To achieve this target for a country like India is not an easy task. Many curious problems associated with solar PV integration have emerged in the parts of the country, such as in July-2016, the southern Indian State of Tamil Nadu, has to experience the first-ever curtailment of solar power generation [4]. It was unable to consume all the power that was produced. Though other countries such as United States, Germany also have already dealt with this issue. There are already signs that the grid's ability to absorb a large amount of unpredictable power with existing infrastructure could be a major bottleneck for higher solar PV penetrations. Distance is also a critical concern, as six states in the western and southern regions of India account for 80 percent of all of the country's presently installed solar capacity having only 38 percent of power demand. In contrast, northern states have the highest power demand. Intermittency, variability and uncertainty occurred due to the unavailability of solar irradiations, cloud transients, or cloud passage; sun eclipse and unwanted things/shedding on solar panels affect the system performance and can affect in balanced operation. Another incident, such as a critical solar eclipse occurred on 21 August 2017 in which some part of the world was completely or partially suffered blockages of solar light [5]**.** Accurate climate forecasting helped to grid managers to hand the situation and forced to shift their solar generations. In the United States, the California system operator has handled the biggest solar crass challenge. Though it was not a complete solar blockage but their 56 to 78 percent obstruction of sunlight will affect in a great manner. Thanks to their rooftops across and utility-scale power solar plants, which help a lot to manage the power shortage transient. Much more such incidents have happened across the world, to which grid operator/ electric power system operators should learn the lessons.

The integration of such large solar energy in the smart grid is an upcoming issue. The conventional transmission and distribution grids may not be able to cooperate due to their unidirectional energy flow and other limitations. However, integrating the DER from both ends (as rooftop PV from the prosumer side and utility-scale power plants, etc.) will make the flow of energy in two way that causes the reversible power flow and voltage regulation malfunctions issues in controlling and monitoring devices during grid operations [6]. According to the various utility pilot projects and studies. in today’s scenario reverse power flow and over-voltage stands as the main hurdle for the expansion of PV DER integration on a distribution grid. Another aspect is the unbalanced allocation of rooftop or in other types of PVs installation (single-phase or three phases) creates a rise in neutral current and neutral voltage in the unbalanced distribution network. This may lead to higher energy losses and may cause the detrimental impact of network devices and assets. Hence, system instability, power quality measures, deferred transmission & distribution infrastructure, and balancing demand & supply are major concerns of the grid operators for the reliable and safe operation due to the high-level PV integration.

This tends to force power utilities and grid planner to deploy the smart grid technologies with a regulatory policy which would allow both the utility and prosumers without affecting system performance. The role of smart grid in solar energy penetration is very crucial in grid modernization. Various initiatives are currently running in India and across the world for energy efficiency, peak load management and monitoring & control, etc. Some of the key attributes in smart grid solutions such as real-time system awareness, advanced Volt/VAR Control (VVC) through a smart inverter, advanced energy management system and integrated storage system that can be helpful for solar power integrations. Modern smart inverters have various attractive features such as voltage & active and reactive power control, frequency regulations, energy flow direction detection, etc. Extensive deployment of inverter also increases power loss in the distribution grid. Therefore, proper control and coordination strategies are required for optimal, efficient and mal free operation. Though the enabling of various technologies may increase the complexity of the system and cost investment, however, with faster development in technology, this issue will not be a major concern.

1.2 Necessity of Electrical Energy Conservation

Energy conservation may be defined as *"It is the idealistic or economic practice of reducing the use of energy by way of increasing energy efficiency and reducing the energy wastage"* [7]. In this context, the enhancement in electrical energy efficiency through energy conservation has emerged as a potential candidate. Form the economic point of view, the cost of energy creation through energy conservation is far less than the cost of energy created through the installation of power plants. The limited availability of natural energy sources, day by day continuously increasing energy demand and a rise in the level of greenhouse gases mainly due to higher carbon dioxide (CO_2) emissions. According to [8], electricity and heat are the key sources of CO_2 emissions, as can be seen in Figure 1.1. This is due to the fact that in many nations, still mainly depends upon burning fossil fuels to fulfill their electricity demand. According to International Energy Agency (IEA), in 2016, about 68% of the global electricity production came from burning coal, gas and oil, with coal accounting for about 38.3% alone, as shown in Figure 1.2 [9]. Recently, the IEA report says that, in 2018, the global electricity demand increased by 4 percent, which is nearly double of the fastest increased rate since 2010. In order to meet the increased electricity demand, the generation from coal- and gas-fired power plants have risen considerably that led to an increase in CO_2 emission from the sector by 2.5%.

In this context, the various initiatives have been floated by developed and developing countries for decarbonizing the electricity generation and implement the policies which are more envisioned towards the energy efficiency enhancement. Besides, the strategies focusing on reducing the electricity demand without negotiating the growth of nations have been encouraged widely in electric power system practices [3].

Usually, the electrical power sector has been divided mainly in the following parts: generation, transmission, distribution, and end-users [10]. In comparison to other parts of the power system, the distribution network has been given less attention in comparison to other parts of the power system.

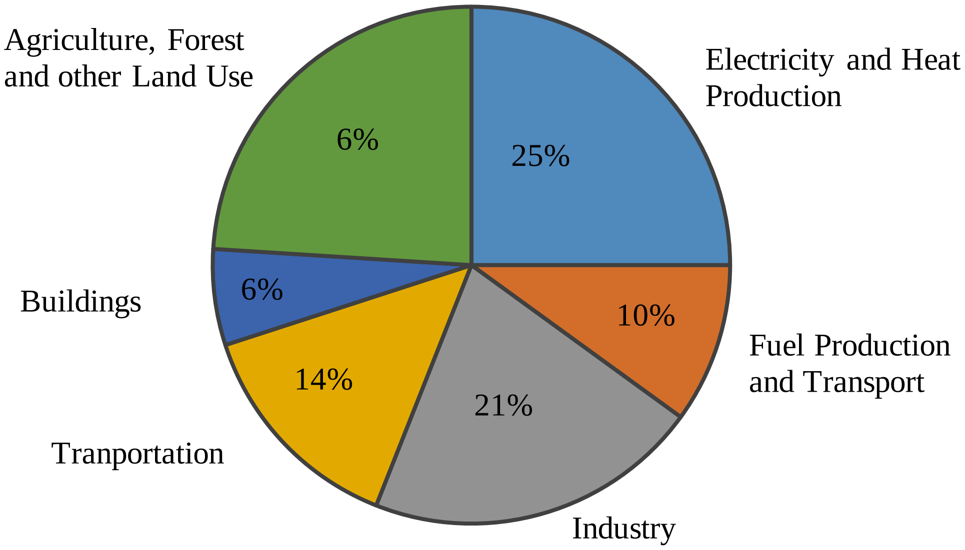

Figure 1.1 Greenhouse gas emissions by economic sectors [8]

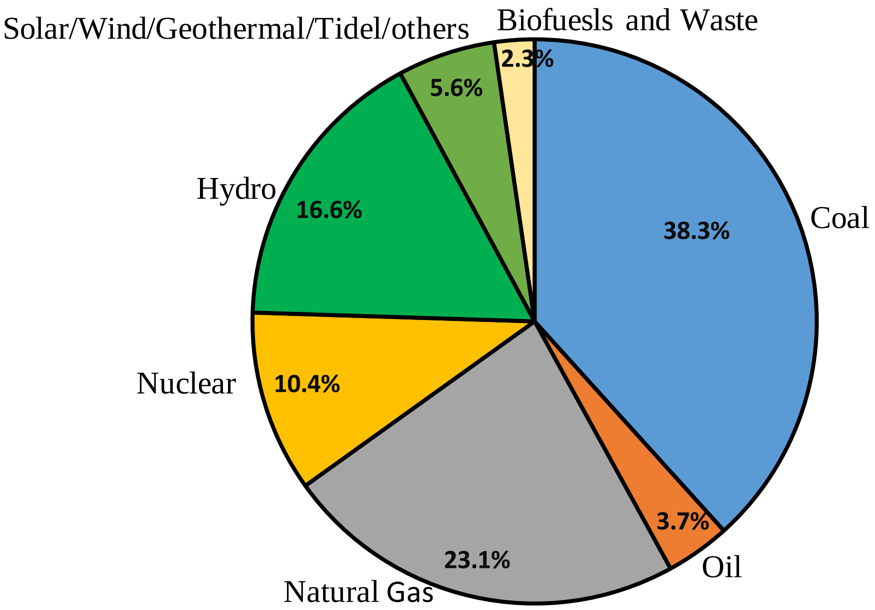

Figure 1.2 World gross electricity production by source in 2016 [9]

Indeed, it needs more attention so that energy crises and the quality of power can be improved. Besides, in the current scenario, energy conservation in the distribution network is one of the essential concerns for power engineers and researchers. Technologies such as Distributed Management System (DMS), Substation Automation, Advanced Metering Infrastructure (AMI), Conservation Voltage Reduction (CVR) and Distribution Generations (DGs) have made significant impact on distribution network operations and controls to make the system more robust, efficient, reliable and secure [10]–[16]. There are still numerous challenging problems such as high aggregate technical and commercial losses (AT&C), inefficient operation, unreliable and poor quality of services (QOS) is faced by the distribution system operator and customers. These are mainly due to the rapid increase in load growth, mismatch load demand and generation ratio, unplanned distribution network, variety of load patterns and reversible power flow due to large integration of DER [14]. In addition, energy distribution systems are significantly affected by political, social and theft hindrances in developing countries. For a complete analysis of the distribution system, it is essential to observe the distribution network at the end of the line (EOL) within the concept of the smart grid. In this context, distribution network optimization and control are one of the prime tasks for electric power utilities to deal with new smart distribution grid systems. Hence, in order to optimize such distribution grids, utilities are adopting more efficient technologies such as advanced Volt/VAR optimization (VVO) methods with multiple objectives such as CVR, loss reduction, network reconfiguration and power factor improvement[11], [12], [15], [16]. CVR technology has the ability to improve the energy efficiency at the distribution level and lower the system losses by conservation of voltage and reducing the load demand of the end-uses.

1.3 Overview of Power Distribution Network

A typical distribution network commences from the distribution substation, which is connected to one or more high-voltage and medium voltage transmission and sub-transmission lines. Each distribution substation is the combination of one or more primary distribution feeders, which feed the electricity to the consumers. Traditionally, distribution networks are designed as passive circuits where unidirectional power flows from high to low voltage levels and generally, DGs are not present at distribution feeder level. Figure 1.3 shows the passive distribution circuit with network components such as line segments, voltage regulation devices and loads mainly that have been detailed explained in later subsection. Integration of DG and/or onsite generations at both the source and load end (i.e., both high/medium voltage and low voltage terminals) of the distribution networks have totally reformed the grid operations. Consequently, the unidirectional power flow direction changed into bi-directional power flow and passive distribution circuits became active distribution circuits. Moreover, the adoption of incentive-based programs such as net metering schemes, tariff driven price mechanism and subsidies have accelerated the integration of renewable DGs around the world in order to reduce the carbon emissions [17]. Moreover, distributed solar PV systems both small scales such as household applications or building rooftop levels and large scale at utility levels, have been installed at a faster rate in both medium and low-level distribution networks.

Presently, consumer has become a “*Prosumer*” that not only consumes the power but also have the ability to feedback the power into the grid. Besides, integration of newly active devices such as DERs, distributed energy storage (DES) and electric vehicle (EV) charging stations with the capability of exchanging the power from the grid have made a passive distribution to the active distribution network (ADN) as can be seen in Figure 1.4.

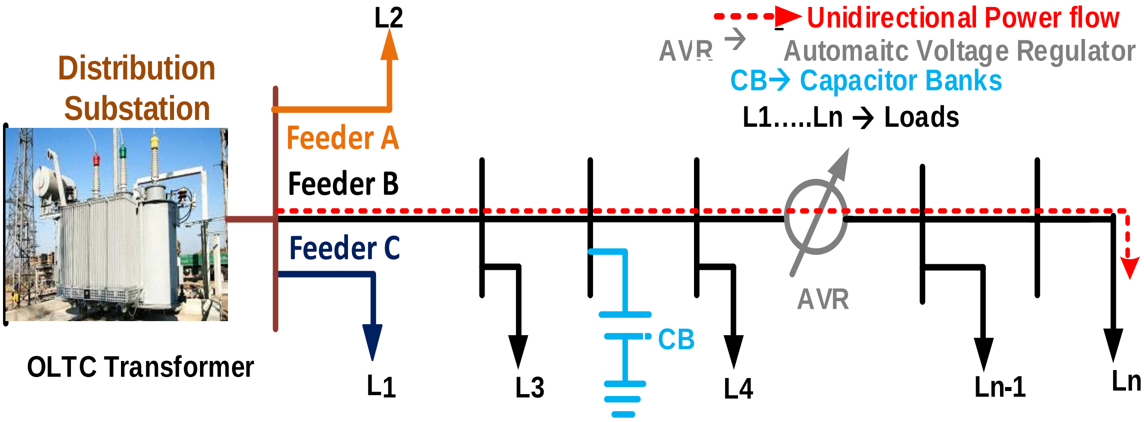

Figure 1.3 Schematics of a passive distribution network

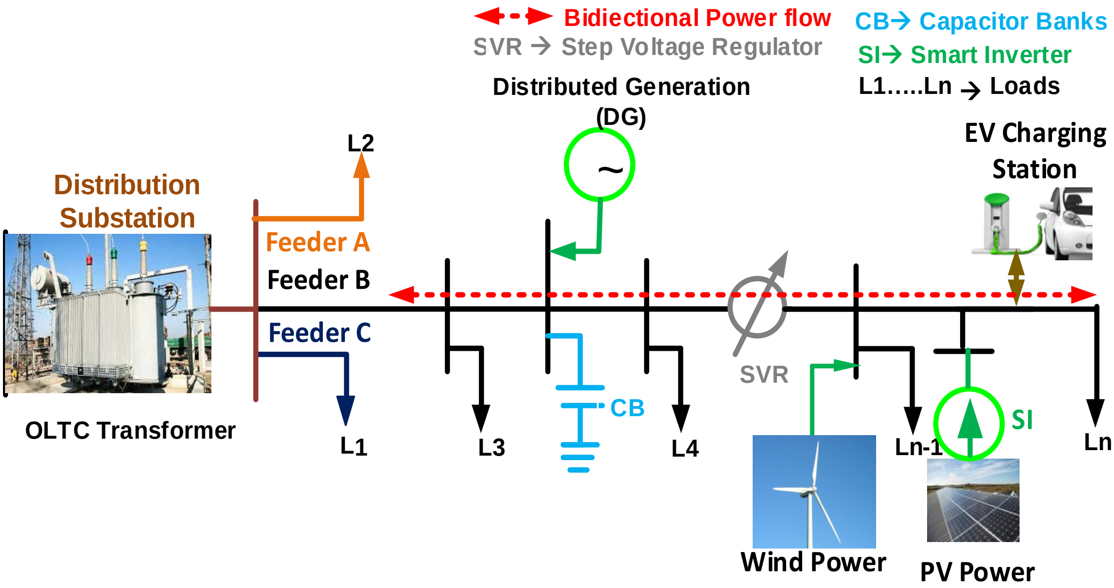

Figure 1.4 Representation of active distribution network

The new ADN not only unlock the benefits of system optimizations but also pave the way for higher-level penetration of low carbon technology. In this context, VVO schemes with high observability and voltage control capabilities fruitfully utilize the CVR benefits unlikely with traditional network operation schemes.

1.4 Description of Distribution Network Components

As earlier said, that distribution network is the combination of one or more feeders. The components of the distribution feeder can be classified as series and shunt network components. Series network components are line segments, Automatic Voltage Regulators (AVR) and transformers, whereas spot & distributed loads and Capacitor Banks (CB) are generally termed as shunt components. Accurate modeling of both series and shunt components is necessary for close observation of distribution feeder.

1.4.1 Line Segment Model

Distribution lines can be represented as exact line segment model. Voltage and current relations for exact line segment model with respect to input node 'h' and output node 'k' can be expressed as shown in Figure 1.5 and related equations are explained below [18]:

$$\left[VLG_{abc}\right]_h = [a]\cdot\left[VLG_{abc}\right]_k + [b]\cdot\left[I_{abc}\right]_k \tag{1.1}$$

where

$$[a] = [u] + \frac{1}{2}[Z_{abc}].[Y_{abc}] \tag{1.2}$$

$$[b] = [Z_{abc}] \tag{1.3}$$

and $[u]$ is identity matrix.

$$\left[VLG_{abc}\right]_k = [a]^{-1}\cdot\left(\left[VLG_{abc}\right]_h - [b]\cdot\left[I_{abc}\right]_k\right) \tag{1.4}$$

$$\left[I_{abc}\right]_h = [c]\cdot\left[VLG_{abc}\right]_k + [d]\cdot\left[I_{abc}\right]_k \tag{1.5}$$

$$[c] = [Y_{abc}] + \frac{1}{4}\cdot[Y_{abc}]\cdot[Z_{abc}]\cdot[Y_{abc}] \tag{1.6}$$

$$[d] = [u] + \frac{1}{2}[Z_{abc}].[Y_{abc}] \tag{1.7}$$

Equations (1.1) and (1.5) can be rearranged in equation (1.8) to yield:

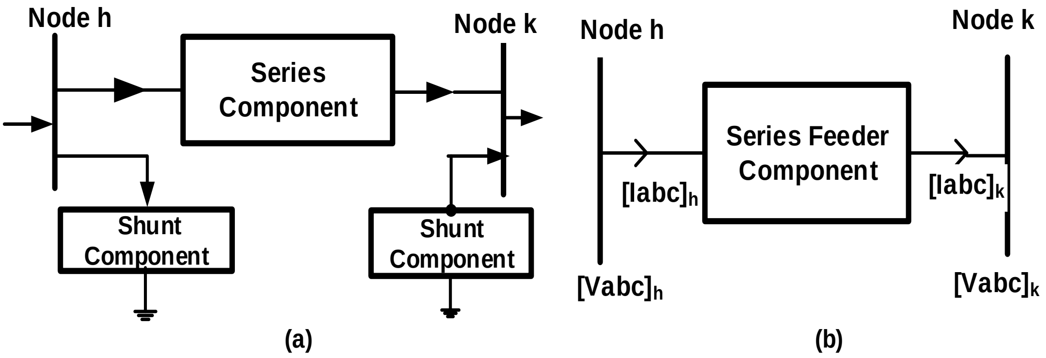

Figure 1.5 (a) Single line diagram of distribution network components (b) Series feeder component connection representation

$$\begin{bmatrix} [VLG_{abc}]_h \\ [I_{abc}]_h \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} [VLG_{abc}]_k \\ [I_{abc}]_k \end{bmatrix} \tag{1.8}$$

where, Z_{abc}, Y_{abc} are the impedance & shunt admittance of the line segment. $[VLG_{abc}]_h$, $[VLG_{abc}]_k$ is the line to ground voltage matrix at node h and k, respectively. $[I_{abc}]_h$, $[I_{abc}]_k$ are the node current matrix at node ‘h’ and ‘k’ respectively. The value of shunt admittance is, in general, very small. Therefore, it can be neglected for simplification of the network. Similarly, voltage and current equations can be obtained for other series components. The generalized equations for series components can be written in the following equations (1.9) and (1.10):

$$[VLG_{abc}]_k = [A][VLG_{abc}]_h - [B][I_{abc}]_k \tag{1.9}$$

$$[I_{abc}]_h = [C]\cdot[VLG_{abc}]_k + [D]\cdot[I_{abc}]_k \tag{1.10}$$

The values of matrices [A], [B], [C] and [D] will change according to the series components. Detail modelling of these series and shunt components is well documented in [18].

1.4.2 *Voltage Regulation Devices*

Voltage regulating devices are widely used for not only maintaining the acceptable voltage profile throughout the network, but they also play a crucial role in the healthy operation of the distribution grids. AVR, online tap changer (OLTC) transformers and CBs are the most commonly used voltage regulating devices. With the advancement in smart grid technologies, grid-connected power sources such as solar PV with smart inverters also provide voltage support to the system as a voltage regulating devices [19]

1.4.2.1 OLTC Transformer and AVR:

An OLTC transformer is used to vary the voltage across the network. It is generally located at the source substation side. The provision of tap changing is made towards high voltage side in off-load changing transformers, whereas the tap changing mechanism is provided towards low voltage side in on-load tap changer. It can be represented as the simple circuitry of an ideal transformer with series branch admittance as described in [19]. The OLTC transformer's tap position and its transformation ratio (a_{tr}) can be utilized to determine the voltage variation as expressed by equation (1.11).

$$a_{tr} = 1 \pm \left(\frac{\Delta V_{tr}}{100} \right) \times \text{Tap} \tag{1.11}$$

In equation (1.11), the minus/plus sign is used to denote the raise/lower in the tap position. AVR is formed by combining an autotransformer and a load tap changing mechanism. It is located at the source end and/or downstream of the feeder. It can be modeled as a tap-changing autotransformer with very small series impedance and shunt admittance. The AVR with taps in the series winding side is considered type A and that having taps on the source side is called type B [18]. Type B is widely used for downstream feeders for which the voltage regulation is governed by equation (1.11).

1.4.2.2 Capacitor Bank

Capacitor banks are a group of fixed and switchable shunt capacitors. CBs should be equipped with controllers (in the case of switchable shunt capacitors) in order to regulate voltage and reactive power flows efficiently. Reactive power supplied by CB at each switching operation is determined using equation (1.12).

$$Q_{cb}^{i} = Sw_{cb}^{i}\,\Delta q_{cb}^{i}, \quad Sw_{cb}^{i} = \left\{0,1,2....,Sw_{cb}^{i,\max}\right\} \tag{1.12}$$

1.4.2.3 Smart Inverter

Apart from the basic inversion function, modern PV inverters have many advance attractive features. They have the capability to inject or consume the reactive power from the grid and operate as a distributed VVC device. In addition, PV inverters contribute significantly to the improvement of distribution network operation by maintaining the voltage profile and losses reduction. However, it may cause some additional loss while performing reactive power support functions.

The actual real and reactive power output from the inverter (P_T^{inv}, Q_T^{inv}) including the inverter losses are determined by following equations at given time T:

$$P_T^{inv} = P_T - P_{T,loss}^{inv} \tag{1.13}$$

$$Q_T^{inv} \approx Q_T \tag{1.14}$$

$$P_{T,loss}^{Inv} = (1-\eta_{inv}).\left(\sqrt{P_T^2+Q_T^2}\right) \tag{1.15}$$

The available $Q_T^{inv,\max}$ is dependent upon the real power generation for a period T which governed by equation (1.16) as applied in[20] [21]:

$$|\,Q_T^{inv,max}\,| = \sqrt{\left(S_{\max}\right)^2-\left(P_T\right)^2} \tag{1.16}$$

On the basis of P_T and S_{max}, $Q_T^{inv,max}$ is recalculated at every time period, T.

1.4.3 Load Models

In order to fruitful utilization and to unlock the potential benefits of VVO and CVR, an accurate and updated load modeling is essential for power flow solutions. The load model structures typically categorized into two types namely static or time-invariant and dynamic loads. The static models such as polynomial (ZIP) load with a combination of constant impedance (Z), constant current (I) and constant power (P) and exponential load model are widely used for non-thermal cycle loads study [22]. On the other hand, loads having thermal cycles such as Heating Ventilation and Air Conditioning (HVAC) and water –heater are considered as dynamic loads and represented by Equivalent Thermal Parameter (ETP) model [23]–[25].

In the context of distribution network studies, this thesis intended to adopt the well-established ZIP and exponential load models to evaluate the CVR impact. The representation of composite ZIP load model has been shown in equations (1.17) and (1.18) respectively.

$$P_{i,t} = P_{o,i,t}\left[Z_p\left(\frac{V_{i,t}}{V_o}\right)^2 + I_p\left(\frac{V_{i,t}}{V_o}\right) + P_p\right] \tag{1.17}$$

$$Q_{i,t} = Q_{o,i,t}\left[Z_q\left(\frac{V_{i,t}}{V_o}\right)^2 + I_q\left(\frac{V_{i,t}}{V_o}\right) + P_q\right] \tag{1.18}$$

$$Z_p + I_p + P_p = 1 \tag{1.19}$$

$$Z_q + I_q + P_q = 1 \tag{1.20}$$

Where in equations (1.19) – (1.20), Z_p, I_p, P_p, and Zq, I_q, P_q are the coefficients of impedance, current, and the power for the real and reactive powers, respectively. $P_{o,i,t}$, $Q_{o,i,t}$, and $V_{i,t}$ are the rated active, reactive power and voltage at the i^{th} load node at instant t, respectively. V_o is the nominal voltage. Moreover, the constituting load models of ZIP representation have been described below [26]:

- *Constant Impedance (Z) Loads:* The relation exists between drained power and voltage is quadratic in nature. In other words, it can be defined as power is directly proportional to the square of the voltage. The resistive appliances such as hobs, electric showers or steam irons are the typical example of this type of loads.

- *Constant Current (I) Loads:* This model considers a linear relationship between power and voltage. A typical example of this type of load is a compact fluorescent lamp.
- *Constant Power (P) Loads:* This type of model drains a constant amount of power without depending upon supply voltage referred to as constant power loads. Usually, escalators and conveyor belts at 24/7 factory can be classified under this model.

Even though both the ZIP and ETP models generally show the characteristics of load to voltage sensitivity. However, most of the feeders do not have detailed load information. Therefore, it is very challenging to model the loads using the ZIP and ETP models in an explicit manner without adequate observability. Meanwhile, in order to model the loads, a method has been proposed by the Electric Power Research Institute (EPRI) [27], [28] considering the practical aspects of user-end behavior. The developed EPRI model known as a nominal linear P, Quadratic Q (feeder mix) load model, as shown in equations (1.21) - (1.22). This model is quite similar to the exponential type load model. EPRI load model uses CVR factors in place of power exponents (active and reactive) of exponential load model. Moreover, the study carried out by EPRI also reveals the impact on real and reactive load power with the variation in voltage profile using the CVR factor [28]. Therefore, apart from ZIP model, this thesis also utilizes the similar load model (feeder mix) to build a relationship among load power, voltage and CVR factor (CVR_f) with the exponential equations (1.21) -(1.22) and analyze the impact of developed CVR control schemes.

$$P_{load}^{k}(t) = P_{n}^{k}\left(\frac{V_k(t)}{V_n}\right)^{CVR_{f(\mathrm{kW})}} \tag{1.21}$$

$$Q_{load}^{k}(t) = Q_{n}^{k}\left(\frac{V_k(t)}{V_n}\right)^{CVR_{f(\mathrm{kVAR})}} \tag{1.22}$$

Where $P_{load}^{k}(t)$ and $Q_{load}^{k}(t)$ are the active and reactive power load, respectively. $CVR_{f(\mathrm{kW})}$ and $CVR_{f(\mathrm{kVAR})}$ are the CVR factors in kW and kVAR respectively.

1.5 The Need of Smart Voltage and VAR Control

Generally, a specific voltage range is defined by manufactures for the smooth operation of electrical equipment. But it is not so easy to provide the same voltage level for all end users because of the voltage drop occurs in each part of the conventional power distribution system. The larger voltage drop occurs in those consumers who have a large power demand or getting their power through larger impedance [10], [15]. This is because of the voltage drop is proportional to the magnitude of demand current and the entire impedance between the source and the consumer and unidirectional power flow. Voltage profiles along a feeder supplying residential loads in a typical passive distribution network have been shown in Figure 1.6 [10]. From Figure 1.6, it is observed that the nearest consumer to the power supply has the least voltage drop, while the last and the farthest consumer has the largest voltage drop [10]. It is achievable to maintain the required voltage level at any point along the feeder with the use of direct voltage control or controlling the flow of reactive power in the distribution system. Due to the flow of reactive power, there is a voltage drop on the inductive element of wires. Therefore, to maintain the voltage profile, voltage and reactive power flow should be considered together. This scheme is called as VVC.

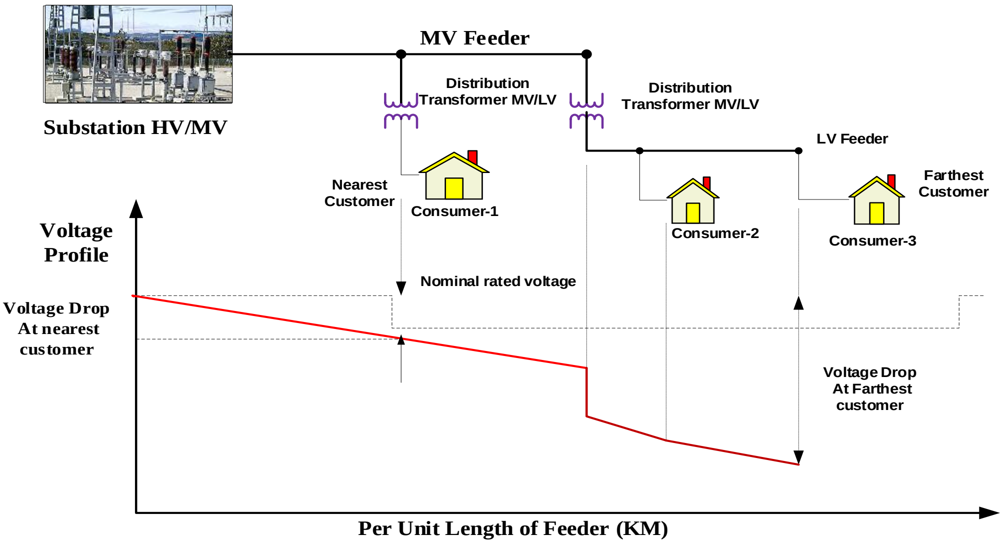

Figure.1.6 Voltage profile along a feeder supplying residential loads [10]

Equipment's such as OLTC transformers, AVR, fixed and switched shunt capacitors are used for controlling of voltage and reactive power flows and referred as slow response conventional VVC devices[11], [21]. On the other side, large scale installation of variable DERs such as solar PV and wind power has created a huge impact on grid operations. Though, the integrations of such devices are unlocking the various benefits such as lowering the carbon emission, pollution-free electricity production and enlarging the CVR energy-saving margin but also causes unwanted technical problems in distribution network operations. Moreover, traditional VVC algorithms also not work efficiently. These include feeder under/overvoltage profile and overloads in transformers, particularly those scenarios when maximum generation and minimum demand, as a result of reverse power flows [29]–[31]. Though centralized VVC with traditional devices works well for a fixed time horizon interval, it might be inflexible for fast-response events such as PV intermittency and sudden change in network behavior.

Hence, there is a need of smart VVC algorithms that coordinate the smooth operation of multiple (both slow and fast-acting) voltage regulation devices in a multi time scale in the purview of CVR implementation in ADN considering the uncertainties in power generation and loads. In this context, a smart VVC framework for ADMS applications has been introduced as shown in Figure 1.7. the proposed framework includes DER controls and coordination with other network devices and assets. Besides, the adoption of slow and fast-acting devices (such as smart inverters having the ability to respond quickly) are explored as an option to regulate the voltages closer to customers, and at the same time, provide the CVR benefits. Moreover, a time horizon based predictive control that provides coordinated management of control devices in centralized and local domains in active distribution networks will be proposed to exploit CVR benefits in cases with and without DER and EVs while catering for system constraints.

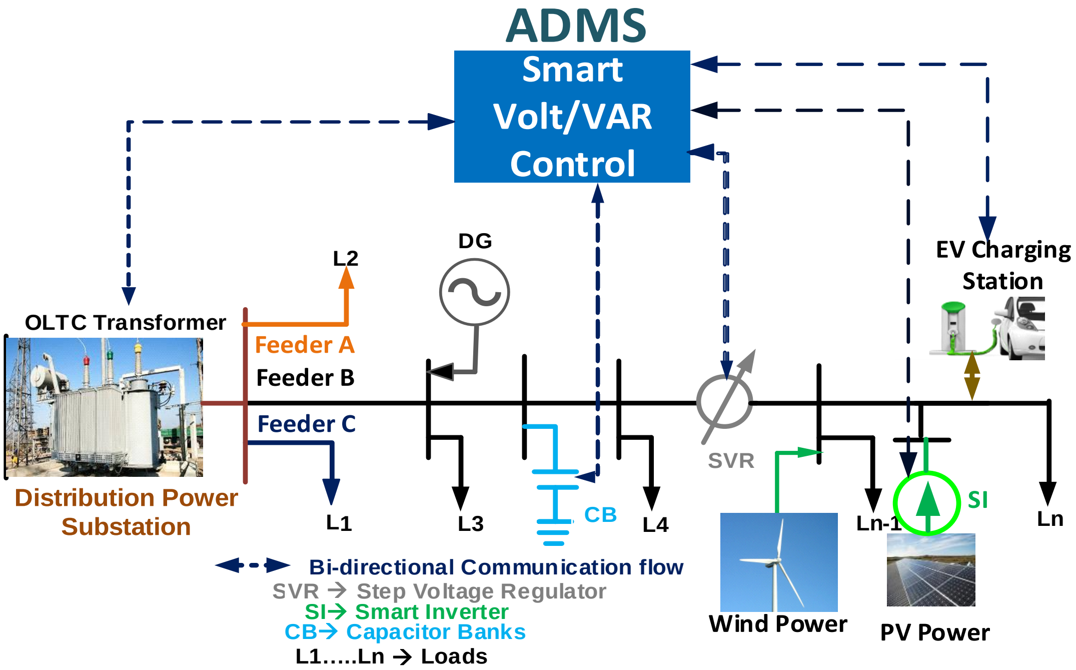

Figure 1.7 Proposed smart VVC framework for active distribution network

1.5.1 Concept of CVR

Voltage conservation produces CVR phenomena. The basic concept of CVR technology is the conservation of energy by a marginal reduction in voltage (normally 2–6% of nominal value) at user end nodes without affecting the performance of the customer's devices. In order to maintain acceptable voltage profile throughout the distribution feeder length and under various loading situations, CVR technology should follow the international Standards such as American National Standard Institute (ANSI) C84.1–2006 and Canadian Standard Association (CAN-C235-83) on voltage regulation [32]–[34]. Moreover, the ANSI C84.1–2006 standard says that the customer appliances can work smoothly on the lower half of the distributed voltage level without disturbing the device's performance. Moreover, CVR is an integral part of voltage and reactive power control. Therefore, it is enabled through the advanced functioning of the integrated VVC mechanism. A schematics of voltage distribution along the feeder length with and without CVR has been shown in Figure 1.8.

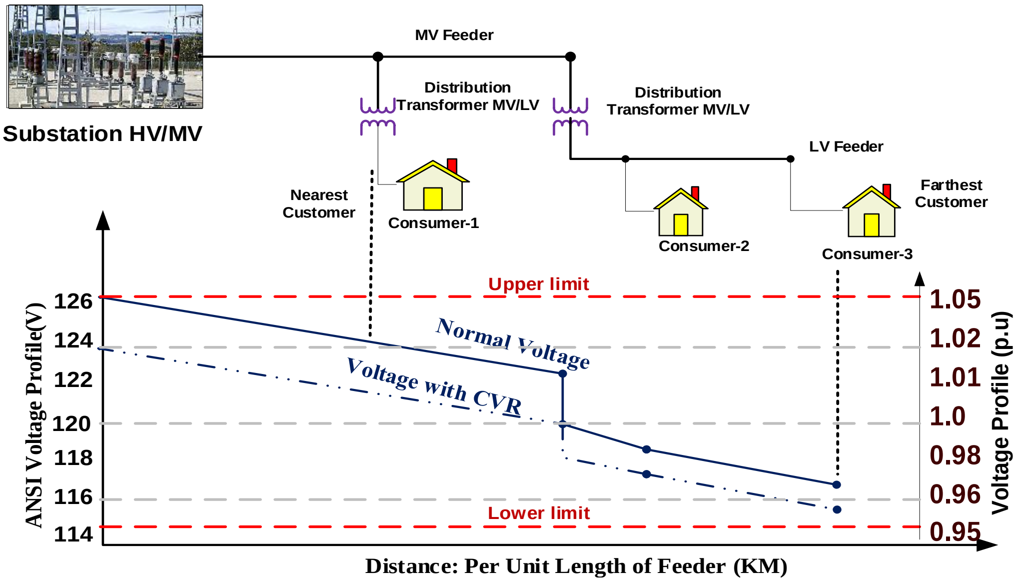

Figure 1.8 Voltage distribution along the feeder length with and without CVR

1.5.1.1 Measuring the CVR effect

Generally, CVR saving depends upon load models, loading type and network topology, etc. CVR effects can be evaluated by the CVR_f, which is defined as follows:

$$CVR_f = \frac{\Delta W}{\Delta V} \tag{1.23}$$

ΔW = % Reduction in quantity (Power, Energy and Cost) ΔV = Percentage of voltage reduction.

1.5.2 *Background of CVR Technology*

CVR is not a new technology in the area of conservation of energy; the tests have been already performed in early 1973 [32]. From Figure 1.9, it can be observed that automated VVC is a thought that has grasped the varying levels of interest over the years [11]. During the decade of 1980-90s, vertically integrated utilities have firstly examined that advanced VVC as an effective technique to reduce power demand and losses in distribution system. After the 1990’s when the deregulation of power system occurred, a serious issue raised that who will be benefited from VVC saving.

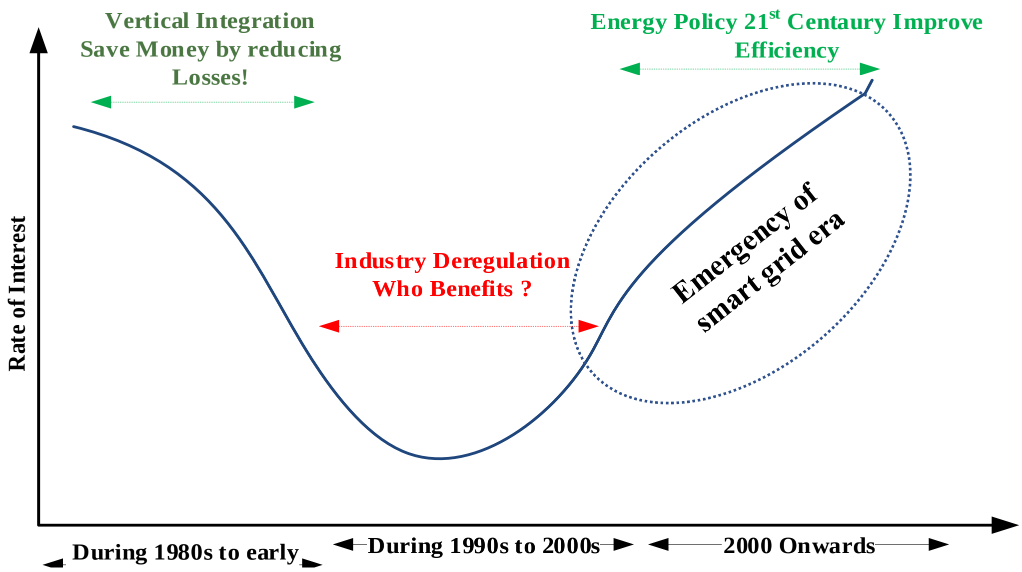

Figure.1.9 Interest cycle of CVR [11]

In many cases, utilities were not benefited from the improvement of VVC because of savings in electrical losses were delivered to customers or absorbed by suppliers and load demand balanced by several forms of generation suppliers. Consequently, during this period of time, the interest in the deployment of VVC improvements fell down dramatically [11]. In the recent scenario, the smart grid era has focused on the need for improved efficiency, energy conservation and integrated VVC techniques such as CVR and VVO to fulfill the smart grid objectives. Therefore, interest in the CVR technique is increasing drastically since 2000 onwards.

The Public Service Commission of New York and American Electric Power System (AEP) have established their first implementation of CVR in 1973 [28]. After that, various researchers [35]–[39] and utilities such as Snohomish County PUD [40], BC Hydro [41], Dominion Virginia Power [42], Southern California Edison (SCE) [43], Hydro Quebec (HQ), Northeast Utilities (NU) [33], Bonneville Power Administration (BPA) [44] and Northwest Energy Efficiency Alliance (NEEA) implemented their CVR tests and gained significant results of energy savings related to voltage reduction [31]. By reducing 1% of feeder voltage, usually 0.3% to 1% load reduction is achieved. Recently, the United States has deployed CVR technology to all distribution feeders and obtained a 3.04% reduction in the annual national energy consumption [45]. CVR was also widely tested in other countries. Australia, Ireland has obtained 2.5% and 1.7% energy saving by a reduction of 1% of voltage, respectively [46], [47]. In twenty-one centaury, the interest rate has increased rapidly due to the implementation of energy policy structures.

1.6 Literature Review

In order to reduce the peak load demand and energy consumption, various power utilities have already applied CVR technology and quantified the achieved savings in terms of CVR factors. The outcomes of various pilot projects and studies reveal that about 1-3% of energy savings can be achieved by 1% of voltage reduction[32],[48]. However, its implementation, assessment and power quality issues pose three technical barriers such as:(i) optimal coordination among voltage and VAR regulatory devices; (ii) appropriate assessment and verification of CVR effects; and (iii) coordination between CVR and other active devices such as DER, energy storage and flexible loads etc. for the adoption of the technology at large scale deployment. In this context, the literature review on CVR has been explored, focusing on two broad categories such as i) CVR implementation strategies and ii) CVR assessment and quantifying method for current and future deployments.

1.6.1 CVR Implementation Strategies

In order to deploy the CVR technology, there are mainly two type approaches have been discussed in the existing literature. The first one is traditional or open-loop VVC schemes and second is closed-loop VVC schemes[13], [16], [32].

1.6.1.1 Traditional or open-loop VVC schemes

Traditionally**,** CVR has been applied by voltage reductions through voltage regulating devices that are as close as possible to consumers. These typical devices are OLTCs at primary substations and line voltage regulators (in the field and/or outside the substations) to compensate for voltage drops in long MV/LV distribution feeders. The methods that are generally used to implement the CVR by the DNOs are on-load tap changer (OLTC), line drop compensation (LDC), spread voltage reduction (SVR), and home voltage reduction (HVR) [31]. The use of LDCs has been widely accepted by DNOs to improve the CVR performance [32], [49]–[55]. Though, the CVR implementation through LDC is relatively simple but poses certain limitations such as the case dependent R &X settings and cannot adapt the dynamic changes [31]. Moreover, the calculated voltage at the farthest point is an estimation only; hence, safety margins are usually considered in the voltage reductions, which limits the voltage reduction range in order to extend the CVR benefits further [31].

The additional reactive power sources such as capacitor banks and D-STATCOM have also been used in various CVR studies and trials to compensate the voltage drops occurred in heavily loaded MV feeders and boost the voltage at critical points for potential use of CVR [47] ,[53], [54], [58], [59]. Voltage reductions through open-loop CVR schemes are a convenient and cost-effective way to implement CVR. However, schemes suffer a lack of real-time information about the voltage and reactive power flows throughout the feeder length. Therefore, the configuration and settings of CVR devices may be either inefficient or ineffective. Major drawbacks of these techniques are the limited depth of voltage reduction, controlling of devices based on local data and poor dynamic adaptability.

1.6.1.2 . Online closed-loop VVC schemes

In order to improve the observability of the distribution feeders, utilities have trailed the installation of monitoring devices at critical locations in the network (typically at the end of feeders and voltage-load sensitive nodes [60]. Some of the installed devices send the measured data directly to primary substations, while others integrate them to the control center through SCADA system, where the DNO takes the decisions (such as tap changing) based on available measurements [55],[61]. Moreover, the advent of smart grid technologies such as smart meters and ADMS have emerged as a potential solution to enhance the system's observability and performance. DNOs saw the opportunity to utilize the real-time information from primary substation feeder to end of the line and close to customers to build an advance closed-loop CVR schemes with the help of smart meters [24],[62],[63]. Moreover, an accurate and realistic load profile across any feeder can be built by using real-time measurements and sample values of voltage, power flows, current, and power factor from these measuring devices [13], [15]. In order to calculate the appropriate setting of VVC devices based on measurements such as accurate voltage profile across the feeder, climatic conditions, and time of utilization, an online adaptive real-time approach for CVR implementation has been introduced in [12],[62],[64]. In this context, centralized and decentralized control approaches are preferred by DNOs as shown in Figure 1.10 [45].

- *Centralized CVR control:* Centralized VVO/CVR control scheme collect AMI sensory data through the interfacing with the metering demand management system in the back office of multiple feeders then running CVR algorithms and sending new setting to the VVC devices in the field via SCADA system. This scheme could be work more efficient and faster if on-demand AMI sensory data available more frequently.
- *Decentralized CVR Control:* Decentralized control scheme utilized the local sensory data control related to every single feeder when CVR algorithm operates locally within each substation referred as a decentralized control scheme. The main complexity in realizing a decentralized CVR control approach is that it needs more frequent AMI data. However, these techniques do not have a direct link to access the faster AMI data.

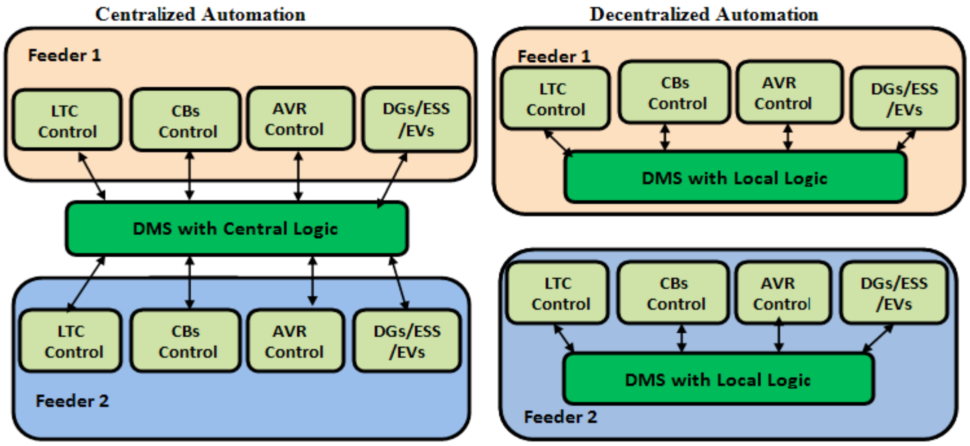

Figure 1.10 Centralized and decentralized controls

In literature, there are three main approaches for real-time VVO controls are SCADA or rule Based VVO, AMI Based VVO and DMS model-based VVO. The authors of [58] have discussed about benefits of VVO/CVR technique through implementing AMI. A real-time adaptive multi-agent system based VVO/CVR engine also based on smart metering have well discussed in [62],[64]. Moreover, the ADMS functionality based real-time VVO approach and non-intrusive energy-saving algorithm for VVC has been described in [16],[54],[65].

In summary, closed-loop techniques have extended the CVR benefits in terms of scalable voltage reduction range and higher observability. However, they also pose some limitations: (i) as these techniques work on some typical fixed local rules, therefore, cannot capable to adapt the network changes such as large load changes and feeder reconfiguration and; (ii) improper coordination among network devices and assets that result in a suboptimal operation. In order to tackle these limitations, the optimal VVC operation for CVR has also been explored and referred as optimal CVR, as delineated in the below subsection.

1.6.1.3 Volt/VAR Optimization (VVO): Optimal CVR

In order to determine the superior action of VVC and higher energy savings, the closed-loop VVC schemes have been suggested with optimal operation referred as VVO.

They offer advanced functions for VVC such as CVR and efficient coordination among VVC devices in centralized and decentralized manner. Though, the selection of optimization methods and algorithms for VVO execution is not a simple task. The main factors which generally decide the selection of right optimization methods are depending upon the nature and number of objective functions, constraints and inner behavior of the control variables. In general, the objective of VVO for CVR is to the minimize the power or energy consumption, system losses and feeder voltage deviations either separately and/or combined [12], [15], [16], [29]–[31], [52], [57], [62], [64]–[66]. As the classical VVO formulation is mixed-integer nonlinear programming (MILP) optimization, therefore, both conventional and metaheuristics optimization methods have been utilized in the literature to solve the VVO problem. Some studies have usages MILP[15], [66], and General Algebraic Modelling System (GAMS), and as solution algorithms considering both operational aspects, such as static and time-varying nature of the demand and generations[13], [20], [30], [50], [54], [59], [61], [67], [68]. Though the conventional algorithms, as suggested in [14], [15], [30], [66], work well but some time solution traps in local minima. Therefore, some researchers adopted meta heuristics optimization methods such as Non-dominated Sorting Genetic Algorithm (NSGA-II) [31], [57], [69], Genetic Algorithm (GA) [62], [64], [70] Tabu-search [71], Gray Wolf Optimization (GWO) [72] and Particle Swarm Optimization (PSO) [29], [52], [73] etc. to obtain the VVO solution. Most of these studies have performed a time-series simulation interval of 15 minutes to 1 hour and optimal control action carried out to above mentioned periods. Though the optimal centralized operation works well for fixed time horizon but in practices, during the sudden dynamic change in demand and generation and transient, these techniques suffers from some operational issues such as under/over voltage and reversible power flows.

Consequently, along with centralized optimal VVC, there is a need decentralized and local control action is required to enhanced the CVR benefits.

1.6.1.4 DER impact on CVR

As discussed in the earlier section, many nations around the globe have adopted incentives to accelerate the installation of renewable DERs generation at large scale and deploy the energy efficiency schemes to reduce carbon emissions. The successive reduction in technology costs has encouraged to DNOs to increase the distributed generation penetration in distribution networks. However, unplanned and unbalanced allocations of these DERs result in some operational issues also. On the other hand, CVR has been known as a method that can assist in accomplishing energy efficiency targets [74]. However, most of the studies performed related to CVR, where DER was not common. Hence, there is a need to better realize the interactions between DER and CVR [32],[74]. The interactions between CVR and widespread DER have been widely studied in [18]-[20],[28]-[29], [49]-[50], [65], [72]-[74]–[83],[84] for different style of distribution networks. While the studies [75], [79], [80], [86] explored the impact of CVR in the presence of various levels of DER with different range of voltages reductions with the common objectives of minimization of substation demand, energy losses and voltage deviations. In [30], [70], [83] an integrated VVO based approach has been suggested to implement the CVR and examine its impact on different load models. Optimal placement, size and integration of DG in the context of CVR application has been investigated in [51],[52],[83],[85],[87] and obtained results exposed that optimal DG allocation can boost voltages at sensitive points, therefore permitting further voltage reductions at primary substations. Moreover, the conclusive results reveal that various distribution operational issues such as under/over voltage, reversible power flow and limited hosting capacity may be resolved with combined operation of CVR and DGs.

However, most of the above-mentioned studies do not consider the effects of widespread renewable PV based where variable power generations (due to intermittency) on distribution operation. In this context, the authors of [21],[81]-[82],[84] have analyzed the CVR impact considering the various levels of PV penetrations and performed various studies such as optimal power flow [81], and rolling horizon-based time-series simulations [84]. Since these studies have mainly focused on centralized control operation with a defined time horizon; hence, there is a need of fast control actions that can compensate for quick fluctuations in PV power due to cloud transient effects.

1.6.1.5 Smart Inverter Based VVC

The large level penetrations of variable power generation such as PV, wind affect the static and dynamic performance of the distribution system. As earlier discussed, the intermittence and transient behaviors of these power sources also highly affect the operation and controls. Moreover, they also influence the impact of reactive power in voltages due to high resistance to reactance (R/X) ratio of distribution networks [20] . Though the voltage and reactive power control through traditional VVC are achieved but there is an ambiguity about the coordination and slow response of these traditional VVC devices with additional power sources during the sudden change in network behavior [32], [88]. In order to achieve a faster response of VVC, PVs equipped with smart inverter are being deployed for additional power support [82].

Distributed PV plants usually have a conventional inverter that is set to operate at maximum power point tracking to maximize output PV power, resulting in unity power factor operation. The revised IEEE 1547 (2018) [89], however, states that every DER must have reactive power support capability when requested by power system operators. Therefore, PV systems are increasingly being paired with smart inverters that can inject and absorb reactive power [19], [68], [77]. Moreover, the *Smart Inverter Working Group*

Phase 3 has recommended eight functions to be included in *California's Rule 21* as mandatory or optional for all inverter-based DER systems [90]. Accordingly, distributed PV has the capability to participate in voltage regulation (both local and centralized control) and act as a VVC device[21]. For a local VVC, a PV inverter operates in autonomous mode, and its reactive power dispatch relies on the local measurements using a predefined volt/VAR curve [20]-[21], [77], [91]-[92]. Optimal volt/VAR curve selection using a heuristics approach has been suggested in [93]. A gradient-based decentralized VVO approach under high DER penetration has been introduced in [94]. In centralized VVC, the smart inverter operates in aggregated mode, and the power factor or the reactive power dispatch is determined by the center operator using the control algorithm [72], [76], [82], [84], [91]. The authors of [20],[68] have suggested combined centralized along with local control VVO approach, but they did not include the uncertainty in the network model. Moreover, the reported methodologies have been validated using time-series simulations in offline mode; only a few strategies have been reported [64], [95], [96] for real-time VVC.

1.6.1.5 Effect of Load Models

In order to achieve a perfect solution of the VVO problem, an accurate and correct load model is required for power flow solutions. The detailed description of load models has been already explained in *subsection 1.4.2.4*. A time-series simulation of end-user loads is used for dynamic modeling. Heating Ventilation and Air Conditioning (HVAC) and Water –Heater is considered as dynamic loads with thermal cycles [25], [26]. Most of the work has considered voltage-dependent and time-invariant loads, mainly polynomial (ZIP) and exponential load for the evolution of VVO system [30]-[31], [51], [53], [68]. In [30]- [31], exponential load models have used for the analysis of VVO operation in distribution system. Moreover, [53] used CVR factors as an exponent in exponential load models. A realization of CVR effect with field demonstration by using equivalent ZIP load models has been discussed in [53]. Authors of [14] present a framework for deploying VVO in distribution system with considering voltage dependence of loads. Effect of different load models on VVC savings have also been investigated in [70].

1.6.1.6 *Information and Communication Technology for CVR*

Information and Communication Technology (ICT)s are playing an important role in the deployment of any smart grid assets. Therefore, the study of ICT is essential for power utilities and grid planners. For distribution and substation automation, generally, IEC-61850 communication protocols are applied by smart power utilities and others [1], [64]. In order to achieve the benefits of VVO/CVR a fast, reliable and secure ICT is required. Basically, ICT links the sensors to DMS, SCADA and connect DMS/SCADA to the automatic controlling devices [97]. Most of the power utilities are applying a two-layer communications system between the ADMS and control devices. The first layer of communication consists of mainly high-speed fiber optics or microwave communication that connects DMS/SCADA to utility substations and second layer connecting substations [98]. Many communication technologies are available in the market based on their requirements. Broadband technologies are classified into two categories by broadband service providers. First one is with wire or fixed-line communication such as power line communications, hybrid/coax fiber, digital Subscriber line, home/curb fiber and another wireless Access technology as radio frequency/Microwave links, wireless fidelity (Wi-Fi), Satellite communication, cellular networks (3G and 4G), WiMAX, ZigBee etc. [1].

According to literature, most of the VVO studies have done in offline environments. Very few researchers/utilities have done their work in real-time VVO/CVR. However, most such studies are still in the early stage of considering a real-time VVO solution for the future smart grid. An intelligent agent-based distributed command and control system for building a real-time load profile for integrated VVO/CVR engines have developed with the use of IEC-61850 communication protocols and narrow band power line communications (NB-PLC) [64]. A combined ICT and power simulation platform have realized of VVO operation in MV distribution feeder with the integration of opnet-modeller as a communication network simulator and Electromagnetic Transient Program (EMTP-RV) for system transients [99]. In [64], [100] a real-time co-simulation for the operation of the adaptive VVO engine using real-time digital simulator (RTDS) model and distributed network protocol (DNP3) protocol has been introduced. Socket based communication has been utilized in [95] to establish the connection between RTDS and external agent real-time co-simulation operation.

1.6.2 CVR Assessment and Quantifying Methods

Evaluating the CVR performance on feeder networks has always been a critical issue in the context of its implementation, selection of targeted feeder and performing the cost/benefit analyses. Generally, DNO assessed the CVR performance by determining its CVR factors according to requirements, as explained in the earlier section. In order to measure the reliably estimated energy-savings, the CVR factor still a driving force for research and deployment of CVR schemes. In this regard, Table 1.1 shows that CVR factors determined by various utilities, authors and conducted studies. However, the uncertainty regarding the achieved energy savings remains a barricade to its acceptance worldwide. The key challenge regarding the quantification of benefits can help for selecting the appropriate voltage reduction scheme, identify the networks where and when it is to enable the CVR for a defined time period. Generally, it is determined by comparing the scenarios such as normal operation or without CVR and one where CVR is applied. But doing this is no simple task because aggregate load consumption may not be exactly known or measured without and with CVR at the given time.

Table 1.1 CVR test performed by various utilities

Utilities/Authors/ Ref.	**CVR Factor (*CVR_f*)**			**Published Year**
	(kW)	**(kVAR)**	**(kWh)**	
American Electric Power System [101]			0.62	1973
San Diego Gas & Electric, CA [38]	0.548 -0.967		0.47-1.04	1982
Krishner & P.Giorsetto [39]			0.41-0.991	1984
American Electric Power System [37]			0.71	1986
Northeast Utilities (NU) [36]			0.57-1.35	1987
Bonneville Power Administration [44]	0.90			1990
Commonwealth Edison, California [102][40]	1.0			
Snohomish PUD, WA Northwest Utilities[40]			0.336-1.103	1991 2002
BC Hydro[41]	0.70			1995
Southern California Edison (SCE) [43]	1.0			
Tia Power[103]	0.57			
Avista utilities [104]	0.84			2005
Northwest Energy Efficiency Alliance [105]	Spring- 0.57, Summer-0.78 Fall-0.60, Winter-0.51			2007
Hydro Quebec (HQ) [106]	Summer (R, C, I) 0.67 ,0.97, 0.1 Winter (R, C, I) -0.12, 0.8, 0.1			2008
Pacific Northwest National Laboratory (PNNL)(report), U.S. [107]	With All distribution feeders 3.04% reduction in the annual national energy consumption			2010
R. Singh et. All [78]			0.67-1.33	2011
EPRI [27]	0.6-0.95	50-6.0		2011
Dominion Virginia Power [42]			0.92	
Sunderman/Utility/ EPRI [108]	0.6-1.119	3.0		2012
Australian Experience [46]			0.4	
Ireland Experience [47]	0.58-0.98	6.0 - 6. 6		
Marc Diaz-Aguiló [53]	0.50-1.0	1.5-2.0		2013
Consolidated Edison Company of NY [55]	0.54		0.55	2014
Zhaoyu Wang, et. All [109]	0.61-1.32			2014
Sacramento Municipal Utility District	0.61			2015
Korea Electric Power Corporation [110]	0.721-0.87	7.8-15.0		2016-17

According to [32], CVR effect accessing methods can be classified into four categories based on comparison, regression, synthesis and simulation studies. In this thesis, the emphasis has been given on a simulation-based approach, particularly to allow and perform detailed network and DER based generations impact in a real-time environment. Therefore, a brief discussion about the abovementioned quantifying methods has been described here. The more details about the methodologies can be found in [32], [111].

The first two techniques (i.e., comparison and regression) depend upon measurements in order to evaluate the implemented CVR schemes and latter two (synthesis and simulation-based) methodologies used to estimate the expected benefits before applying the CVR scheme in practices.

1.6.2.1 Comparison-based Method

In the comparison-based method, two basic schemes are considered; the first one is to select two similar networks (feeders) having the same configuration, characteristics and loading condition, etc. CVR scheme is implemented at one feeder while another feeder is operating in normal conditions at the same time. The second scheme is to implement the voltage reduction on a network and apply a normal voltage to the network during different time range having similar weather conditions. Then the CVR effects are determined based on the measurements such as energy consumptions, voltages from the two tests and afterward calculating the CVR factor. Utilities such as Detroit Edison and Snohomish County Public Utility District (Snohomish PUD) [40], [112] respectively have performed CVR test using this approach. Though these two methods are relatively simple to device for DNOs, but having problems as load consumption may change due to other factors such as small weather differences, measurement noises rather than voltage reduction, which can reduce the small CVR effect.

1.6.2.2 Regression-Based method

In regression-based methods, load modeling includes not only voltage level but other factors such as temperature, day type and month that can influence loading conditions. In order to calculate the more accurate CVR factor, these models used linear regression to identify the normal voltage loads and measured reduced voltage [32]. In [39], [111] a relation between network energy demand, applied voltage reduction and temperature variations for a month and day of the week has been built in order to access the CVR effect with other impacts. Authors in [49] tried to regulate the feeder-level and demand with respect to temperature; however study reveals that using measurements from an analogous network provided better regression models. Since the achieved energy savings through voltage reduction are a few percentages of load consumptions, hence it may lie in the range of regression models that limit the typical CVR using this method. Moreover, most of the authors used these linear models are known to be nonlinear functions of the exogenous variables [32]. These limitations can be handled using recently developed techniques (such as artificial neural networks and support vector regression etc.) on nonlinear regression methods.

1.6.2.3 Synthesis Based Method

This method aggregates load to voltage behaviors for a group of loads in order to estimate the corresponding CVR benefits of a network. The aggregation can be performed by synthesizing the load components and customer classes. In the component-based approach, the energy consumption of the main appliances is modeled as a function of voltage, which is obtained from laboratory tests [111]. Thus, the total load demand at network level can be estimated by aggregating the voltage-dependent load components with respect to their shares. The second method generally uses type of customer classes, which is defined as residential, commercial and industrial. Different customer classes have a different share in the network and CVR factors [44]. Moreover, the literature survey presented in [32] clearly explained that, in general, residential and commercial feeders realize higher energy savings under CVR than industrial ones. Though, the synthesis-based approach is simple to apply and permits for fast estimation of energy savings before implementing the CVR. However, it does not provide any information about the time-varying load composition. Besides, sometimes, it is very difficult for DNOs to collect accurate load models and quantifying the participation of load demands. Thus, CVR effect assessed through synthesis methods are needed to understand before implementing in field trials.

1.6.2.4 Simulation-Based Methods

These methods are based on modeling of network, loads and execute the power flow analysis under various operating scenarios with and without considering the voltage reduction effect. The CVR benefits estimation can be calculated by comparing the results obtained from voltage reduction to normal operating conditions. In order to achieve this, estimation of load demand and appropriate modeling of loads in the function of voltage are to be carried out considering the various dominating factors such as season, solar irradiance and temperature. The main challenges of simulation methods are how to build an accurate representation of loads and their dependence on the voltage that can contribute to the major energy-saving effect. The details regarding load models have already been discussed in the previous section. Past decade literature related to simulation-based CVR studies focused on utilized aggregate power loads and average voltages to build the time-invariant load models. Moreover, few researchers have tried to develop the load models for individual appliances with appropriate rules for obtaining aggregated models based on participation factors [22],[24]-[25]. In the current scenario, the inclusion of the time-varying loads for CVR-related studies has been introduced and demonstrated in [26],[45], [60],[109].

1.7 Objectives and Scope of the Thesis

The main objective of this thesis is to develop the smart voltage and VAR control algorithms to conserve the energy in ADN. In order to accomplish this goal, the research work further sectionalized in the following objectives

- First objective is to develop the closed-loop CVR framework with better monitoring and controllability. In order to achieve this, a closed-loop smart grid-enabled CVR method assisted through ADMS and feedback by advanced metering infrastructure data have been proposed in this work. In addition, effect of different load models on achieved savings using proposed method is to be analyzed.
- The second and foremost objective of the thesis is the development of advanced control algorithms for coordination among the network devices and network assets in an optimal manner. Therefore, optimal CVR operation using centralized VVO method has been suggested in this thesis. The impact of DERs in VVO formulation has also been incorporated. A centralized approach works well for a fixed time horizon interval, but it might be inflexible for fast-response events such as PV intermittency. Therefore, a time horizon-based model predictive VVO methodology has been proposed to resolve the deterministic VVO issues.

  Besides, the impact of EV charging loads with different profiles have been considered in stochastic VVO formulation under CVR scenarios. The noteworthy application of vehicle to grid (V2G) reactive power dispatch from EV charging station for voltage regulation has also been demonstrated.
- Third objective deals to validate the developed methods and models in real-time environment. Therefore, a real-time event-driven predictive framework has been

proposed to check the effectiveness of the developed control algorithms and framework. In addition, a coordinated three-level hierarchical dispatching structure is proposed to realize the event-driven predictive online framework. The development of a dynamic real-time droop controller for smart inverter operations has also been proposed. Besides, a real-time co-simulation platform using the RTDS in distribution mode through co-simulation with models based on Python and OpenDSS is proposed.

- Quantify the value of energy and cost savings for utilities, electricity savings for customers, and carbon emissions reduction is the fourth prime objective of the thesis. The investigation incorporates the CVR factor-driven scheme to assess the load-reduction effects via CVR using developed VVO algorithms. CVR factors in terms of power, energy, and cost have been proposed for different time durations such as peak load hours, peak day and annually. Besides, the operating costs of distributed network devices and maintenance costs of assets have been incorporated in the proposed VVO formulations. The techno-economic-environmental analysis of CVR implementation has also been carried out. Further, analyze the impact of load reductions as value addition in terms of cost and carbon footprint reduction has been analyzed.

1.8 Organization of the Thesis

The work embodied in the present thesis is organized into eight chapters. The organization of the same is as follows:

Chapter 1: Introduction

This chapter briefly introduces the necessity of electrical energy conservation, the basic concept of power distribution network and the need of smart voltage and VAR control. Besides, the basic concept of CVR has also been discussed. Further, it also presents a comprehensive literature survey of the research carried out in Volt/VAR control, CVR implementation and assessments of its effect with and without the presence of DER. Finally, the chapter concludes with the research objective and detailed organization of the thesis.

Chapter 2: Concept of Smart Grid Enabled CVR

In this chapter, a smart grid-enabled CVR methodology has been introduced. The basic concept of the proposed methodology has also been described. Further, the proposed methodology has been implemented using traditional LDC scheme with the help of conventional VVC devices such as OLTC, AVR and capacitor banks. Besides, the effect of different load models on CVR operation has been analyzed. In addition, assessment of the CVR effect with additional reactive power support from capacitor banks has also been carried out. Finally, the proposed methodology and its effects have been demonstrated on the modified IEEE 13-node and 34-node distribution feeder test system

Chapter 3: Distributed Energy Resources Impact on CVR

This chapter describes the impact of DER on CVR energy savings and distribution grid operations. Besides, the combined effect of DER and CVR has also been analyzed using proposed smart grid-enabled CVR method. The PV smart inverter-based voltage and reactive power control of the ADN have been introduced in this chapter. In addition, the LDC approach has also been utilized to implement the proposed methodology. At last, the proposed smart PV inverter based VVC methodology has been validated on a modified IEEE 123-node unbalance distribution feeder test system. Moreover, the modeling and simulations have been carried out on OpenDSS and MATLAB platforms.

Chapter 4: Optimal CVR: Centralized Volt/VAR Optimization

In chapter 4, the implementation of optimal CVR in ADN using VVO methodology has been introduced. A centralized discrete gravitation search algorithm-driven VVO