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Coordinated Volt-Var control in multiple smart inverters in Smart Distribution Networks for Voltage Regulation

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Abstract

The inevitable growing demand for electrical power, depleting sources of conventional power generation, and wold wide concern about global warming are major factors to boost the trend of renewable integration in grids. This rising trend is causing many technical and operational challenges where one of the most prominent problem is the overvoltage caused by distributed generation units, interfaced at the consumer end, and power injections at random nodes. This in contrast with predefined power flows of conventional grids gives rise to bidirectional power flows that demand for modern, coordinated and robust voltage regulation scheme with minimal communication infrastructure. A centralized, coordinated, differential evolution based Volt/VAR regulation scheme is proposed to eliminate the voltage deviations caused by excessive photovoltaic integration in distribution systems. Time step simulation utilizing OpenDSS interfaced with MATLAB on standard IEEE-123 feeder are implemented to test the effectiveness of the proposed scheme.

Abbreviations

ANM	Active Network Management
AVR	Automatic Voltage Regulator
CB	Capacitor Banks
DLC	Direct Load Control
DC	Distributed Controller
DER	Distributed Energy Resources
DG	Distributed Generator
DS	Distribution System
MC	Master Controller
MU	Measurement Units
PMU	Phasor Measurement Unit
PCC	Point Of Common Coupling
PFC	Power Factor Control
PLC	Power Line Carriers
RTU	Remote Terminal Units
SCADA	Supervisory Control And Data Acquisition
SOP	Soft Open Point
SVR	Static Voltage Regulator
VPP	Virtual Power Plant
VAR	Volt Ampere Reactive
VQF	Voltage Quality Factor
ZC	Zone Controller
VR	Voltage Regulator
VQFN	Voltage Quality Factor under Normal Conditions
VQFPP	Voltage Quality Factor with PVs Penetration
VQFVV	Voltage Quality Factor with Volt/VAR

Nomenclature

v_{ai}, v_{bi}, and v_{ci}	Voltage of phase-a, phase-b, and phase-c for the i^{th} bus
n	Number of nodes
S	Solar irradiance in kW/m^2
a, b	Parameters of the beta distribution
μ	Mean
σ	Standard deviation
N	Total number of PV models
F	Fill Factor
V_O	Open-circuit voltage
K_V	Temperature coefficient for voltage
K_I	Temperature coefficient for voltage
I_L	Short circuit current
T	Cell temperature
T_a	Ambient temperature
T_n	Nominal temperature
V_{mp}	Maximum power point voltage
I_{mp}	Maximum power point current
$QP_s^{N_p}$	Single gene for N_p^{th} chromosome of s^{th} PV inverter
α, β, and γ	Random variables from the previous generation,
ω	Differential weight, mutation factor, or scaling factor.
$\mathbf{m_i}$	Donor vector
CR	Crossover probability
ζ	Loss function

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1 Chapter 1: Introduction

The improvements in power distribution systems are growing rapidly with the trends of distribution generators, bi-directional power flow, SCADA, and enhanced communication systems.

1.1 Background and Motivations

The ever increasing demand for electrical energy has put on a lot of stress on conventional generation methods that are leading to the rapid depletion of these reserves. Global warming is also a warning call to reduce carbon emissions by cutting down thermal power generation. The adverse environmental effects of conventional power generation methods are leading the world towards more eco-friendly renewable power generation methods. Also, the financial benefit of exporting out the excess generation to power companies through net metering along with reduced expenditures and billing is an extra perk for renewable energy stakeholders.

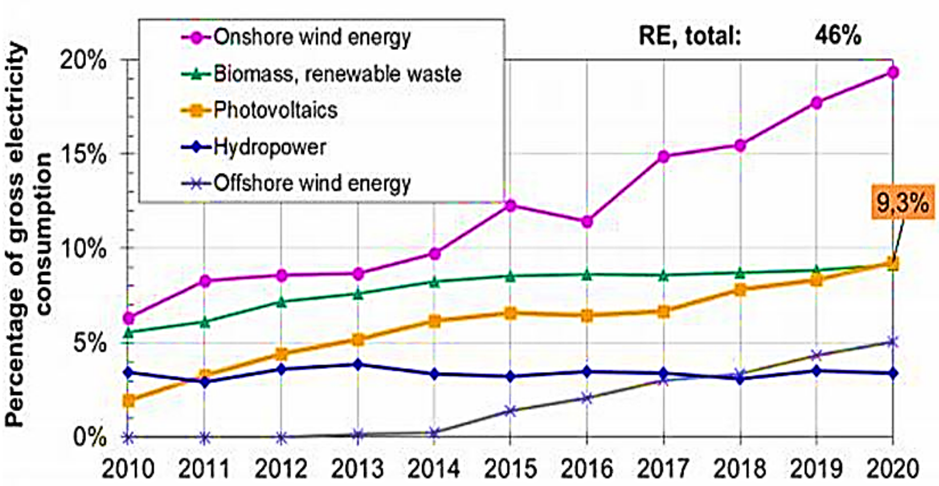

Figure 1: Electricity Generation Percentage of various renewable energy sources with respect to total generation for Germany [1].

The global growth trend of renewable energy sources is increasing day by day owing to enormous advantages i.e. they are inexpensive, inexhaustible, environment-friendly, have low carbon footprints, and comparatively lower maintenance and running expenses. The significantly rising trend of the Distributed Energy Resources (DER) growth is evident in Figure 1 as it can be seen that in 2020 DERs were a prominent 42% constituent of the overall expansion in the capacity of power generation [2]. Also, from 2012 through 2020 the average growth rate of distributed power is 4.8% as compared to the 2.8% growth rate of centralized power. Various attractive incentives have been announced worldwide in recent years to encourage consumers to actively participate in the power industry through distributed renewable generation via net metering. Smart grid infrastructure flexibly enables household users to install renewable energy sources and integrate them with the distribution network. By doing so, they can generate revenue by trading their excessive power generation to the power grid. That brings the freedom of distributed generation close to load centres eliminating wide span transmission networks and accompanying power losses. On the other hand, global electricity demand is increasing day by day [3] and with the limitation of expansion in an existing central generation, the electricity companies are also moving towards distributed generation as well as encouraging households about the adaptation of distributed generation.

Among several Distributed Generators (DGs) like Photovoltaic (PV), wind, hydropower, and biomass combustion, the trend of rooftop solar panels (PVs) is increasing globally. In 2019, 8% of the total power generation capacity of Germany was based on only Photovoltaic (PVs) generation units while in 2020, it is further increased to 9.3%. However, the increasing integration of renewable resources into power distribution systems also causes many technical and operational challenges. One of the most prominent effects is the voltage rise issues due to distributed units power injections at random nodes. The conventional voltage regulation techniques used in power systems are typically designed to operate on a predefined top-down approach that knows well the power flows through system elements. However, the scenario changes when there is heavy integration of distributed energy resources in grids as the power may flow forward as well as in reverse direction depending upon the operational state of the system. Thus, there needs to be a tailored solution for such problems that can ensure the power and voltage quality standards well without significantly disturbing the operation of distributed energy units.

The voltage rise issue can be catered to in multiple ways but the topology and involvement of communication infrastructure make a significant difference. Many centralized and decentralized and autonomous control schemes have been developed to overcome the issue of voltage rise due to random varying power injections of distributed energy resources.

Local control schemes take only the status of the point of connection as a decision parameter requiring no remote data. The major benefit of autonomous or local control is its fast response to any changes in the system as it is not affected by communication delays and is independent of system topology. Being independent of extensive communication makes this category unlikely to be affected by communication failures. However, the limitation is its inability to produce a globally optimal solution as it does not incorporate the wider scenario of operational parameters all along the feeder to which the DG is connected making it unfit for plug and play operation. To improve the voltage quality, multiple methods and devices are proposed in the literature like Step voltage regulators [4], Static reactive power compensators [5], and Static Synchronous compensators (STATCOM) [6], Transformer Tap-Changers (TTCs). These devices need additional installation charges and maintenance costs along with a refined coordinated control system. However, the smart PV inverters that are used to integrate a PV with a distribution network, have the potential to control the exchange of active and reactive powers along with power factors for improving the voltage profile of the host power network e.g. Volt-Watt Control [7], Volt-VAR Control [8] etc. Volt-Watt Control method is to restrict the real power output of the inverter in response to the voltage at its terminal whereas the Volt/VAR Control method is to restrict the reactive power output of the inverter in response to the voltage at its terminal. Volt-Watt control method is limited in application as it compromises the benefit of stakeholders by curtailing the generation of the real power of DGs. On the other hand, the Volt/VAR method imposes no real power generation loss but manipulates the exchange of reactive power between the power network and the DG unit. Another advantage of inverter control is that a power electronic device that needs very little time to react has a speedy and robust response to perturbations as compared to conventional devices. So, Volt/VAR Control technique is the best suitable technique to improve the voltage profile among all other techniques in every aspect.

1.2 Objectives

Volt/VAR control refers to the process of improving voltage profile through controlling reactive power exchange. Both the quantities are linked with each other as reactive power injection into the grid causes voltage rise while reactive power absorption from the power system causes a voltage drop. IEEE standard-1547 states that voltage deviation should be in the range of ±5% in large systems and ±2.5% for smaller systems. So, to keep the deviation in the maintained range, positive or negative VARs can be released or absorbed by using smart PV inverters controlled via a master controller in the distribution network.

In this thesis, we propose a Volt/VAR technique to improve the voltage profile of the distribution network. The optimized VARs are obtained by Differential Evolution (DE) and then injected into the DGs to enhance the power quality. The results are shown quantitatively to prove the effectiveness of the proposed algorithm. It is also proved that the proposed technique is much faster than the previous techniques and can converge to minima in a few iterations. The standard IEEE-123 bus system is used for simulation purposes utilizing OpenDSS for system modelling and MATLAB for control, optimization and the implementation of the Volt/Var strategy.

1.3 Thesis structure

The rest of the thesis structure is defined as follows. Chapter **3** explains, how the problem of voltage optimization is addressed in the literature and the gaps in the literature that needed to be filled. Chapter **4** explains the modelling of the proposed technique and its mathematical representation. Chapter **5** is the discussion part in which the results of the proposed scheme are discussed. In the last, Chapter **6** will conclude the discussion by linking them with the achievements.

2 Chapter 2: Literature Review

To meet the electricity demand of the modern era, solar energy is the most suitable renewable energy source in terms of simplicity of installation, environmentally friendly nature and very less running cost. Solar energy can be extracted from PVs including building integration, ground mounting, and rooftop integration. Despite all the advantages, excessive PV penetration into the distribution network has some serious effects on power quality resulting in violations of operational standards of power systems. To overcome the effects of excessive PVs penetration, multiple methods are used in the literature that are explained in this section.

A Hybrid Volt/Var control approach based AI technique such as machine learning and multi-agent system based models is proposed in [9]. The advantage of using a hybrid approach is that it can handle both centralized and decentralized infrastructure. But this approach optimally calculates the VARs that are to be injected into the system through a PV inverter and need some complex computations hence cannot be implemented in online mode. The optimal parameter selection of Volt/VAR control strategy is proposed in [10] which is based on some particular scenarios like if the voltage of the PCC (Point of Common Coupling) is in a predefined range then what should be the value of reactive power that is to be injected into the system to improve the voltage profile. This method cannot work for larger systems in which the voltage difference is larger between PCC and the far end node of the system. In [11] the determination method of optimal Volt/VAR curve and Volt/WATT curves is proposed. However, we already know that use of the Volt/WATT method is not a good approach as this method restricts the generation of active power.

The evolutionary algorithm based on the ant colony optimization approach is proposed to determine the best possible Watts, and Vars of the capacitors and tap positions to improve the distribution voltage profile [11]. In [12, 13] a Genetic algorithm-based approach is used to determine the best optimal VARs to improve the voltage profile of the distribution system. Some disadvantages of GA are,

1. It is much more sensitive to the population size.
2. Its convergence increases exponentially with an increase in population size.
3. It can stuck in local minima.

Therefore, with the increase in the number of DGs, GA will outperform because it will take so much time to converge. The drawbacks of PSO are,

1. It is sensitive to the population size but less sensitive than GA.
2. It does not always converge to global minima.

In [14] a hierarchical hybrid architecture for Volt/VAR control strategy is proposed. This method includes three layers with specified operations and then the appropriate coordination between each layer is introduced to meet combined goals of optimization and accommodation of load and generation uncertainties in near real-time.

The issue of the voltage rise due to PVs is addressed by lowering the primary side voltage in [15]. However, this approach will result in low voltages in some parts of the distribution feeder as all the buses are not getting equally affected by the integration of PVs. In [16, 17] this problem is addressed by increasing the size of the diameters of all the lines as this will result in decreasing the impedance of the lines, but this is not an economical and practical approach. Moreover, these methods are not adaptive and by keeping in mind the variability of the nature of PV generation these methods are not applicable. VRs (Voltage Regulators) [18], Capacitor Banks [19], and On Load Tap changer [20] are also used to solve this problem but the main problem to use these devices are they work digitally and the PV generation is analogue in behaviour, so due to slow response, these devices are not the optimal solution to this problem. The best optimal solution for the voltage rise problem is the use of smart PV inverters for the integration of PVs.

A smart PV inverter is an adaptive power electronics device that is used to interface PVs with the distribution network. The following listed control and regulation strategies are implemented using smart PV inverters.

Power factor plays an important role in voltage stability, and it is always an ideal condition for a distribution network to work on unity power factor, but in the case of excessive PVs integration unity power factor is not the optimal condition for the distribution network [21]. So, new optimal conditions for all the nodes are calculated and then by fixing these optimal power factors in the smart PV inverter voltage profile is improved [22].

Local control considers only the parameter of the point of connection of DG with the grid. No remote data is taken and no long span communication is involved. Multiple local control schemes have been proposed priorly [23, 24]. Among all the local Volt/Var control techniques, the droop control technique is the most used and the most optimal technique and that will be the scope of this work.

In [24] a non- droop-based Volt/Var method is proposed that is based on the unlimited Vars resources, whereas in real scenarios it is not possible to have unlimited Vars from an inverter. In [25] a simple approach based on line impedance compensation was proposed that was exactly like line drop compensation methods. All the stated methods have some serious disadvantages like they are not adaptive and cannot provide good results with variable nature of PVs generation and these control methods run on the assumptions of DC Power flow So, cannot run in practical/AC/nonlinear power flow.

It is a relatively simple and robust technique of Volt/VAR control proposed for the first time in the EPRI report [26]. It works on a piecewise linear objective function including adjustment of VAR according to voltage levels. This control technique has been widely explored by many researchers in the recent past with some variations in parameter selection criteria. [27-29]. The only limitation is that the objective of optimizing the whole network voltage profile while the decision-making process is based solely on the voltage of the point of coupling. The work presented here is also based on droop control of inverters to optimally select the VAR output level of DG so that its operation does not cause any significant voltage deviations in the distribution network.

Optimized VARs are obtained by using some methods that can reduce the voltage deviation and maintain all the voltage closer to reference. To solve such problems with multiple constraints there are multiple optimization methods used in literature e.g. PSO algorithm, and graph data model (GDM) in [30], Genetic Algorithm (GA) in [12, 13], Ant Colony Optimization approach in [11].

In this research thesis, we proposed an optimization algorithm that is based on Differential Evolution (DE). There are multiple advantages of DE like,

1. It does not stuck on local minima and always converges to the best optimal solution
2. very less sensitive to the population size as compared to GA and PSO

Our proposed technique works on reactive powers of inverter interfaced photovoltaic distributed generation units to optimize the network voltage profile by eliminating the disturbances caused by PV integration. The results are shown quantitatively to prove the robustness, effectiveness and superiority of our proposed scheme over previous techniques.

3 Chapter 3: Modeling and Methodology

To meet the electricity demand of the modern era, solar energy is the most suitable renewable energy source in terms of simplicity of installation, environmentally friendly nature and very less running cost. Solar energy can be extracted from PVs including building integration, ground mounting, and rooftop integration. Despite all the advantages, excessive PV penetration into the distribution network has some serious effects on power quality resulting in violations of operational standards of power systems.

3.1 Voltage Rise Issue

Distributed Generators (DGs) are installed on the distribution end in an unbalanced manner. As the concept of DGs integration is available on the secondary distribution network and when PVs are installed on different phases then an unbalanced voltage situation occurs. Disturbance in voltage profile is also a cause of excessive PVs installation on multiple phases of the distribution network.

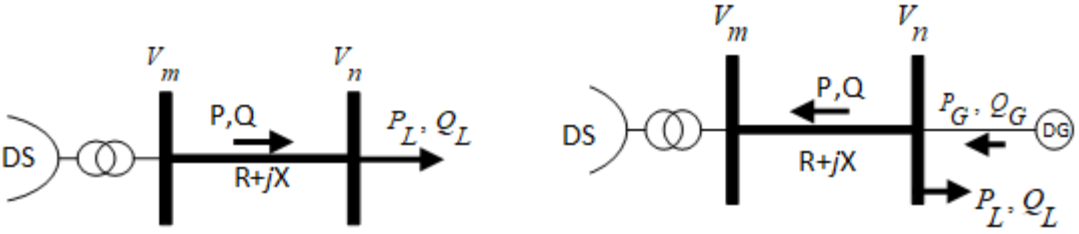

Figure 2: A distribution network with only two buses and one line [31]. Left-sided Image is without DG and the right-sided Image is with a DG.

In Figure 2 V_S is the sending end voltage, V_R is the receiving end voltage, I is the current flowing from V_S to V_R, $R+jX$ is the impedance of the line, DG is the distributed Generator, P_L is the active power of the load, Q_L is the reactive power of the Load, P_G is the real power generated from DG Q_G is the reactive power generated from DG and Q_C is the reactive power of the capacitor bank. Sending end voltage can be written as,

$$V_s = V_R + I(R + jX) \qquad 1$$

We also know that, $$V_s I^* = P + jQ$$

$$I^* = \frac{P - jQ}{V_s} \qquad 2$$

From Eq. 1 and Eq. 2 we can write as,

$$V_S = V_R + \frac{RP + XQ}{V_S} + j\frac{XP - RQ}{V_S}$$

So,

$$\Delta V = V_S - V_R = \frac{RP + XQ}{V_S} + j\frac{XP - RQ}{V_S}$$

The angle between V_S and V_R is very small. So, the imaginary part of the above equation is close to zero. If V_s is taken as a reference bus then the magnitude V_s is approximately equal to one. So,

$$V_R \approx RP + XQ \qquad 3$$

This shows the stable voltage profile in the case of a conventional distribution network. Now if we connect a DG at the receiving end then, like in the right part of Figure 2.

If $P = (P_G - P_L)$ and $Q = \pm Q_C - Q_L \pm Q_G$, the Eq. 3 now becomes,

$$V_{GEN} \approx R(P_G - P_L) + X(\pm Q_C - Q_L \pm Q_G) \qquad 4$$

In steady-state conditions, voltage is stable in the distribution network in the case of a conventional distribution network. However, when distributed generators are connected to the distribution network then the effect in the power flow voltage profile also gets affected as you can see from Eq. 3 and Eq. 4. Now, the power that flows through the line can be in either direction and V_{GEN} is depending on the relative magnitudes of the real and reactive powers of the load, the generator, and the losses in the network.

A rise in voltage due to excessive PV injection is a serious concern for the consumer. As it can cause some serious damage to the consumer’s appliances as well as to the power network. On the other hand, the voltage rise across the safe band is the main limitation to the PV integration in the distribution network. By resolving the voltage rise issue the capability of the PVs integration into the distribution network can be enhanced.

3.2 Volt/ VAR Regulation

The function of the Volt/VAR method is like controlling the VAR output of the inverter to regulate the system voltage on point of connection of DG as well as neighbouring nodes.

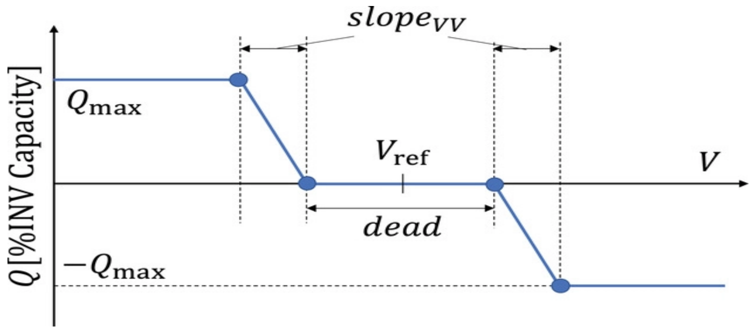

Figure 3: Working of Volt/Var method [32]. Droop based inverter Var output control.

Figure 3 shows that if a voltage is in the dead band, it means the voltage is in the safe range of ±5%, $slope_{vv}$ indicating the region where reactive power varies with the resulting variation in voltage. $\pm Q_{\max}$ marks the positive and negative maximum controlled value of reactive power limits of a DG unit [33-35].

The proposed Volt/VAR topology is addressed for the over-voltage issues due to the excessive penetration of PV generators. Implementing the proposed Volt/VAR regulation involves the variation of reactive power set-points of inverters interfacing the PV generators at the distribution system. The beginning of the process reads the voltage profile of the whole feeder taking as input the phase voltages per unit of all 123 nodes of the feeder. The single bus voltage is calculated by taking the average of all phase voltages as shown in Eq. 5

$$v_i = \frac{1}{n_i} \sum v_{xi} \qquad v_{xi} \in [v_{ai}, v_{bi}, v_{ci}] \tag{5}$$

where v_i is the node voltage of i^{th} bus, n_i is the total number of active phases present in i^{th} node, and v_{ai}, v_{bi}, and v_{ci} is the voltage of phase-a, phase-b, and phase-c for the i^{th} bus respectively. So, for the n number of nodes, the complete voltage profile is shown in Eq. 6.

$$\mathbf{v} = \begin{bmatrix} v_1 & v_2 & \dots & v_n \end{bmatrix} \tag{6}$$

The objective of this research is to improve the voltage profile of the complete network. There are some defined standards of IEEE for an improved voltage profile. i.e. as per IEEE standard 1547, the permitted voltage deviation range for the smaller systems is $\pm 2.5\%$ and for the larger systems is $\pm 5\%$. In normal conditions, all the voltages are in a safe range. So, considering the later range, the safe band for our system is described in Eq. 7.

$$0.95\text{pu} \le v_i \le 1.05\text{pu} \qquad \forall v_i \in v \tag{7}$$

To meet the electricity demand of the modern era, solar energy is the most suitable renewable energy source in terms of simplicity of installation, environmentally friendly nature and very reasonable running expenses. Solar energy can be extracted from PVs including building integration, ground mounting, and rooftop integration. Despite all the advantages, excessive PV penetration into the distribution network has some adverse effects on power quality. As some sink buses now become source buses so, the most commonly studied issue in case of excessive penetration is the issue of voltage rise. After the PV installation, there is a significant change in the host node voltage as well as the other node's in-vicinity as shown in Eq. 8.

$$\mathbf{v} = \begin{bmatrix} v_1 + c_1 & v_2 + c_2 & \dots & v_n + c_n \end{bmatrix} \tag{8}$$

c_1, c_2, and c_n are the constants showing the voltage disturbance appearing after active PV injections. Some of the disturbances are so high that the affected buses may cross the safe range as described in Eq. 9 e.g. if v_m is an array of affected buses, over the safe range, resulting from excessive PV penetration then,

$$\mathbf{v_m} \ge 1.05\text{pu} \qquad v_m \subset v \tag{9}$$

The objective of this research is to improve the voltage profile by minimizing the change that appeared after the installation of PVs and to bring the voltages of all the buses in the safe range as close as possible to 1pu by utilizing the controlling potential of PV inverters by manipulating the kVARs output of the active PVs.

3.3 PVs Modelling

A production unit deployed with Photovoltaic is modelled to imitate real-time performance environments. Seasonal, daily and hourly dispatch curves are generated after the implication of beta distribution [36] over the real-time temperature and irradiance data of several years as described in Eq. 10.

$$f_\beta(s) = \begin{cases} \left(\dfrac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}\right) s^{(a-1)}(1-s)^{(b-1)} & \text{for } 0 \le s \le 1, a \ge 0, b \ge 0 \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

Where a, and b are the parameters of the beta distribution function respectively. s is the solar irradiance in kW/m^2. Beta distribution parameters a, and b can be calculated by using Eq. 11 and Eq. 12 respectively.

$$a = \frac{\mu b}{1-\mu} \tag{11}$$

$$b = (1-\mu)\left(\frac{\mu(1+\mu)}{\sigma^2} - 1\right) \tag{12}$$

where μ is the mean and σ is the standard deviation of the solar irradiance s. The electrical power output of a PV unit can be calculated by Eq. 13

$$P_{PVs} = NVIF \tag{13}$$

Where, N is the total number of PV models, V and I is the voltage and current, and F is the fill factor. Voltage, current, and fill factor can be calculated by given equations.

$$\begin{aligned} V &= V_O - K_V T \\ T &= T_a + I_t\left(\frac{T_n - 20}{0.8}\right) \\ I &= I_t(I_S + K_I(T-25)) \\ F &= \left(\frac{V_{mp} I_{mp}}{V_O I_S}\right) \end{aligned} \tag{14}$$

Where, V_O is the open-circuit voltage, K_V and K_I is the temperature coefficient for voltage and current, I_L is the short circuit current, T is the cell temperature, T_a is the ambient temperature, T_n is the nominal temperature, I_t is the short circuit current, V_{mp} and I_{mp} is the maximum power point voltage and current.

3.4 Problem Formulation

This research aims to optimize the voltage profile of the whole active distribution network with high PV penetration in a coordinated, centralized manner utilizing a differential evolution algorithm.

3.4.1 Formulation of Objective Function

The optimization targets to achieve improved voltage quality along feeder with actively distributed generators. The nodal voltages are compared to the reference point voltage and the resulting absolute differences are minimized through a constrained optimization algorithm. The objective function can be mathematically shown as Eq. 15.

$$f(Q) = \min \zeta \qquad 15$$

$$\zeta = (\sum_{i=1}^{n} \| v_{ref} - v_i \|) \qquad 16$$

Where v_i are nodal voltages and v_{ref} is the optimal voltage point of 1pu.

3.4.2 Formulation of Constraints

As explained earlier, the voltage can be controlled through VARs. These constraint boundaries ensure that the reactive power regulation imposed on a DG is within its capability to generate or absorb VARs at that particular operational state according to ambient conditions. Let there be a PV having kVA and kW capacity of S and P, respectively. The kVAR output act as a specific power factor can be shown as Eq. 18.

$$P = S\cos\theta, \qquad Q = S\sin\theta \text{ and } \qquad \theta = \cos^{-1}(PF) \qquad 17$$

Hence from Eq. 17,

$$Q = P\tan\cos^{-1}(PF) \qquad 18$$

The allowable range of reactive power in both generation and absorption mode is constrained as shown in Figure 4 which explains the relationship between real and the reactive power, so that the operation of PV inverters may not affect the power factor more than the safe range ± 0.9 . Therefore, it sets the minimum and maximum range for the reactive power generation and absorption for PV inverters as shown in Eq. 19

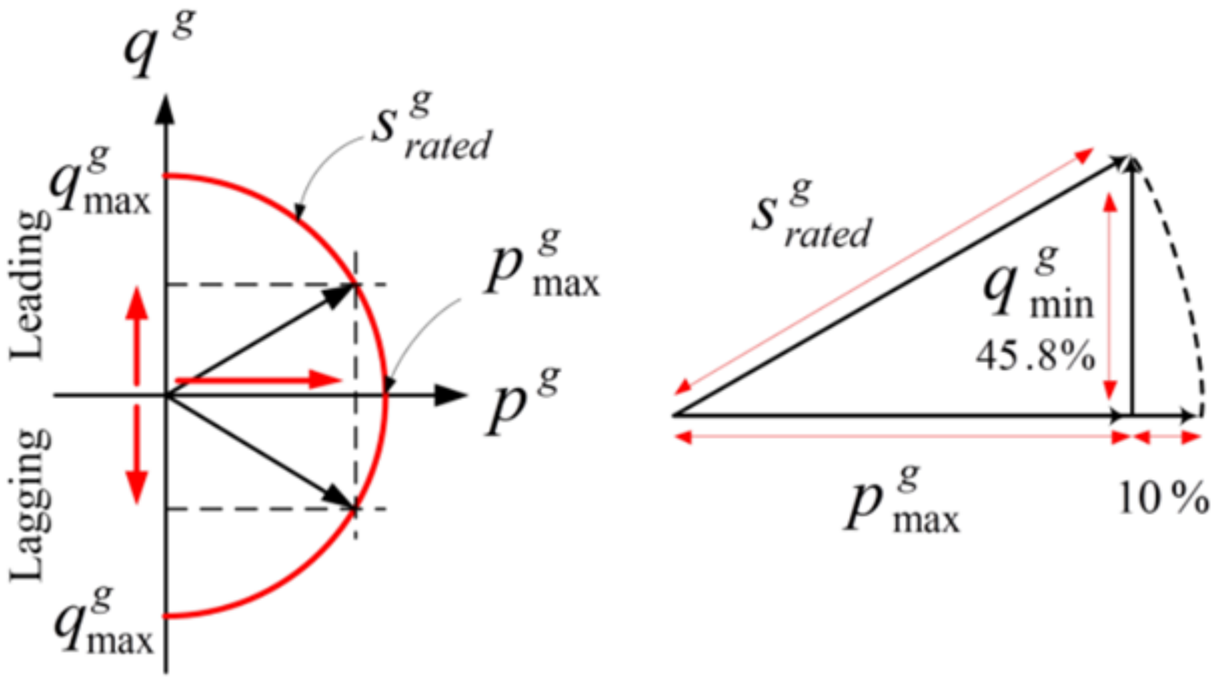

Figure 4: The capability curve of the PV inverter is shown on the left side of the image which describes the relationship between the generated real power and the allowable range of the reactive power. Where q^g is the generated reactive power, p^g is the generated real power. $q^g_{\max}$ is the maximum allowable reactive power, $q^g_{\min}$ is the minimum allowable reactive power, and S^g_{rated} is the rated apparent. The relationship between Pmax and the Qmax for any instant is shown on the right side [37].

$$s.t. \quad Q_{\min} \le Q_k \le Q_{\max} \quad \text{for } k = \{PV_1, PV_2, \ldots PV_s\} \tag{19}$$

3.5 Differential Evolution

Differential evolution (DE) is a meta-heuristic search algorithm that eventually minimizes the issue by repetitively upgrading the target solution based on the evolutionary process. Such algorithms incorporate little or no thought about the basic development problem and can quickly dig into a very large span of multidimensional problems.

3.5.1 Initialization

First of all, a population ($\mathbf{QP}$) is generated with N_p number of variants. If there are s number of PVs are installed, then the population can be represented as $N_p \times s$ dimensional matrix as shown in Eq. 20.

$$\mathbf{QP} = \begin{bmatrix} QP_1^1 & QP_2^1 & \cdots & QP_s^1 \\ QP_1^2 & QP_2^2 & \cdots & QP_s^2 \\ \vdots & \vdots & \ddots & \vdots \\ QP_1^{N_p} & QP_2^{N_p} & \cdots & QP_s^{N_p} \end{bmatrix} \qquad 20$$

Where each row of the matrix $\mathbf{QP}$ represents a chromosome, and each entry of a chromosome represents a gene e.g. $QP_s^{N_p}$ denotes a single gene for N_p^{th} chromosome of s^{th} PV inverter. Every gene is randomly generated considering its corresponding constraints of Q_{max} and Q_{min} as described in the previous section. After initialization, each chromosome undergoes mutation followed by recombination or cross over. The selection of a better solution is performed after the generation of all the trial vectors. This process continuously iterates until one of the termination criteria is achieved.

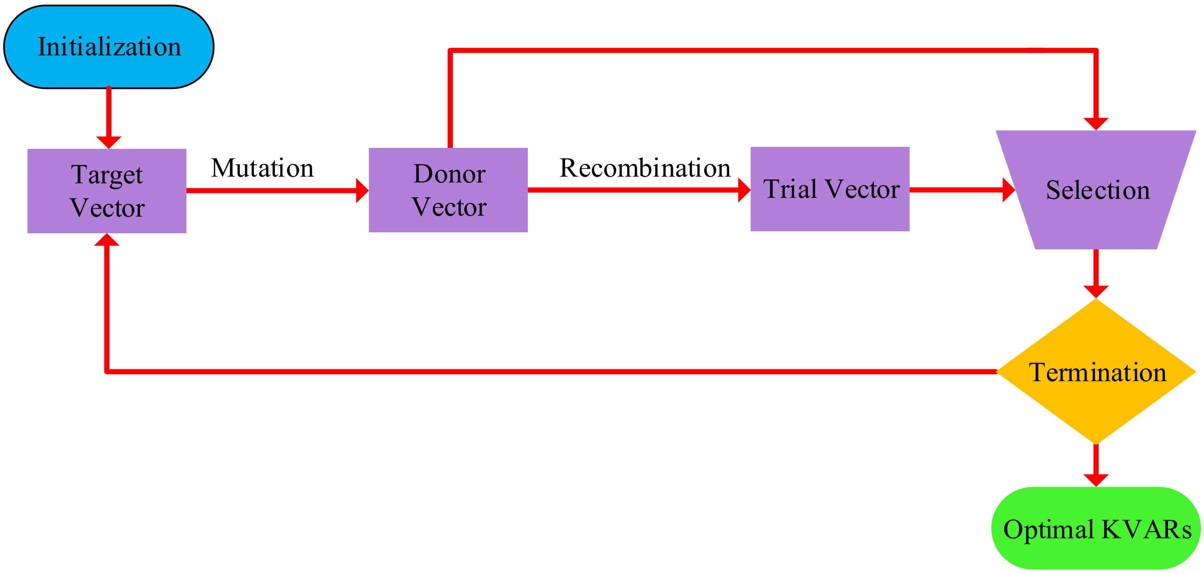

Figure 5: Complete procedure of Differential Evolution Algorithm

3.5.2 Mutation

In every generation or iteration G, Differential Evolution uses the mutation operator for producing the chromosome of a donor vector $\mathbf{m_i}$, for each chromosome of the target vector q_i shown in Eq. 21.

$$m_i = x_\alpha + \omega(x_\beta - x_\gamma) \qquad \alpha, \beta, \gamma \in \{1, 2, \ldots N_p\} \qquad 21$$

$$\textbf{s.t.} \qquad \alpha \neq \beta \neq \gamma \neq i$$

Where α, β, and γ are random variables from the previous generation, $\omega \in [0,2]$ is called differential weight, or mutation factor, or scaling factor. For each target vector ($\mathbf{qi}$) at generation G, the associated donor vector ($\mathbf{m_i}$) is produced using the mutation scheme described in Eq. 21.

3.5.3 Crossover

Binomial Crossover is performed to obtain the trial vector u_j. This action is performed to increase the diversity in the population or to get the global minima.

$$u_j(s) = \begin{cases} m_j & \textbf{if } r \leq CR \ or \ j = \delta \\ q_j & \textbf{otherwise} \end{cases} \qquad 22$$

Where δ is a randomly selected location from a chromosome and r is the random number between 0 and 1. δ ensures that at least one crossover is performed. At least one variable is selected from the donor vector. $CR \in [0,1]$is the crossover probability or crossover control parameter. The high value of CR results in more variables from the donor vector(m_i), and the low CR value results in more variables from the target vector(q_i).

The population is updated through the greedy selection from donor or trial vector. Then these resulting arrays of kVARs ($\mathbf{QP^i}$) are injected into all the PV inverters, and loss is calculated through Eq. 16.

3.5.4 Termination Criteria

The process is repeated until one of the specified stopping conditions is met i.e. either the maximum number of generations is reached as defined in Eq. 23, or there is not any significant loss reduction anymore as shown in Eq. 24.

$$G \geq G_{\mathbf{max}} \qquad 23$$

Where G is the current generation or iteration and $G_{\max}$ is the maximum number of generations defined.

$$\zeta_t - \zeta_G < 10^{-8} \qquad s.t. \qquad t \gg G \qquad 24$$

Here ζ is the loss function, ζ_G which is the loss for G^{th} generation and ζ_t is the loss for t^{th} a generation.

4 Chapter 4: Results and simulation

This Section elaborates the simulation results and outcomes performed to test the effectiveness of the proposed local inverter Volt/VAR control scheme for voltage regulation of distribution network with high integration of PV units. The simulations are done on MATLAB R2020a and OpenDss 9.3.0.1 64 bit.

4.1 System Modelling

The validation of the proposed coordinated Volt/VAR regulation scheme IEEE-123 standard feeder is taken as a test distribution system. The network is mainly characterized by 123 main buses, one substation transformer rated 5000kVA (115kV/4.16kV) on the point of common coupling (PCC) with the grid along with another transformer XFM1 rated 150kVA (4.16kV/0.48kV). Load and line parameters are considered as given by standard IEEE data with time step variations as explained in the following Section. The test system is modelled in OpenDSS in interfacing with MATLAB, and the one-line diagram is shown in Figure 6 for reference. The Remote Terminal Units (RTUs) are interfaced at each node to monitor the nodal voltage status at each time step.

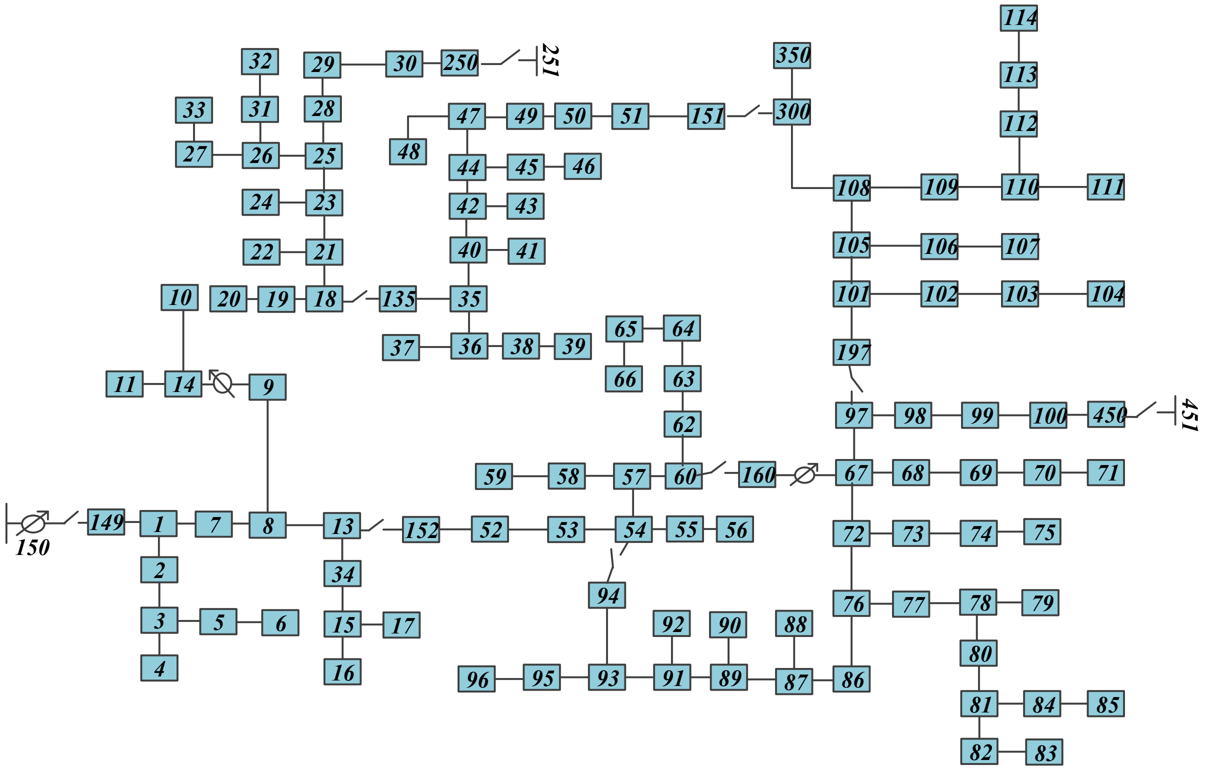

Figure 6: Standard IEEE-123 bus Feeder with 123 buses, 7 OLTCs, 4 voltage regulators

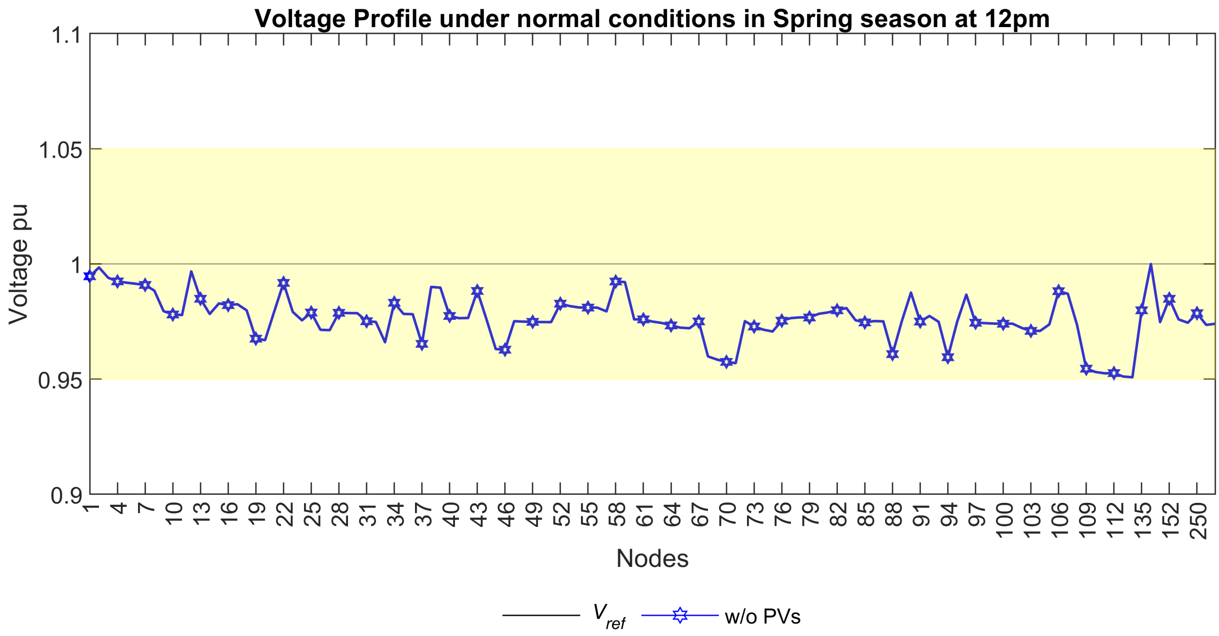

Figure 7: The voltage profile of all the nodes under normal operational conditions at 12 PM.

The voltage profile of a normal operational test system for the 12 PM of a normal spring day per unit (PU) is shown in Figure 7. The highlighted band shows the maximum and minimum range of allowable voltage levels for nodes as per the IEEE standard of renewable integration. Whereas V_{ref} shows the ideal operational voltage level. It is evident that under a normal operational state, all the system nodal voltages lie within the safe range as defined by IEEE standards.

4.2 PV Modelling

The Photo Voltaic distributed generation units are modelled by applying Beta distribution over the real-time data of several years. Seasonal solar irradiance variations and ambient temperature are incorporated for more realistic modelling. The entire year is divided into four seasons with a span of three months each, i.e. Spring season extends from March to May, the Summer season spans over the period of June to August, the Autumn season constitutes of September to November, and the period of December to February corresponds to Winter season. Therefore the real-time data of solar irradiance and ambient temperature for seventeen years is stochastically modelled through beta distribution to obtain the seasonal dispatch curves shown in Figure 8 for PV generators.

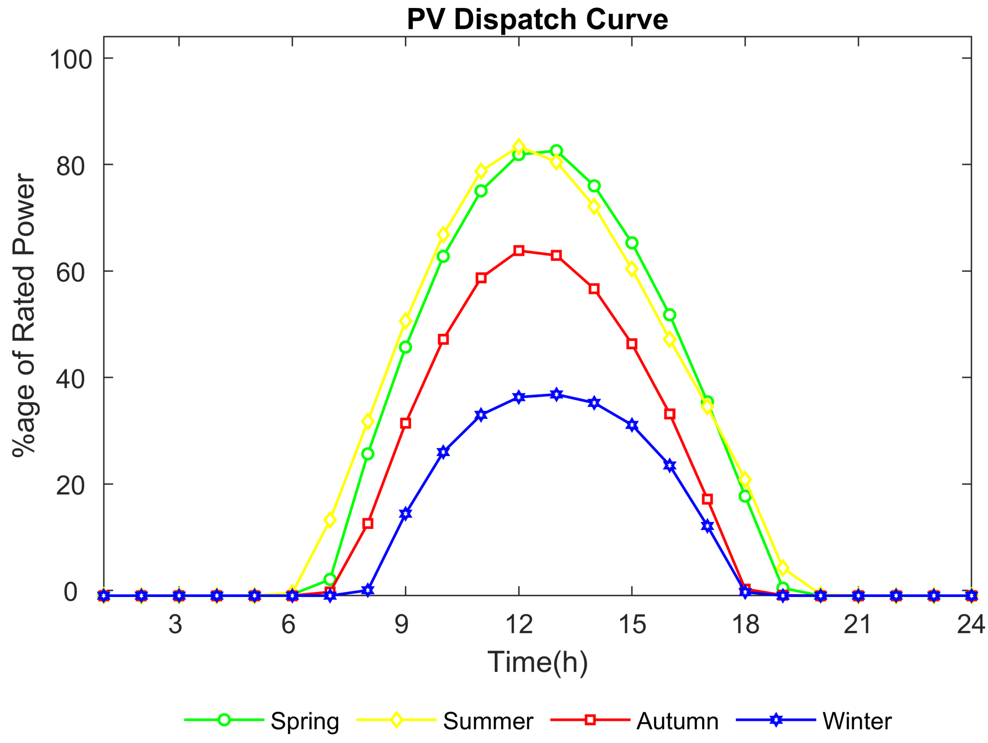

Figure 8: PV Dispatch Curves for all four seasons.

It can be seen from the dispatch curves that PV generation units are active for only the span of daytime when the solar irradiance is non zero and gradually reduces to zero with the sunset. The specifications for the parameters used for PV panel output power estimation as well as the number of panels required as per the power rating of distributed generation units are given in Table 1.

Table 1: Specifications of PV panel parameters used for the modelling of PV generators.

Name	**KV Rating**	**KW Rating**	**Phases**
Open Circuit Voltage	V_O	21.98	V
Short Circuit Current	I_S	5.32	A
Maximum Power Point Voltage	V_{mp}	17.32	V
Maximum Power Point Current	I_{mp}	4.76	A

Voltage Temperature Coefficient	K_V	14.4	$mV/^{o}C$
Current Temperature Coefficient	K_I	1.22	$mA/^{o}C$
Nominal Operating Temperature	T_n	43	^{o}C
Peak Power Output	P_P	75	W
Rated Power	P_r	kW Rating	kW
No. of PV Panels	N_{PV}	P_r/P_P	-

4.3 Load Modelling

Loads are modelled according to the standard IEEE-123 system load data, and the demand curves are stochastically modelled for incorporating the continuously varying nature of demand patterns. The demand curves of loads with seasonal variations are shown in Figure 9 on an hourly basis. Then simulations are done by providing these dispatch curves to the loads in MATLAB and OpenDSS.

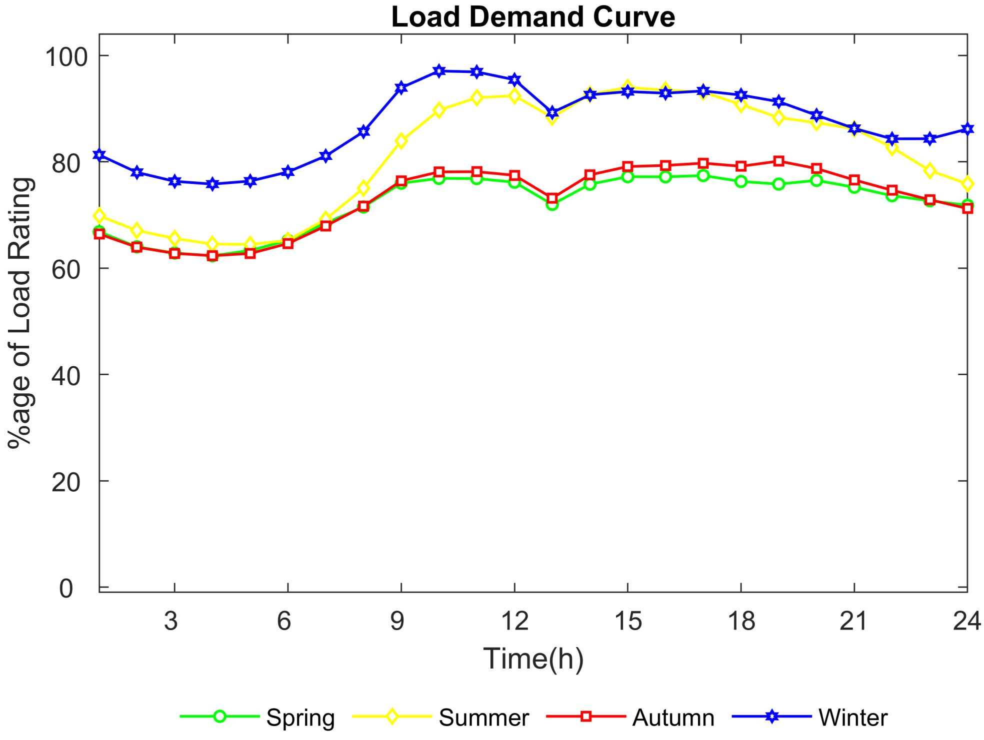

Figure 9: Load Dispatch Curves for four seasons.

4.4 PVs integration

Six PV units with variable generation capacity are integrated into the test system at randomly selected placement locations to validate the proposed scheme. The detailed specifications of PV units along with placement details are displayed in Table 2.

Table 2:Generation capacity and placement locations of distributed PV units.

Name	**Bus**	**KW Rating**
PV-1	23	600
PV-2	47	500
PV-3	54	700
PV-4	72	650
PV-5	87	550
PV-6	105	450

For clarity, the placement of PV systems is displayed in one line diagram of the test system as shown in Figure 10.

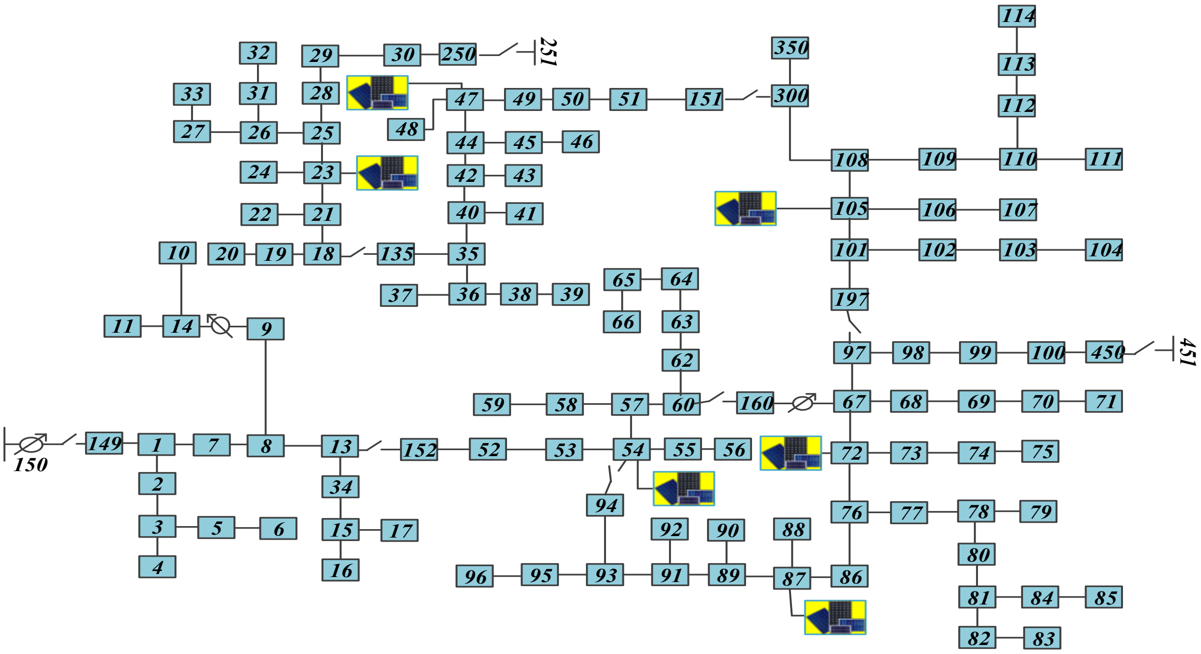

Figure 10: Standard IEEE-123 bus Feeder with PVs integrated on several buses

Some assumptions regarding the modelling of the network are,

- The power network must be balanced.
- It is a centralized approach so complex communication infrastructure should be present in the power network.
- There might be some nodes on the far end of the point of common coupling that cannot be fully optimized So, the system must not be very large.

4.5 Voltage Rise Issue

Once the integrated PV units start injecting power into the distribution network, the voltage profile of the system varies depending upon the amount of active and reactive power injections of active DGs. The resulting status of bus voltages for 2 PM of an ordinary spring day as recorded by RTUs is shown in Figure 11 along with the highlighted patch showing the safe band of operational voltages.

It is evident from the results that the power injections of integrated PV units disturbed the nodal voltages at their host nodes, and the rise propagates to neighbouring nodes also. The impact is so significant at some nodes that their voltage exceeds the maximum limit of the safe band ±5%.

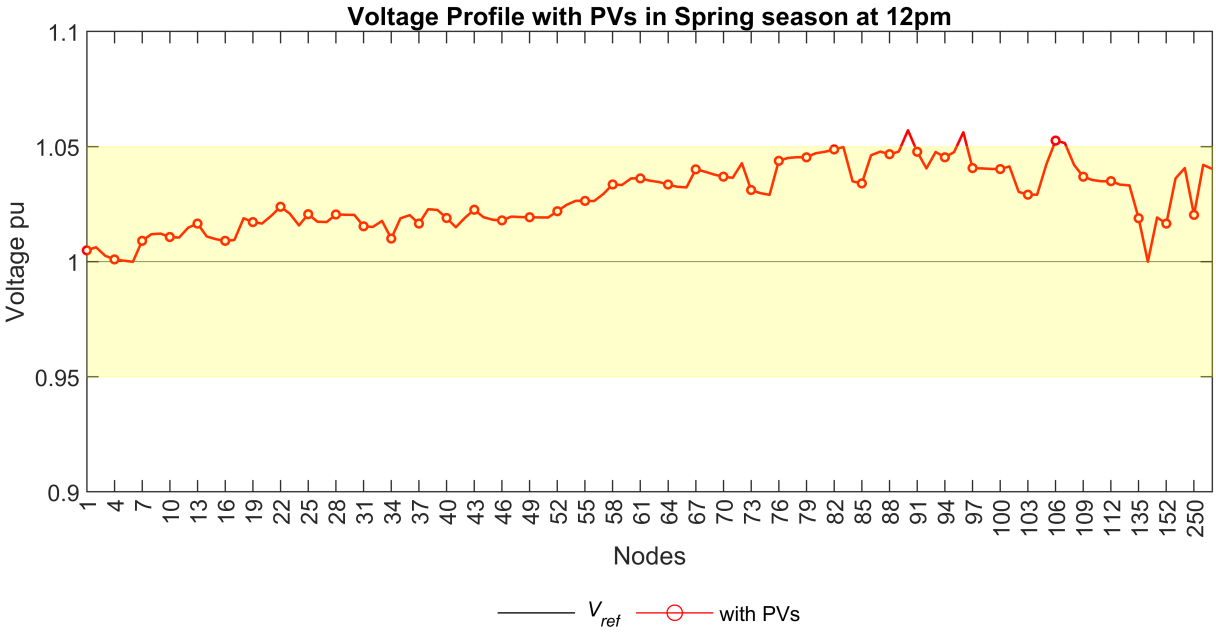

Figure 11: The voltage profile of all the RTUs in case of PVs penetration at 12PM.

4.6 Volt/VAR Optimization-based Voltage Regulation

The over-voltage issue explained in the previous Section resulting from power injections of excessive interfacing of distributed generation units is eliminated by applying the proposed coordinated Volt/VAR regulation technique described in Section 3.4. The RTU measurements of nodal voltages are communicated to the master controller, which evaluates the optimal VAR generation or absorption levels for PV inverters to minimize the voltage rise issue and make bus voltages as close as possible to V_{ref} through evolutionary algorithm-based optimization. Six numbers of PVs are integrated with the system at each phase. The total number of variables for all the three phases of Differential Evolution is 18. A simple criterion for the initialization of the population is given in Eq. 1.

$$Population\ size = 5 * No.\ of\ \ variables \qquad 1$$

Therefore, for 18 variables total population size is 90 and the size of QP is 90×18. The mutation value ω is taken as 1 because it is assumed as an integer problem. Because kVARs range is vast and if it is taken as a non-integer problem, convergence will take a considerable time. The value of CR is not fixed. It is taken as the inverse function of the quality of the new generation. The quality of the new generation is based on the loss function ζ .

The optimization problem terminates at meeting one of the criteria defined in Section 3.5.4 and the resulting population of VAR levels are assigned to PV generators. Thus the reactive absorption mode of PV inverters reduces the nodal voltages to ensure that the safe operating voltage limits are maintained without any potential cut down of active power output of PVs. The resulting nodal voltage status of the test feeder for the same time step is shown in Fig. Figure 12 with evident optimization of bus voltage levels. All PVs act as agents to coordinate with each other to achieve an optimized voltage profile for the whole feeder. The VAR states of the previous time step are fed to the next time step optimization stage as the initial population resumes the optimization from where it terminated for the previous time step.

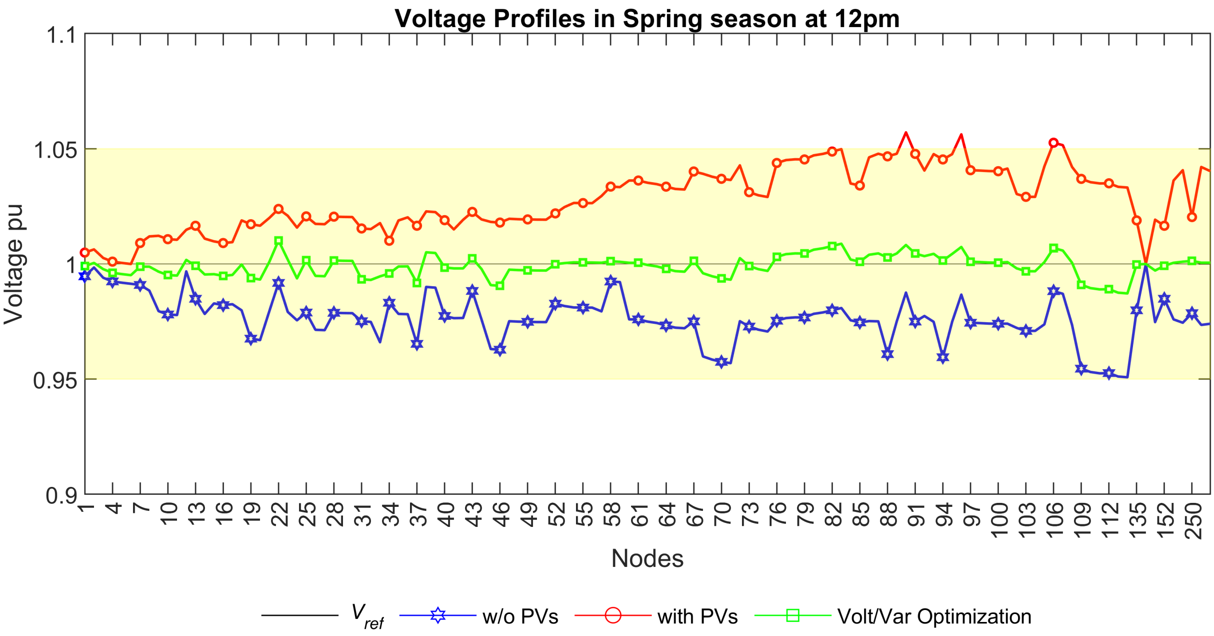

Figure 12: Voltage profile of the complete system at 12 PM of a normal day of the spring season in all scenarios i.e Voltage profile in the absence of DGs, Voltage profile after installing PVs, and improved voltage profile after the optimization through Volt/Var method.

Some other results are attached below to show the robustness of our proposed technique.

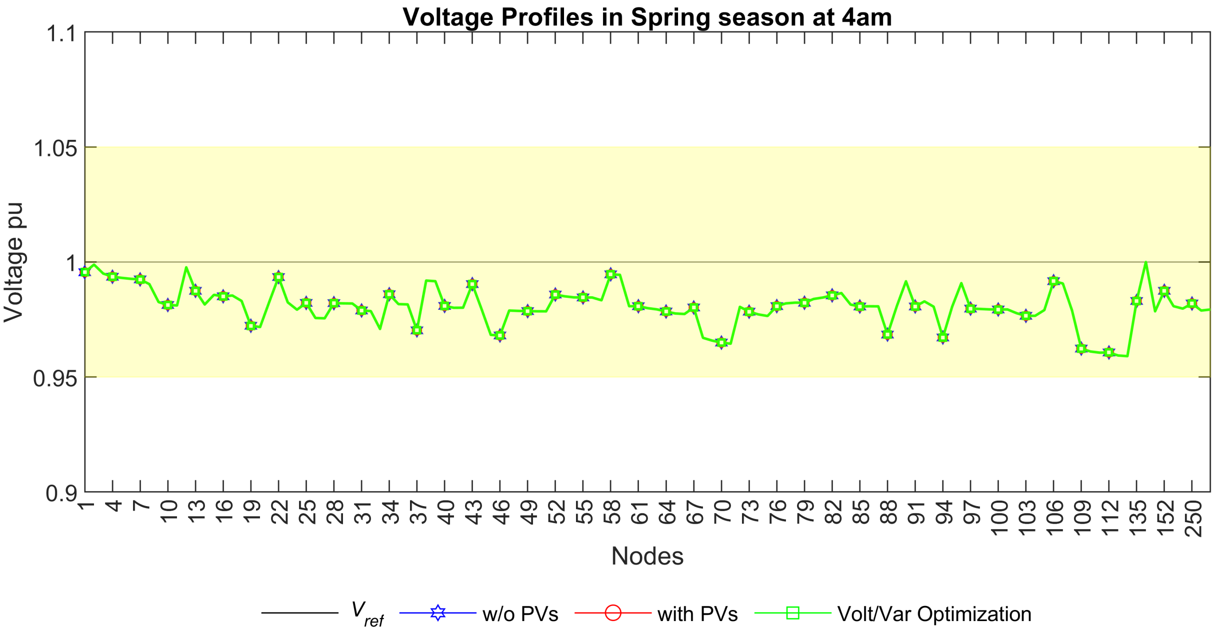

Figure 13: Voltage profile of the complete system at 4 AM of a normal day of the spring season in all scenarios i.e Voltage profile in the absence of DGs, Voltage profile after installing PVs, and improved voltage profile after the optimization through Volt/Var method.

Voltage profile of the complete system at 8 AM of a normal day of the spring season for all scenarios i.e in the absence of DGs, after installing PVs, and after the optimization through Volt/Var method shown in Figure 14. It can be seen that the most optimal voltage profile is shown in green colour.

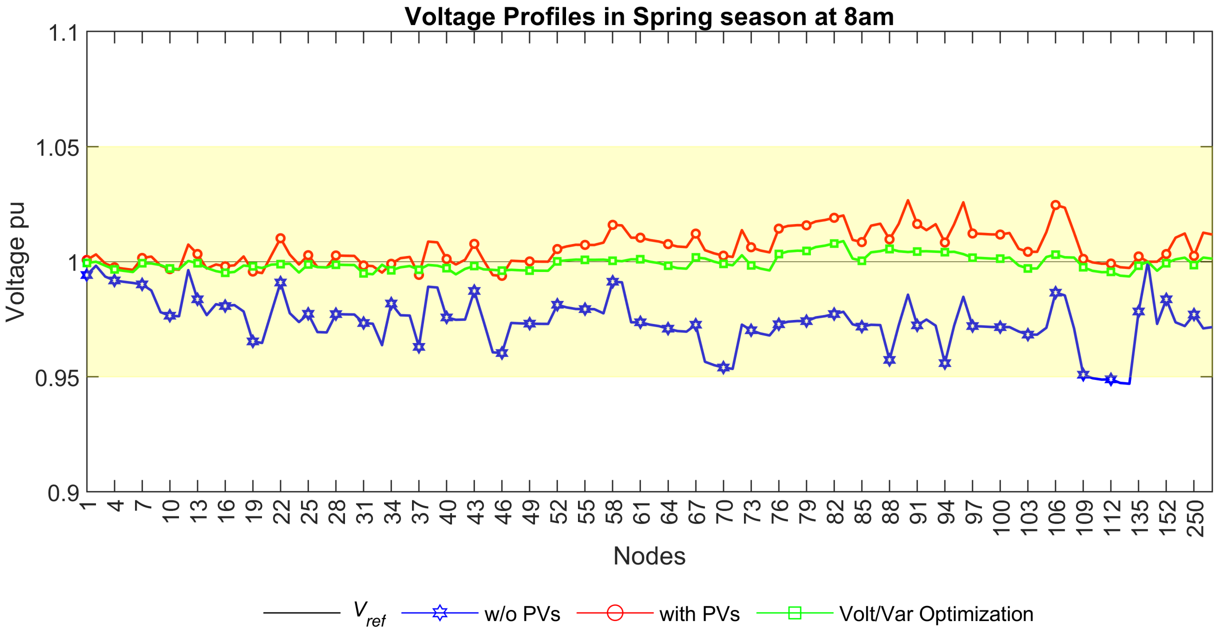

Figure 14: Voltage profile of the complete system at 8 AM of a normal day of the spring season in all scenarios i.e Voltage profile in the absence of DGs, Voltage profile after installing PVs, and improved voltage profile after the optimization through Volt/Var method

Voltage profile of the complete system at 4 PM of a normal day of the spring season for all scenarios i.e in the absence of DGs, after installing PVs, and after the optimization through Volt/VAR method shown in Figure 15. It can be seen that the most optimal voltage profile is shown in green colour

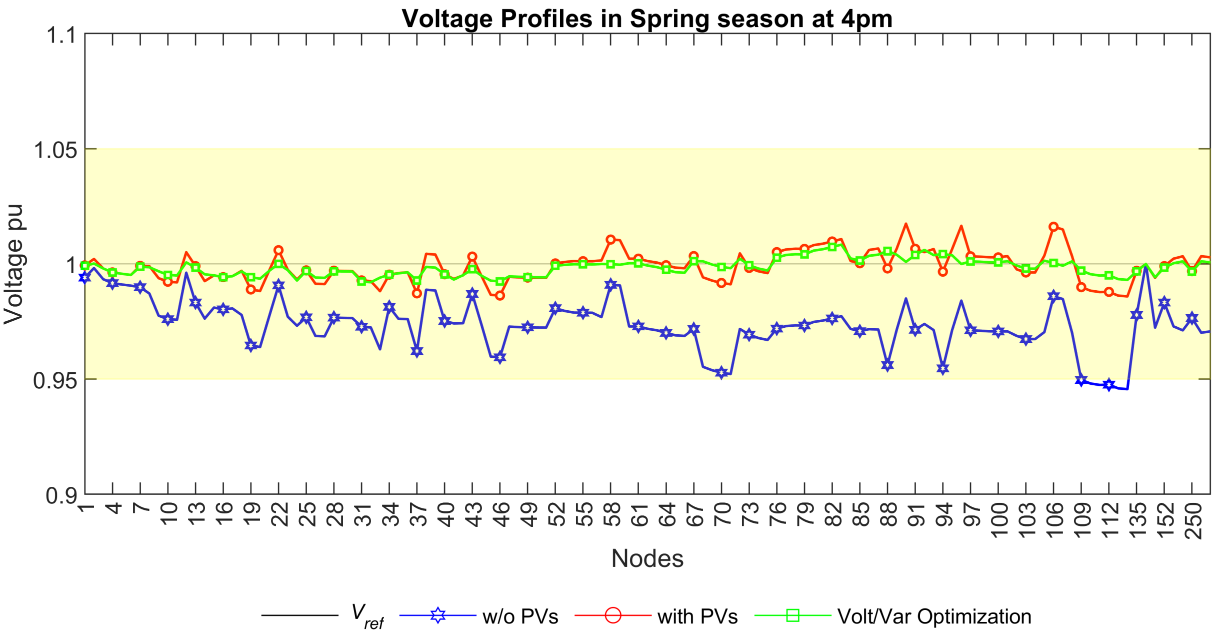

Figure 15: Voltage profile of the complete system at 4 PM of a normal day of the spring season in all scenarios i.e Voltage profile in the absence of DGs, Voltage profile after installing PVs, and improved voltage profile after the optimization through Volt/Var method.

Voltage profile of the complete system at 8 PM of a normal day of the spring season for all scenarios i.e in the absence of DGs, after installing PVs, and after the optimization through the Volt/VAR method shown in Figure 16Figure 15. It can be seen that all the curves are the same because PV Generator is not actively working at this hour. That is why PV is not disturbing the voltage profile and in the off state, it also can not improve the voltage profile as it also does not provide positive or negative VARs.

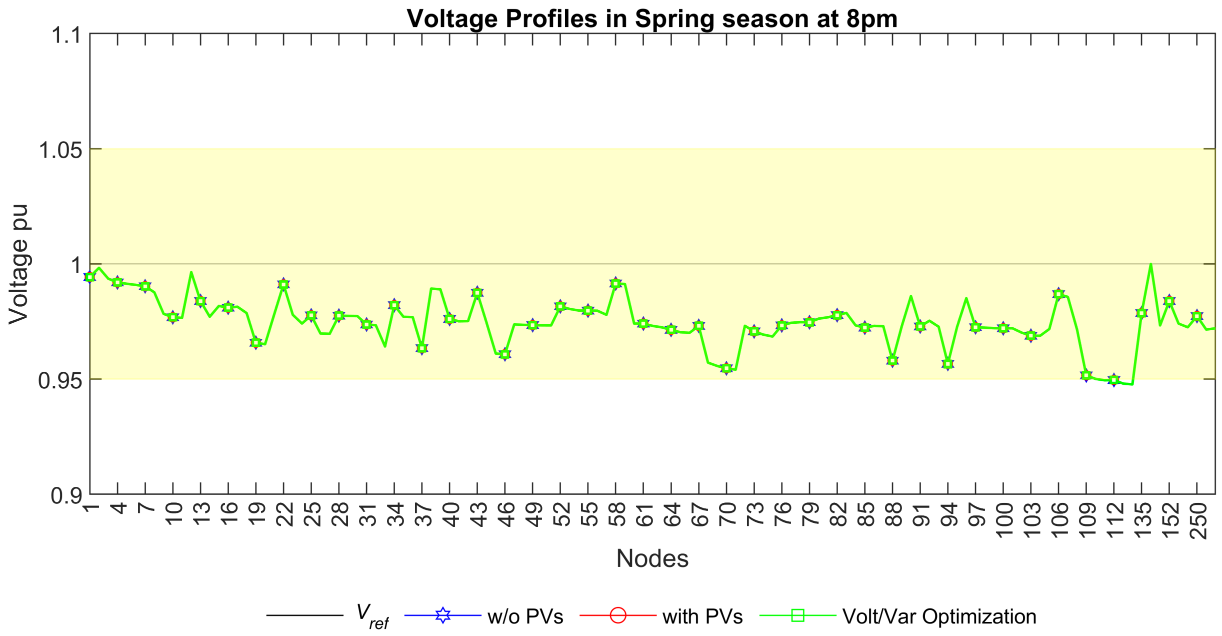

Figure 16: Voltage profile of the complete system at 8 PM of a normal day of the spring season in all scenarios i.e Voltage profile in the absence of DGs, Voltage profile after installing PVs, and improved voltage profile after the optimization through Volt/Var method.

4.7 Convergence

There were three stopping criteria defined earlier i.e. the maximum number of generations, the loss is not decreasing anymore, and loss is not significantly changing after i iterations. Figure 17 shows how the loss of the complete voltage profile converges to a minimum from their initial operating points with ongoing time steps.

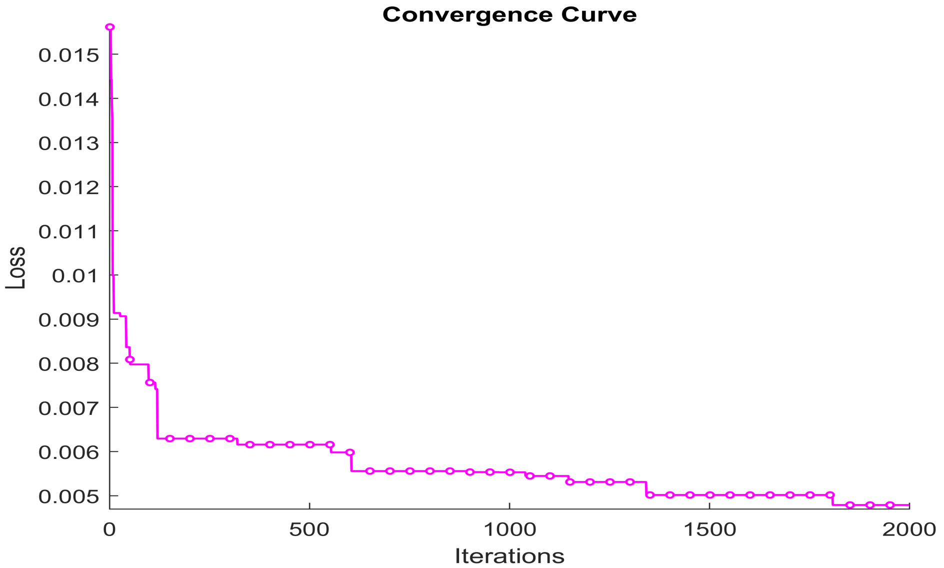

Figure 17: Convergence Curve for the maximum number of iterations.

4.8 Host Node/DG Node Voltage Variation

The DGs are installed on some specific nodes stated in Table 2. The voltage variation of the nodes hosting DGs is shown in the figures below.

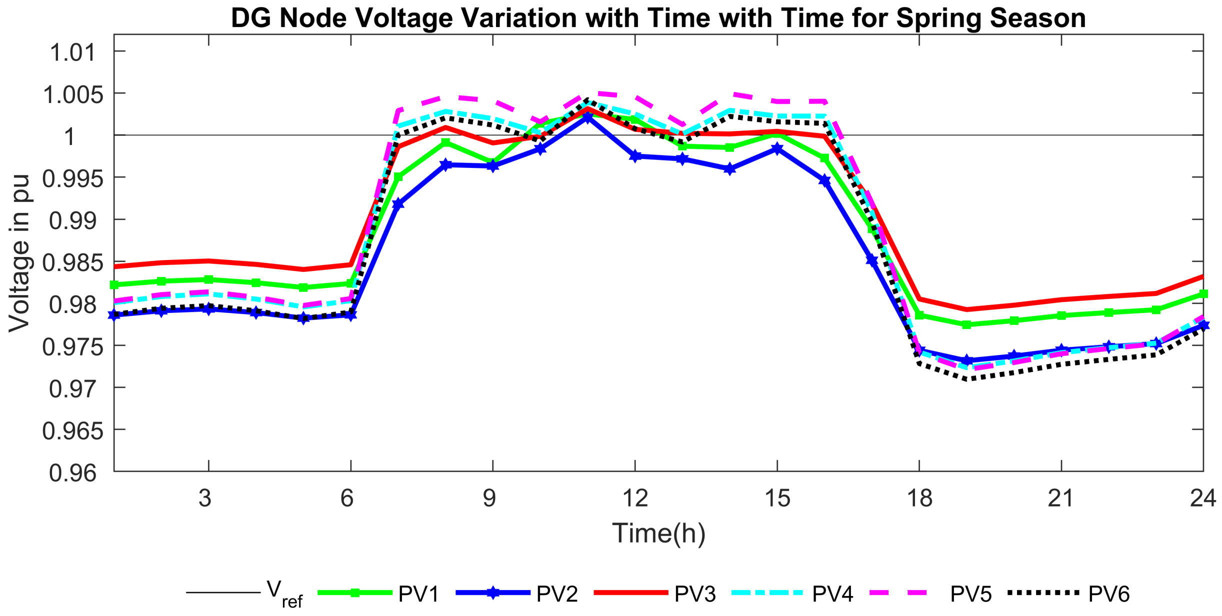

Figure 18: The voltage variation of all the hosting nodes for a complete spring day.

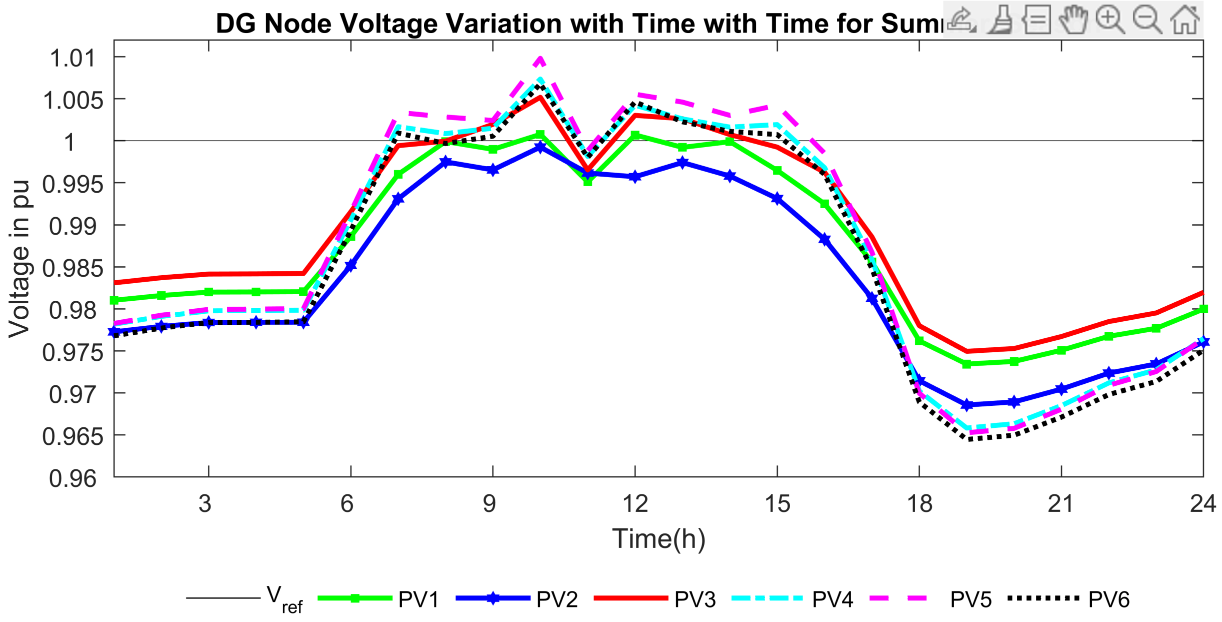

Figure 19: The voltage variation of all the hosting nodes for a complete summer day.

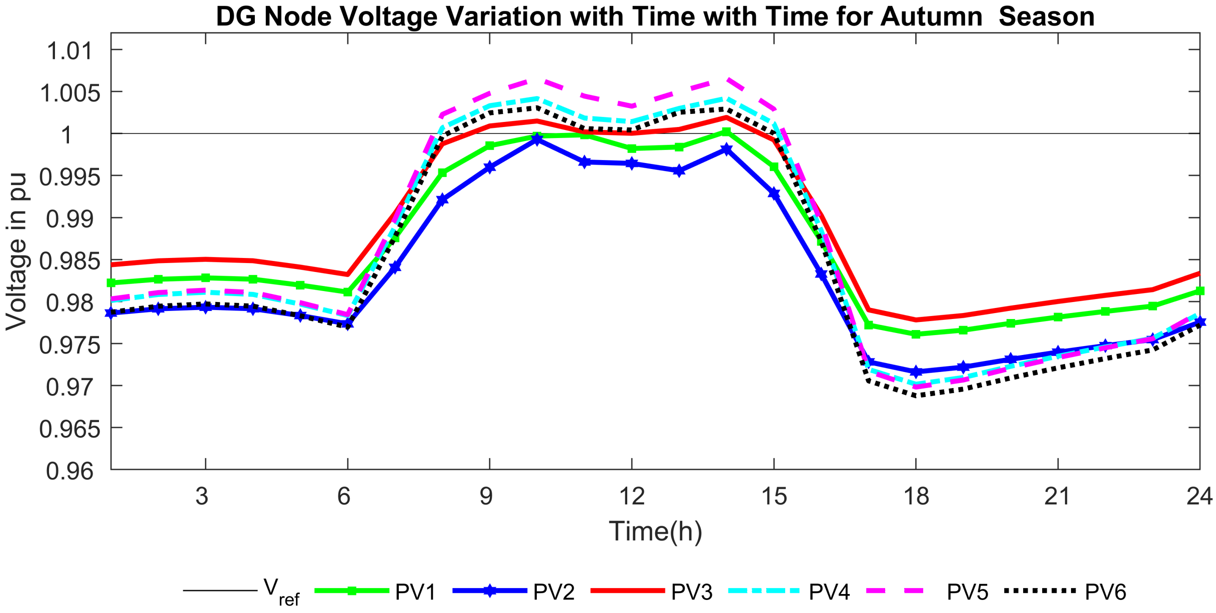

Figure 20: The voltage variation of all the hosting nodes for a complete Autumn day.

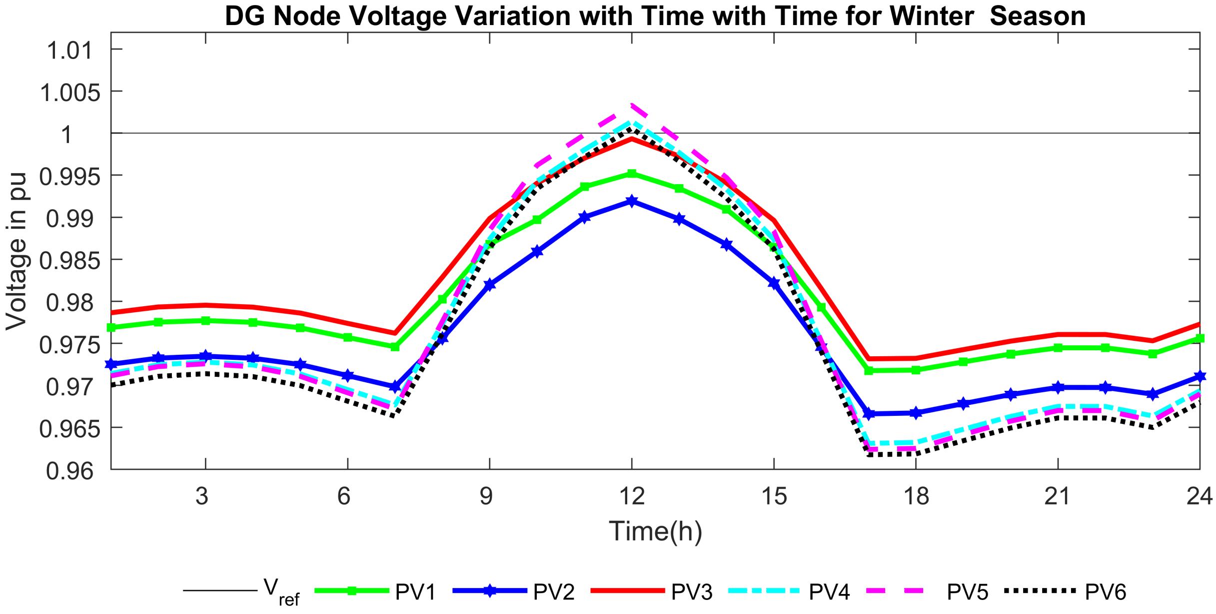

Figure 21: The voltage variation of all the hosting nodes for a complete winter day.

The reactive power variation of all the hosting nodes are shown below.

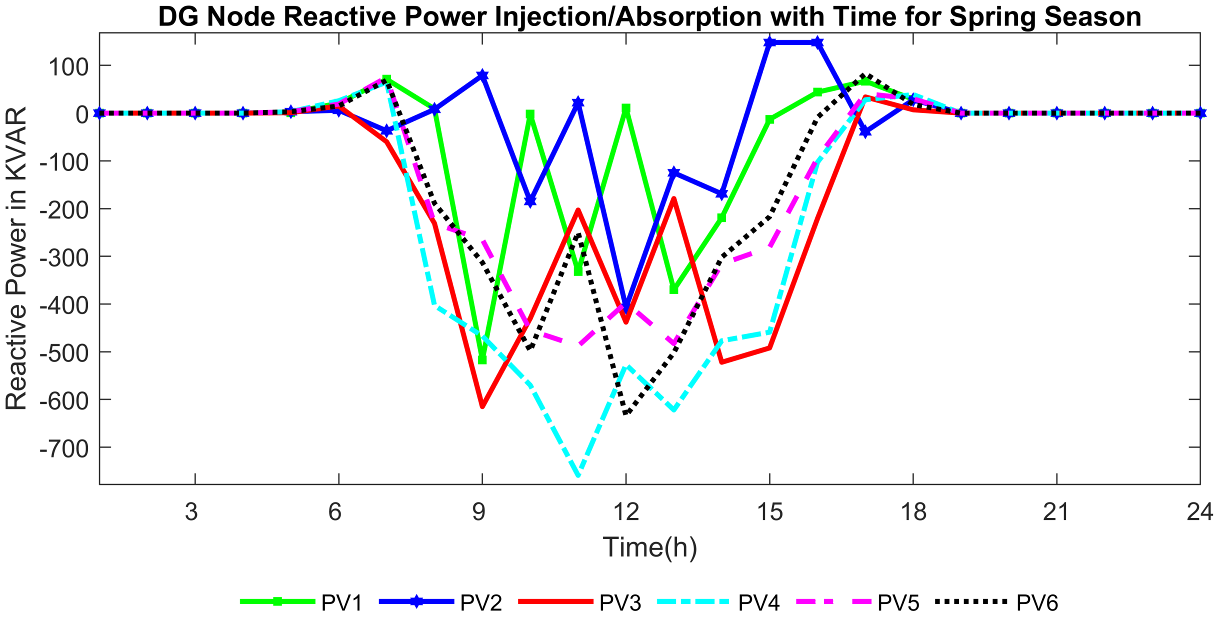

Figure 22: Reactive power variation of all the hosting nodes throughout a normal spring day.

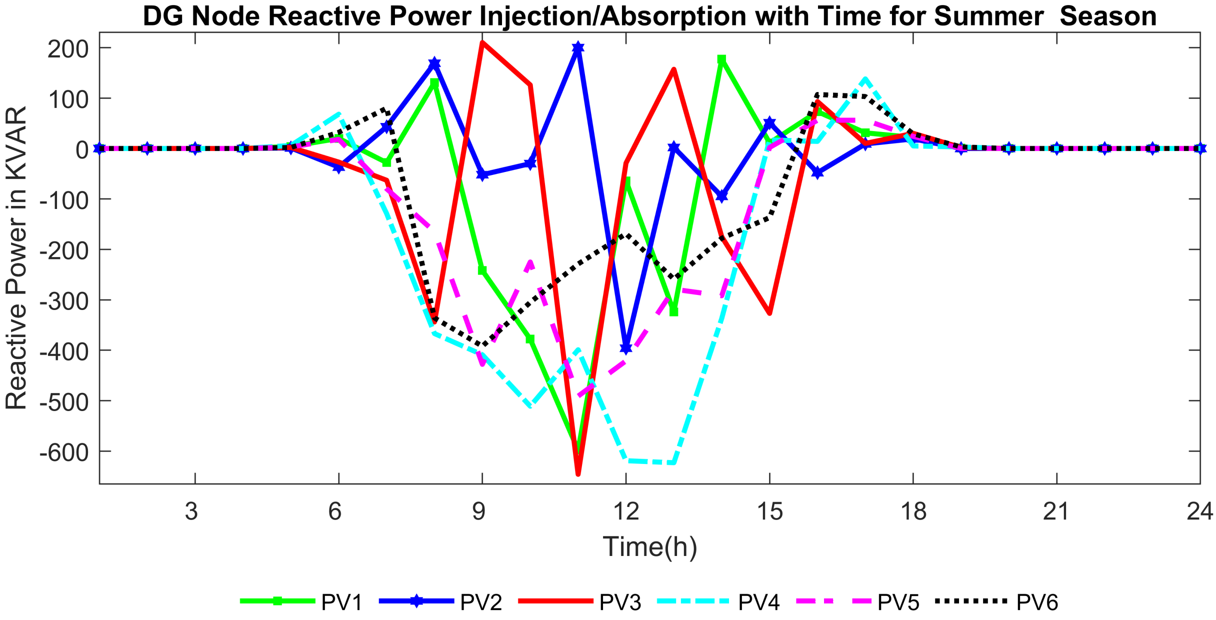

Figure 23: Reactive power variation of all the hosting nodes throughout a normal summer day.

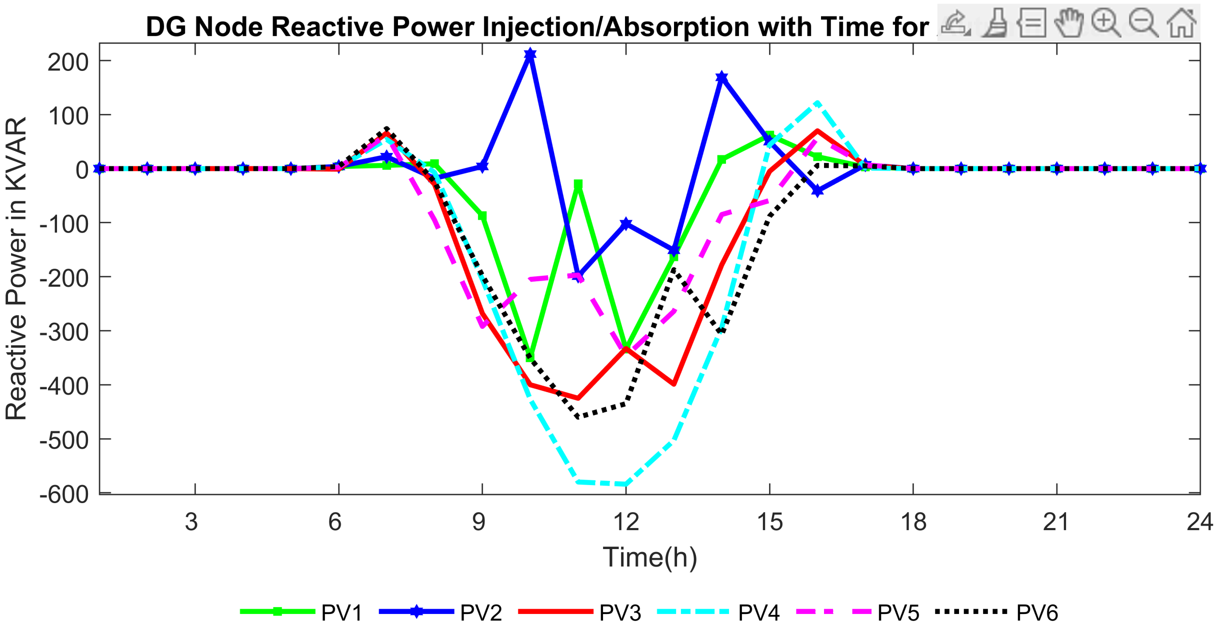

Figure 24: Reactive power variation of all the hosting nodes throughout a normal autumn day.

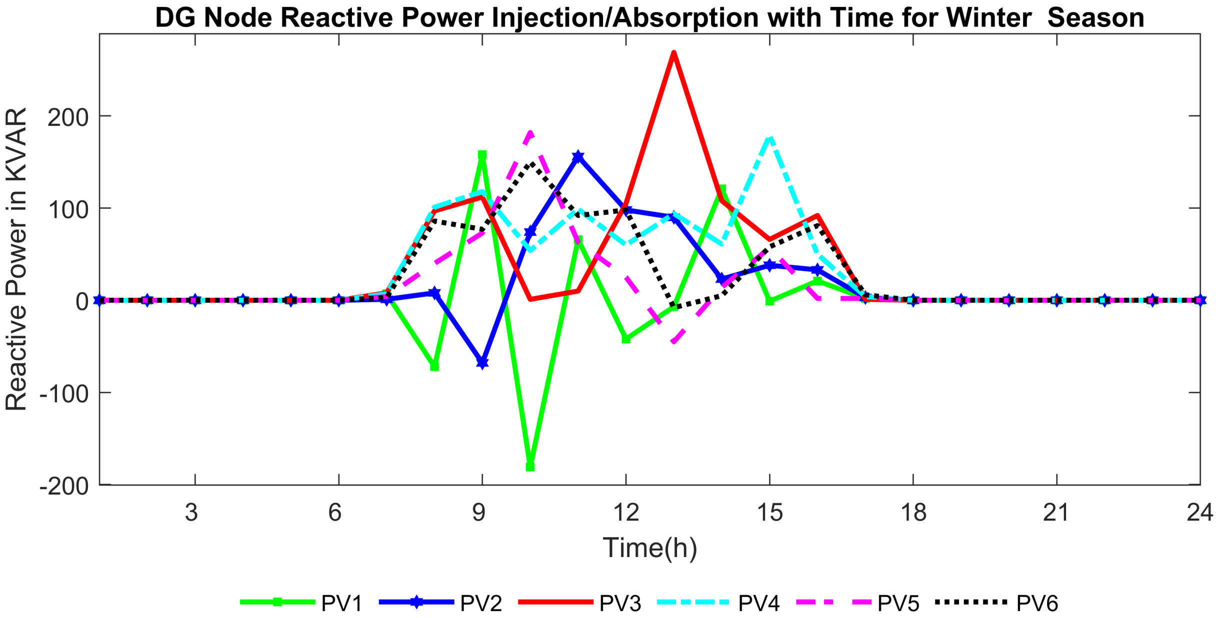

Figure 25: Reactive power variation of all the hosting nodes throughout a normal winter day.

4.9 The efficiency of the Voltage Profile

The efficiency of the proposed Volt/VAR approach is calculated for the voltage profile in terms of how much closer a nodal voltage is to the ideal voltage. So, we can write it as,

$$\eta = 1 - \zeta \qquad 2$$

Where ζ is the loss function.

The results prove that the reactive power readjustments have brought back the standard operating voltages of all system nodes and eliminated the voltage disturbance caused by power injection of distributed generation units. All the distributed units are gradually readjusted to such operational points that their power injections no longer create over-voltages at any node, thus presenting a stable integrated operation with the grid. Hence, the effectiveness of the proposed volt/var regulation scheme is proved by simulation results.

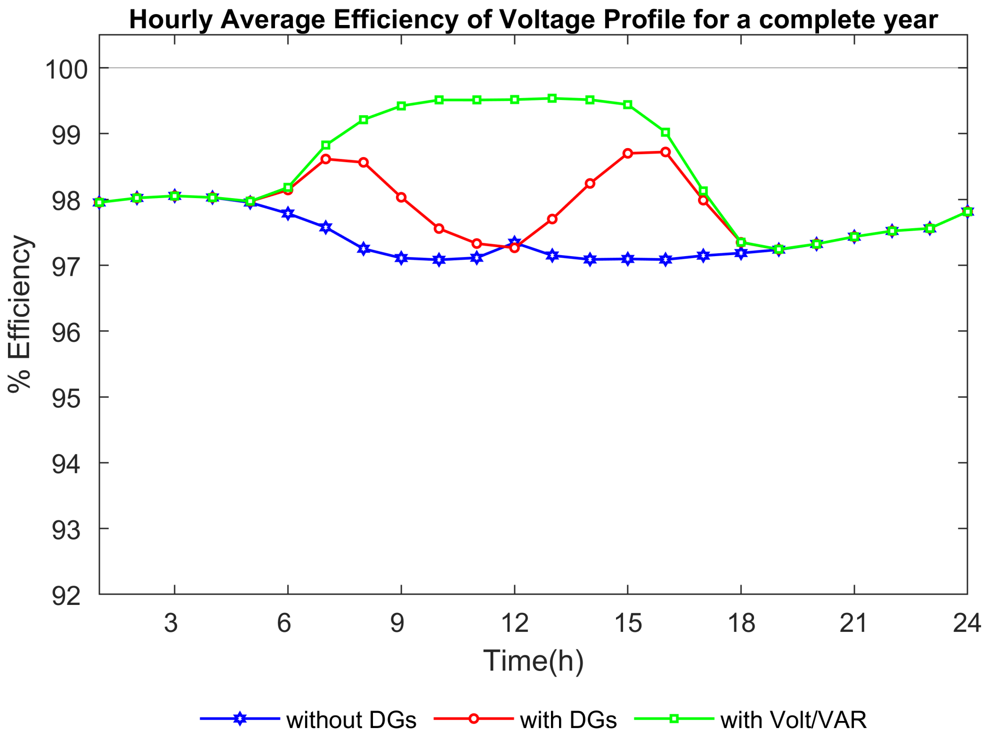

Figure 26: Hourly average efficiency of voltage profile curves for a complete year including all four seasons in case of normal operations, with the penetration of DGs, and with the Volt/VAR optimization through Differential Evolution

5 Chapter 5: Discussion

In Figure 7 the voltage profile under normal conditions is plotted and the safe band is shown in the green patch. The voltages of all the RTUs are in the safe range of±5%. Then multiple DGs are installed as described in Table 2. The new graph of the complete voltage profile is displayed in Figure 11. The disturbance in the voltage profile can be clearly seen as some of the voltages go beyond the safe zone. The proposed Volt/VAR technique is applied and then then the new updated voltage profile of all the RTUs is displayed in Figure 12 in which it can be clearly seen that the voltage profile of all the nodes is in the safe range and even better than the voltage profile of the normal conditions. Multiple results under different time hours of the different seasons are displayed in Figure 13, Figure 14, Figure 15, and Figure 16, to prove the robustness of the proposed strategy. All the figures show that the proposed Volt/VAR scheme does not fail in any conditions.

Table 3: Hourly average voltage quality factor of the voltage profile for a complete year including all four seasons for VQFN(Voltage Quality Factor in case of Normal conditions), VQFN (Voltage Quality Factor in case of PV Penetration), VQFN (Voltage Quality Factor in case of Volt/VAR)

Time	**VQFN**	**VQFPP**	**VQFV**	**Time**	**VQFn**	**VQFPP**	**VQFVV**
1:00 AM	97.95%	97.95%	97.95%	1:00 PM	97.15%	98.38%	99.59%
2:00 AM	98.02%	98.02%	98.02%	2:00 PM	97.09%	98.76%	99.55%
3:00 AM	98.05%	98.05%	98.05%	3:00 PM	97.1%	98.92%	99.41%
4:00 AM	98.03%	98.03%	98.03%	4:00 PM	97.09%	98.615	98.88%
5:00 AM	97.95%	97.97%	97.97%	5:00 PM	97.15%	97.88%	97.96%
6:00 AM	97.79%	98.09%	98.12%	6:00 PM	97.19%	97.31%	97.31%
7:00 AM	97.58%	98.59%	98.8%	7:00 PM	97.24%	97.24%	97.24%
8:00 AM	97.25%	98.81%	99.24%	8:00 PM	97.32%	97.32%	97.32%
9:00 AM	97.11%	98.61%	99.42%	9:00 PM	97.43%	97.43%	97.43%
10:00 AM	97.08%	98.24%	99.52%	10:00 PM	97.52%	97.52%	97.52%
11:00 AM	97.11%	98.04%	99.54%	11:00 PM	97.56%	97.56%	97.56%
12:00 PM	97.34%	98%	99.61%	12:00 AM	97.82%	97.82%	97.82%

To show more effectiveness of the proposed scheme the average Voltage Quality Factor (VQF) of all the seasons is displayed in Table 3 hourly fashion. It can be clearly observed that from 7 PM to 4 AM no solar energy is available so, PVs are practically inactive. So for those particular time hours, PVs cannot disturb the voltage profile hence Volt/ VAR scheme does not come into action. For 5 AM and 6 PM, a very small amount of solar energy is available therefore PVs produced a very small amount of Watts and VARs. The amount of active and reactive power is so small that instead of disturbing the voltage profile PVs are improving it. The proposed Volt/VAR technique comes into action but the available window of VARs is so small that it could not improve the voltage profile further. Volt/ VAR strategy produced very good results for the remaining time hours as highlighted in green colour when solar energy is available and PVs are actively working.

6 Chapter 6: Conclusion

The integration of renewable energy units in distribution systems causes voltages to rise on both nodes of integration and some neighbouring nodes. This over-voltage situation violates the IEEE standard of renewable integration and must be addressed. The reactive power control of inverter interfaced distribution units is a very efficient remedy for the stated problem. The proposed scheme to optimally adjust the reactive power of photo-voltaic units according to the real-time scenario of the feeder voltage profile is proved to be a robust voltage regulation scheme. The proposed scheme effectively eradicates the voltage rise issues due to power injections at random nodes. Through simulations, we have shown that our proposed volt/VAR optimization technique through Differential Evolution can improve voltage profile and makes the power network more stable.

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