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MASTER THESIS

SUSTAINABLE ENERGY TECHNOLOGY

FAIR POWER FEED-IN ALGORITHMS FOR PV CURTAILMENT WITH GRID COMPLIANCE IN LV DISTRIBUTION GRID

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1. ABSTRACT

The modern LV distribution grid consists of prosumers who feed excess power back to the grid in addition to consumption of power. This additional feed-in of power causes power quality issues like over-voltages, voltage unbalances during low load and high PV generation conditions. As grid reinforcement techniques involve a lot of capital investment, power curtailment seems to be a cost-effective solution to control such over-voltages. Curtailment however creates an unfair opportunity for prosumers connected to the grid as the PV system of prosumer at the end of the feeder gets curtailed more. This necessitates research on fair PV curtailment strategies. In a practical case, the LV grid can have a mixture of multiple types of PV systems connected including single phase central inverters, three phase central inverters, micro-inverters. The assignment involves implementation and comparison of various PV curtailment algorithms for a practical grid scenario, while maintaining power quality, bringing in fairness and reducing the total energy curtailed during over-voltage situations in a low voltage distribution grid.

2. INTRODUCTION

This chapter introduces the aim of the thesis with a brief background about the topic, the problem statement and the research questions that will be answered in this work.

2.1. Background

The conventional AC grid infrastructure is primarily designed for centralized generation and a unidirectional flow of power from power station to consumers. The low voltage (LV) distribution grid consists of residential houses and other small scale enterprises who are passive consumers of electricity from the grid. Recently the emergence of renewable distributed energy resources (DER) like solar energy has led to new elements in the system like producer-consumers also called as prosumers. Prosumers not only consume energy from the utility grid but they also generate their own energy.

The modern LV grid can have prosumers who typically have a grid connected photovoltaic (PV) system which beyond their self-consumption at times also feed in excess energy to the grid. The additional feed-in of power may cause power quality issues like over-voltages, voltage unbalances especially during low load and high PV generation conditions [1,2]. High voltage rise during low load and high PV generation conditions can also cause reverse power flow. Such problems mainly occur in areas where there is a high penetration of prosumers.

However, it is the responsibility of the Distribution System Operator (DSO) to maintain the voltage rise within grid limitations. The DSO can establish measures to reduce over-voltages in the grid by means of grid reinforcement techniques. These techniques include using a transformer tap changer, increasing the conductor size and implementing energy storage systems [1,2]. In most cases it is not possible to regulate the voltage using a tap changer because most distribution transformers are equipped with off-load tap changers [2]. Further, increasing conductor size and energy storage systems involve a lot of capital investment. Control of voltage through reactive power is also not effective in a LV network due to its high R/X ratio and power factor [2]. In these circumstances, curtailment seems to be a cost-effective solution to control over-voltages. Curtailment involves reduction in the capacity of the DERs that are feeding power to the grid. In case of PV systems, inverter controls are used to reduce the active power fed back to the grid and to regulate voltage levels. However, the curtailment methods have some drawbacks of unfair curtailment, as different PV systems connected to the grid experience different scale of curtailment. For effective implementation of curtailment strategies, an algorithm that ensures fairness in curtailment among PV owners and simultaneously reduces the total power curtailed is required.

2.2. Problem Statement

Although PV curtailment is effective in controlling over-voltages, it creates an unfair situation among prosumers connected to the grid. For instance, during times when the supply is higher than the demand, the PV system of the prosumer at the farthest end of the feeder is curtailed more often than the one near to the transformer as the farthest prosumer experiences the highest voltage rise. The loss of PV generation fed to the grid leads to loss of money for the PV owner. Note that in some cases, the prosumers get financially compensated by the DSO for their lost energy due to curtailment. Although adequate financial compensation can solve the problem in short-term, the method cannot be sustained over years as the number of prosumer keeps increasing. Hence, financial compensation is not a long term sustainable solution to the problem. There is thus a need for a technical solution so that DSOs can create an equal opportunity for PV feed-in to the grid instead of using financial compensation. This necessitates research on fair PV curtailment algorithms. Further to investigate their practical capabilities, the curtailment algorithms should be implemented and tested for a practical grid scenario. In a concrete case, the grid can have a mixture of multiple types of PV systems connected to the grid including single phase central inverters, three phase central inverters and micro-inverters. Also the developed algorithms need to be tested for the worst case low load and high generation conditions and the fairness is to be maintained based on size of the given PV installation. So a common practical scenario is required for a more reliable testing of these PV curtailment algorithms in their ability to avoid exceeding grid limitations and maintain fairness among PV installation owners. The control algorithms also need to be stable especially during PV generation fluctuations due to clouds.

2.3. Research Question

With the goal to find a solution to the defined problem, the current work focuses on implementing and testing PV curtailment algorithms for a practical low voltage grid scenario and at the same time ensuring fairness and compliance to grid code. The answers to the following research questions will provide an effective solution to the problem:

How can a heterogeneous set of PV inverters be controlled to curtail power in a fair way while respecting grid limitations?

To answer this research question, the following sub-questions are considered:

- How should fairness be defined?
- What is a realistic scenario with different types of PV inverters and which problems are expected in such scenarios?
- Which control algorithms can tackle these problems in an effective and fair manner?
- How and which trade-offs can be made between minimizing energy curtailment and maximizing fairness among PV owners?

2.4. Scope

The main scope of the work lays in the PV curtailment strategies for grid compliance in a low voltage distribution grid. The focus is only on domestic household level PV systems and loads in the LV distribution network. The assignment involves the implementation and comparison of various PV curtailment strategies for a practical grid scenario, maintaining power quality and bringing in fairness during curtailment in a low voltage distribution network. This work adds value to algorithms towards a fair PV curtailment strategy in a practical grid scenario. A heterogeneous set of PV systems and inverters is considered for the implementation and testing of the algorithms during low load, high PV conditions and their ability to control in a way that the grid parameters stay within their limits. Although this work is focused on only small scale PV systems in LV grid, it can effectively be extended to larger scale or other type of DERs that are connected to the distribution grid.

The thesis is organized as follows. Chapter 3 gives a summary of literature on grid structures, grid standards, PV curtailment algorithms and case studies. Chapter 4 is focused on the modeling of a LV of grid and components including feeders, PV systems and houses. Chapter 5 presents various scenarios that can occur in the grid based on various combinations of components and the problems that can occur in those scenarios. The working of four PV curtailment algorithms is considered in Chapter 6. In Chapter 7, the scenarios discussed in Chapter 5 are simulated with various curtailment algorithms from Chapter 6. A comparison of the results achieved by various algorithms is discussed for each scenario. Further, Chapter 8 includes a summary of the discussed algorithms and answers to the research questions as a conclusion. The thesis ends in Chapter 9 with some recommendations for future works.

3. LITERATURE SURVEY

The aim of the literature survey is to study various PV curtailment algorithms and their implementation. For this, it is also required to study LV grid models and scenarios to design a more practical scenario to test the algorithms. So the literature survey also focuses on the LV grid structure, the problems due to integration of PV in the grid and grid regulations for curtailment. Further, this section also presents a brief overview of case studies and field tests on PV curtailment that have been performed in various countries.

3.1.LV grid structure

A typical European LV feeder is a radially connected three phase distribution system with a MV/LV transformer feeding the loads at line voltage of 400V [3,4]. In Europe, most country-side and sub-urban localities are equipped with 160 kVA, 250 kVA or 400 kVA transformers respectively [5]. Also according to [6], more than 2/3rd of the distribution transformers in EU have a capacity below 400kVA with most of them typically of 250 kVA. [7] implemented a grid model for testing of strategies for PV storage systems which includes a 160 kVA transformer feeding houses through 150 mm^2 cables and 50 mm^2 cables for house connections. The feeder cables and house connection cables had an impedance of 0.206+j0.091 and 0.641+j0.085 ohm/km respectively. The grid model presented in [8] consists of feeder lines of cross section area 70mm^2 and 54 mm^2 for neutral lines. The houses are connected to the grid using 10mm^2 cables. Also according to the European Commission report on DSOs [9], most MV/LV transformers are installed with a capacity of 250 or 400 kVA and 400 or 630 kVA in rural and urban areas respectively. The underground LV feeders typically have an ampacity of 255 A of resistance 0.39+j0.075 ohm/km.

3.2.PV panels and inverters

PV systems have become an easy and widely used option for consumers who wants to generate their own energy and become prosumers. A typical grid connected PV system consists of multiple PV panels, an inverter, a smart meter and cables that connect the system to the grid. Unlike standalone PV systems that require a battery to store excess generated energy, the grid connected PV systems manage excess/lack of energy by a bidirectional flow of power to and from the AC grid.

A string inverter configuration consists of multiple PV modules connected in series to a central single phase or three phase PV inverter. As a complete failure/shading of one module in a string would open circuit the entire string, nowadays PV modules come with bypass diodes that could help to solve this problem [10]. Larger PV systems might require a three phase PV system to distribute energy over all the phases.

A micro-inverter technology consists of a small inverter per PV module which are finally coupled together. This technology has become more popular due to its increases energy harvesting capacity, reliability and superior performance during shading compared to a string inverter [11].

3.3.Grid regulations for curtailment

The EN50160 standard [12] defines European voltage characteristics of electricity supply. The frequency of supply has to be maintained within 0.5Hz variation measured on a mean of 10 second intervals. The voltage levels at the customer end should not exceed 1.1pu for more than 10 minutes and strictly not more than 1.15pu [2,13].

Due to the penetration of DERs like PV systems, new standards like IEEE 1547-2018 [14], which govern the requirements and specifications for DERs connecting to the grid are introduced. Under this standard, the point of common coupling (PCC) is taken as a reference for measurements. All DERs must be able to respond to external signals and cease operation (or trip) in no more than 2 seconds. The DERs should disconnect from the grid within 0.16 seconds if the voltage at their PCC is equal to or greater than 1.2 pu. The DERs must also be capable of reducing their active power to the required percentage of their nominal power in 30 seconds. The DERs must be capable of voltage regulation through reactive power management.

3.4.PV curtailment algorithms

Apart from the grid components, an implementation of a PV curtailment strategy requires additional hardware and software. According to [15], the 5 key elements required to implement a curtailment strategy in a network are:

- Device functionality (PV inverter controller),
- Communication protocol for communication between grid operator and end device,

- Communication network infrastructure,
- Management system (either human or PLC controlled),
- Interconnection agreement between the customer and operator.

In a practical case of a MV/LV transformer feeding a bus with multiple feeders connected to houses (prosumers), the maximum over-voltage occurs at the farthest end of the feeder. So during times when the supply is higher than the demand, the PV system of the prosumer at the farthest end of the feeder is curtailed more often than the one near to the transformer [1,2]. This type of PV curtailment although is effective in controlling over-voltages, it creates an unfair opportunity for prosumers connected to the grid. Many studies discuss fair algorithms for PV curtailment in LV networks. From literature, PV curtailment algorithms can be broadly classified as seen in the classification diagram in Figure 1.

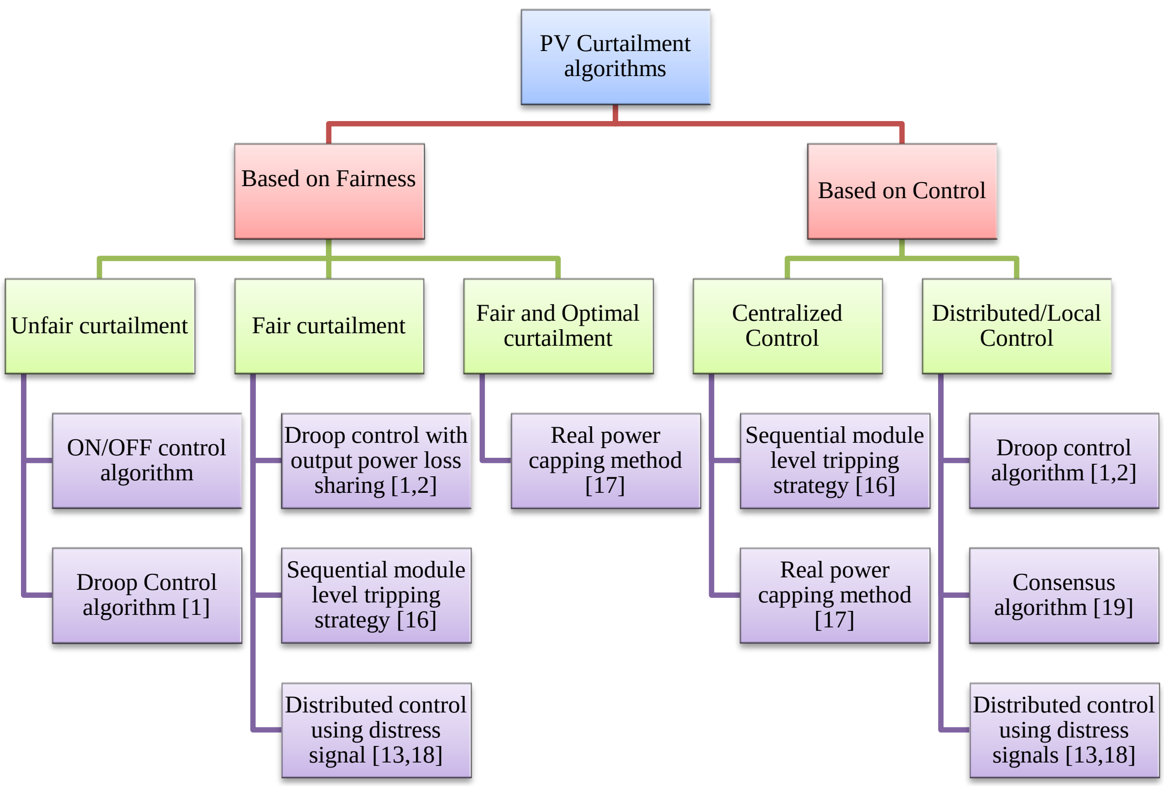

Figure 1: Classification of PV curtailment algorithms from literature

3.4.1. Conventional curtailment algorithms

The most common and practically used algorithm for PV curtailment is the droop control algorithm [1]. This algorithm is the simplest and requires the least modification to the existing system and at the same time is effective for voltage control. The droop control algorithm involves the use of a droop coefficient that can reduce the amount of active power fed to the grid from the highest possible maximum power produced by the MPPT (Maximum Power Point Tracking) system. Though being a conventional algorithm, a lot of researches focus on add-ons to this algorithm to bring in fairness and optimization.

In [1], two approaches of droop control are discussed. One, in which all the PV inverters connected to a bus have the same droop coefficient, and the other case in which the PV inverters have different coefficients so as to share the total active power curtailed. A different droop coefficient is calculated based on the voltage at the bus without curtailment. In all cases the voltage operation limits are strictly maintained. It was also seen that the total power curtailed is higher when curtailment has to be shared equally. In [2], a droop control curtailment strategy is presented, which uses a variable droop coefficients based on the voltage sensitivity and it can also bring a fair curtailment among PV owners [2].

3.4.2. Inverter type specific curtailment algorithms

PV curtailment algorithms can also be specifically designed to control specific type of PV inverters, for example micro inverters. Nowadays micro-inverters are being widely used due to their increased efficiency in extracting energy and their independent operation. These features over-power the string inverters which have the problems of MPPT due to local shading and series failure due to failure of one module. If all the PV modules have an independent micro-inverter, then each inverter can be seen as an independent grid connected PV system allowing a wide range of curtailment options. [16] implemented a sequential module level tripping algorithm for voltage control. In some cases the DSO can also choose between priorities like economics, strict voltage levels, prioritizing renewables, feeder output, curtailment execution time etc. The algorithm in [16] works on a trip time delay and the sequence of tripping of micro-inverters. In the Branch trip delay (BD) scheme, only a branch level tripping sequence is implemented and the same sequence is repeated in all branches connected to the bus. Since all micro-inverters are connected only to one phase of the three phase distribution system, the trip sequence is rotated by phase on different branches to avoid voltage unbalance between phases. This scheme gives a faster voltage reduction response but involves a lot of PV power curtailed. In the Branch and bus trip delay (BBD) scheme, none of the inverters connected to a bus trips simultaneously. This algorithm involves less energy curtailed but at the same time the voltage reduction rate is slow compared to the BD scheme.

3.4.3. Fair and optimal curtailment algorithms

A real power capping method (RPCM) which aims for not only a fair curtailment algorithm, but also an optimal curtailment strategy, such that the total PV power curtailed is reduced is discussed in [17]. Previous works such as [1] on fair algorithms also shows more total power being curtailed when implementing fair algorithms compared to unfair strategies. The fair and optimal curtailment algorithm works on adaptive optimal power dispatch based on the predicted values of irradiance and load. The strategy makes use of a penalty weighting factor for each PV system connected to the network. Any changes in the predicted curtailment values compared to the real time values are adjusted by penalty weighting factors. The weighting factors are proportional to the accumulated PV power curtailed. This algorithm consists of a central controller that generates optimal generation signals and sends it to the local controllers or inverters that act on curtailment of PV power. The central controller calculates the generation limits for each PV system and sends it to the local controllers. The local inverters then decide on how much power needs to be curtailed. This algorithm retains fairness over a given time period (eg. a week) and not during every time instant of curtailment. The results show that the total power curtailed with this algorithm is less than other unfair and fair curtailment algorithms.

3.4.4. Distributed control algorithms

A distributed control scheme that makes use of reactive power management and active power curtailment to prevent over-voltages in the grid is discussed in [18]. The algorithm does not require any communication between inverters but requires them to be connected to send and receive distress signals (eg. radio, PLCC – Power Line Carrier Communication). The algorithm does not require any network model or any location of PV systems in the feeder. All inverters connected function in 5 modes of operation based on their local voltage and signals from other nodes. Any inverter that senses a local over-voltage sends a distress signal via the communication medium which is received by all inverters connected to the feeder. In normal mode of operation, the inverters keep active power at MPP (maximum power point) and the reactive power as a function of voltage at PCC. When a distress signal is received all PV inverters start to adjust reactive power to their maximum. If the distress signal still persists, then they switch to active power curtailment mode. If there is no further a distress signal until a reset time, then all the power returns to the normal mode of operation. By this way, all PV systems in the same feeder share losses and the same percentage of PV power curtailed except in rare cases of communication delays and failures. [13] implemented the same algorithm for a three phase distribution network. In a three phase network scenario, single phase PV inverters would be connected to any one of the 3 phases. So this algorithm would work parallelly in four groups – one for each phase and another for 3 phase PV inverters. An over-voltage in one phase and the resulting distress signal will affect inverters connected to the particular phase. Three phase inverters will respond or send distress to any phase that experiences an over-voltage. All inverters of the same group are always in the same mode of operation. The total power curtailed is more than the optimal power flow algorithm but less than the ON/OFF control strategy.

Further, a consensus based distributed control algorithm for optimization of droop parameters given in [19], works by communication between adjacent nodes. The utilization of PV system is the ratio of power injected to the grid to the MPPT power of the system. In this method, the utilization ratio of each PV system connected to the feeder is calculated. This value is communicated between adjacent nodes (inverters) in the network and a local optimization is done to make their utilization factors consistent with one another. In this algorithm, the data is shared only with adjacent nodes and not at a global scale.

3.4.5. Curtailment strategies involving storage systems

Works in literature also focus on using storage systems as a means of voltage regulation. [20] discussed a control strategy for distributed control of battery storages for voltage regulation in LV networks with high PV penetration. This is a combination of droop control and distributed consensus strategy which works on bringing in fairness in terms of installed capacity and state of charge (SoC) of batteries. Further, [21] presents a combined PV curtailment and energy storage system for voltage regulation in distribution network. In this work, the hybrid energy storage system (battery and capacitors) are used as a first means for voltage control. Whenever, the power handling limits of the energy storage system is reached, the PV curtailment strategy is used for control of voltage. This hybrid strategy finds a trade-off between the high price of energy storage systems and the energy loss due to curtailment.

3.4.6. Other curtailment algorithms

A neural network based active power curtailment algorithm for over-voltage prevention in LV network is discussed in [22]. This method involves the feedback of the voltage at the PCC to the neural network based predictive model that decides the amount of power to be curtailed from the maximum power. The predictive model needs to be pre-trained and tested using practically recorded values with a desired accuracy with respect to root mean squared error, mean relative error and correlation coefficient achieved.

3.5. Case Studies

This section explains scenarios of increased PV penetration in different countries and the measures that are taken in each of those cases.

3.5.1. Germany

Germany which is seen as a leader in PV integration to the grid implemented several measures to comply with voltage limits. The experiences of 10 German DSOs are summarized in [23]. Several measures including replacement of local distribution transformer, segmenting of grid, laying additional parallel cables, laying new cables with large cross section, voltage regulators, use of on-load tap changing transformers, wide area control by manipulating MV side voltage, reactive power feed in through PV inverters, changing grid topology temporarily, grid monitoring and feed-in management are implemented. Initially changing grid structure and wide area control were seen as the most economical measures. But due to further increase in penetration of PV costly measures like laying parallel cables and replacing local transformers also have to be carried out. Measures like curtailment of PV were only being tested in pilot phases until 2012, when as a part of feed-in management strategy remote controlled throttling of PV inverters was introduced to handle grid emergencies and congestions [24]. However, this later evolved as a curtailment strategy in 2017 when it was allowed to curtail PV power when required by the DSO as an alternative to other measures that requires grid expansion. The DSOs mandated prosumers <30kW to either accept a curtailment control agreement or permanently limit power feed to 70% of installed capacity. Hereby, the curtailment strategy is implemented as a unidirectional control signal from the DSO to the PV systems. Independent active power curtailment strategies, battery systems, and demand side control are tested as pilots in Germany.

3.5.2. Rest of the world

A lot other countries faced grid problems and power quality issues due to increased penetration of DERs and implemented their own measures to curtail them. [24] analyzed some case studies round the globe that implemented PV curtailment strategies, of which the curtailment strategy and the fairness agreement is of our interest. The cases of Hawaiian electric, grid operators in Japan, Germany, Arizona, Horizon Power and Energy Queensland in Australia are discussed. All of these case studies implemented either an ON/OFF control method which involves the entire system being shut down frequently or the droop control method which is an unfair strategy through the length of the feeder. However, most of these cases ruled that DER curtailment can be done only during grid emergencies and no compensation was given for curtailment. Grid operators in Japan are mandated to limit curtailment to 360 hours/year beyond which they need to provide compensation to customers. Energy Queensland Australia signed curtailment agreements with customers who apply for a grid tied PV system after the local network has reached its hosting capacity. However, the long-term aim for Energy Queensland is to maintain a hosting capacity such that the curtailment remains less than 10% of the installed PV capacity.

3.5.3. GridBox BKW Pilot project

The GridBox BKW Pilot [25] in Switzerland in 2016 can be seen as an example of testing DER curtailment in rural LV networks. GridBox Pilot consists of a distributed network of measurement devices that measure voltage and current at various locations in the grid which enables the DSO to control DERs by means of an optimal power flow (OPF) algorithm. The project successfully tested active power curtailment and reactive power management to bring down grid voltages to nominal values during high irradiance hours. The setup also used battery storages to absorb or inject active power to assist in voltage regulation. The ideal objectives of the implemented OPF algorithm include reduction of energy losses, PV active power curtailment, operation of capacitors and voltage regulators, eliminating voltage violations and reverse power flow [26]. The centralized OPF control is considered the most effective as it considers the power flow balance at each node. With the development of smart inverters, they can also absorb/inject reactive power on a limited capacity to regulate voltage. However, the active power curtailment is more effective to due to the highly resistive nature of LV network. The general OPF model aims for maximizing yield, minimizing loss and demand and also meets constraints of active-reactive power balance at each node, voltage bounds, reverse power flow constraints, and inverter capacity limits by controlling active and reactive power dispatch [27].

4. MODELING OF COMPONENTS

In order to implement and test the PV curtailment algorithms, a low voltage grid model with multiple houses and PV systems needs to be modeled. The LV grid has individual components like grid connected PV systems, houses/small enterprises, and the LV feeder. The specifications and characterization of the modeled LV grid based on data specifically focused on the Netherlands. The modeling of LV grid and its components are carried out in DEMKit (see Section 4.1).

4.1.Introduction to DEMKit

The Decentralized Energy Management toolKit (DEMKit) is a software developed at the University of Twente for research on smart grid technologies [28]. DEMKit is written in Python using a cyber-physical system approach which consists of abstract device models and optimization algorithms to model, implement and simulate solutions for smart grids. Basic devices like buffer, converter, time-shiftable, curtailable devices are available which can be used to model components of a grid like house loads, PV panel, batteries etc. DEMKit also consists of network components like feeders and transformers that can simulate a power system and apply load flow analysis.

Another important feature of DEMKit is the Artificial Load Profile Generator (ALPG) [28] that can create an energy usage profile of all sources and loads that can be a part of an energy system. It can generate profiles like PV output power, active power, reactive power, start time of time-shiftable devices, heat profile, battery usages etc.

4.2.Modeling of LV feeder

In the Netherlands, most low voltage networks are characterized by a three phase radial structure that connects a small group of houses to a three phase distribution transformer through underground cables [3]. In a distribution grid, the feeders transport power from the distribution transformer to the houses and follow the street layout. The feeder can have simple or multiple levels of branching and also can have short service line cables that connect the houses to the feeder.

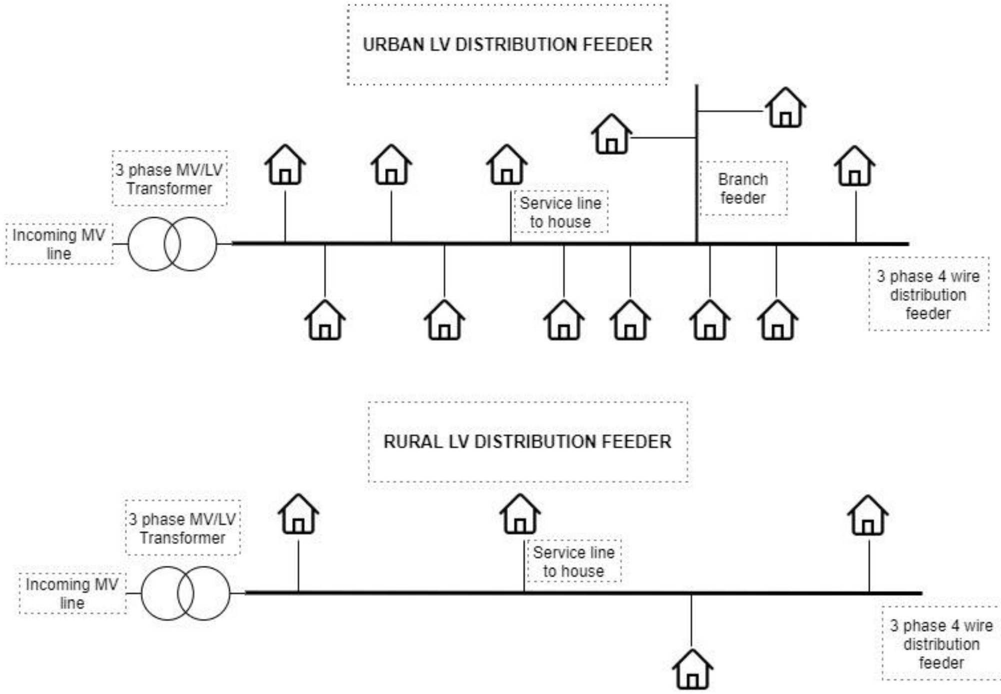

Figure 2: Urban and rural LV feeder models

4.2.1. Types of feeder

Based on the location and type of customers, low voltage feeders can be classified as:

- Urban LV distribution feeders,
- Rural LV distribution feeders.

Figure 2 shows typical urban and rural low voltage feeders in the Netherlands.

Urban feeders consist of multiple houses (nodes) connected close to each other [29]. The node density depends on the locality and type of houses. For example, localities with a lot of apartments can have a high density of nodes connected to the feeder. Usually urban feeders are short in length.

Rural feeders on the other hand are long and have a low density of houses [29]. The house connection cables can also be long compared to the urban cables.

4.2.2. Feeder parameters

In this section, typical feeder parameters like the length of feeder, transformer size, number of houses in a feeder, branching type, and cable type are investigated.

European feeders are supplied by small transformers typically 400 or 250 kVA [5]. Most feeders in the Netherlands are short in length <500 m except for the rural feeders which are longer in length due to sparse distribution of houses. More than 80% of the feeders have less than 50 customers [30]. Further, more than 90% of feeders have no branches or have a simple branching structure [31]. Aluminum cables with a cross section of 150mm^2 and 120mm^2 are mostly used for feeder cables and 70mm^2 or 35 mm^2 aluminum or copper cables are used for service lines to the houses. The frequency of occurrences of various parameters is shown in Figure 3.

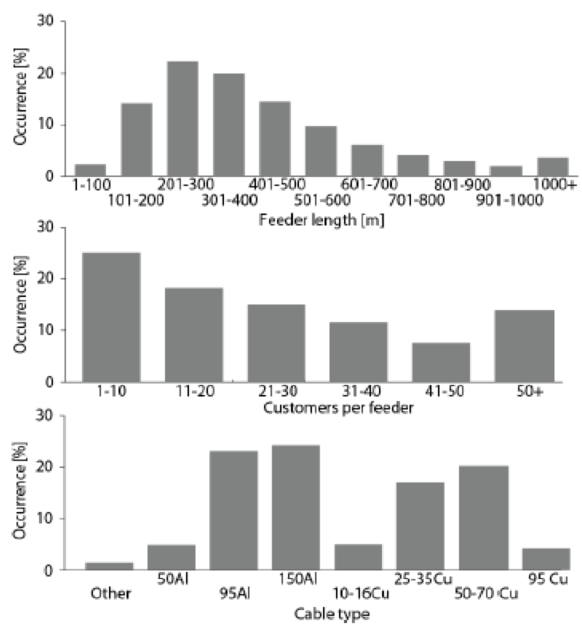

Figure 3: Occurrence of various grid parameters in LV grid in Netherlands [30]

4.2.3. Feeder model in DEMKit

A generic low voltage urban and rural feeder in the Netherlands is modeled in DEMKit based on the data given in Table 1. The length and number of houses in a feeder are based on [32] and further extended to a worst case future scenario. The typical cable impedances based on their cross section area is obtained from [31].

Table 1: LV urban and rural feeder parameters

Parameters	Urban feeder	Rural feeder
Feeder length	450 m	1200 m
Number of houses connected to the feeder	39	9
Distance between nodes/PCC of each house	5 m	130 m
Feeder cable characteristics	150 mm^2 Al cable of impedance (0.206+0.08j) Ω	120 mm^2 Al cable of impedance (0.253+0.08j) Ω
Service cable characteristics	70 mm^2 Al cable of length 5 m and impedance (0.443+0.07j) Ω	35 mm^2 Al cable of length 10 m and impedance (0.868+0.08j) Ω

A visual representation of a three phase rural feeder modeled in DEMKit is shown in Figure 4.

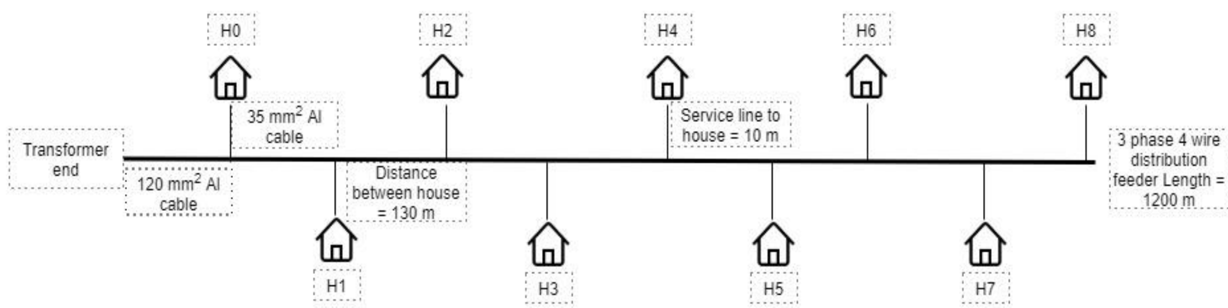

Figure 4: A model of a three phase rural feeder modeled in DEMKit

4.3.Modeling of PV systems

The PV system consists of multiple PV panels and inverters that connect to the low voltage feeder. Grid connected PV systems connect to the grid to feed in excess power with adequate protective equipment which comply with IEEE 1547-2018 standards [14]. These systems usually have a smart meter that can record power flow in both directions.

4.3.1. Types of PV systems

Houses can have various types of grid connected PV systems including:

- PV system with single phase central PV inverter

Single phase central inverter systems have only one node connection at one phase in the feeder to feed in all the PV power that needs to be fed to the grid. Sometimes it is also possible that the house can have a three phase load and a single phase PV inverter. In such a case, power flow in one of the phases is bidirectional and the other phases have a unidirectional power flow from grid to load.

- PV systems with three phase central PV inverter

Three phase PV inverter systems distribute the PV power generated to all the three phases in the feeder. Some inverters are only capable of feeding the same amount of power on all the three phases while some modern inverters can be controlled to feed in variable power to different phases depending on the grid conditions. For example, the commercial inverter described in [33], is capable of feeding a variable power of 0 to 1/3rd of the nominal capacity of the inverter on each phase independently. With such a system, there is a bidirectional power flow between the house and the grid in all the three phases.

- PV systems with multiple micro-inverters

Micro-inverter type PV systems consist of multiple independent small scale PV inverters connecting to the feeder. From a grid level perspective, this can be seen as multiple PV systems connected to various nodes in the feeder but belong to the same house/PV owner.

4.3.2. PV systems model in DEMKit

The three types of PV systems are modeled in DEMKit. The size and orientation of the PV systems is obtained from the ALPG data for PV systems. Each PV system consists of PV panels, inverter, a control algorithm and a grid connection through a smart meter. A detailed diagram of each type of PV system and how they connect to the grid is shown in Figure 5.

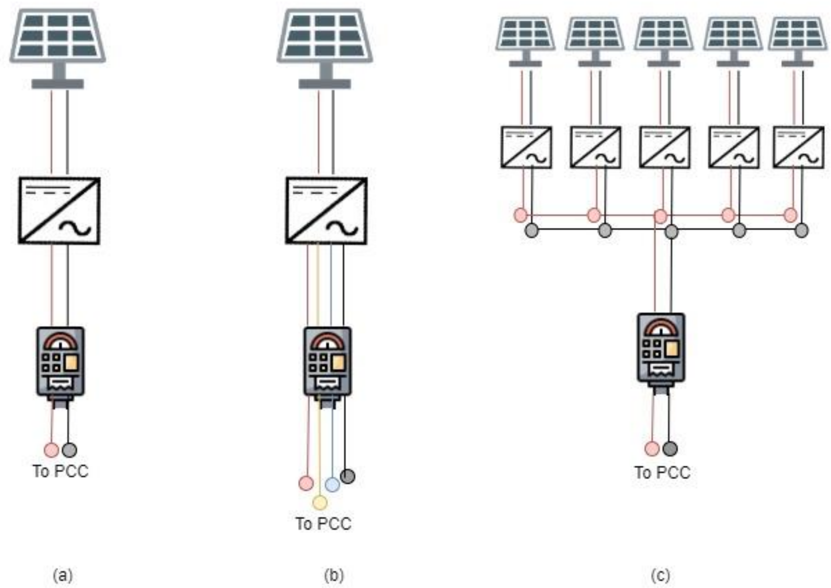

Figure 5: Connection of various PV systems a) PV system with single phase central PV inverter, b) PV systems with three phase central PV inverter, c) PV systems with multiple micro-inverters

4.4. Modeling of Houses

Houses (or prosumers) in a grid consist of components like base-loads, time-shiftable loads and PV systems that are connected to the distribution grid. DEMKit creates a house model based on these components with customizable specifications. The modeling of houses was carried out based on the type of household connected to the grid.

4.4.1. Types of houses

Rural and urban areas can have different types of houses. Urban localities may have a lot of apartments and semi-detached houses. Rural areas are most likely to have many detached houses. The housing type not only affects the energy consumption of the house but also the roof area. The type of house also determines the scale of PV system connected to the grid [29]. Table 2 shows the roof areas and the corresponding PV system capacities for various types of houses.

Table 2: Roof areas of different types of houses [29]

House type	**Roof area**	**Max PV capacity at 20% efficiency**
Detached house	20-25 m^2	5 kW
Semi-detached house	15-18 m^2	3.6 kW
Terraced house	10-15 m^2	3 kW
Apartment	2-5 m^2	1 kW

4.4.2. Loading conditions in a house

Loading conditions of a house can vary based on the various parameters like the number of people, type of appliances and user behavior. A no-load condition represents a situation where all electrical appliances in the house are switched off. A base-load condition is a situation where limited basic appliances like lights, electric kettle or heater, computers etc. are used. In a full load condition, the house is fully occupied by people who simultaneously use different appliances and time shiftable loads like washing machine, electric cars are connected switched on.

4.4.3. House model in DEMKit

The house model in DEMKit is considered to be a single phase PV system (not necessarily) and base-load that can be connected to any one or multiple phases of the three phase distribution system. The scenarios are simulated for a no load case to visualize the effect of control algorithms clearly. Further, some scenarios are simulated with base-load conditions to simulate the practically occurring scenarios.

5. MODELING OF SCENARIOS IN DEMKIT

A combination of an LV feeder, houses with PV system, and load profile forms a scenario. By considering various combinations of number of houses, length of feeder, type of PV system, type of load, connection of houses to phases, and type of cables used, many scenarios of a low voltage feeder can be modeled.

5.1. Scenario categorization and modeling

To analyze various problems that can occur in a low voltage grid with high PV penetration, several possible scenarios are created using various combinations of individual components. The scenarios can be categorized based on the following characteristics.

- The type of feeder
  - Rural feeder
  - Urban feeder
- Type of PV systems in houses
  - Only single phase PV systems
  - Only three phase PV systems
  - Mixture of various types of PV systems
- Load conditions
  - Full load conditions
  - Base load conditions
  - No load conditions
- Position and direction of PV panels
  - South (S) facing panels
  - East/West (E/W) facing panels
- Cable type, length and impedance
  - Lengthy/short cables
  - Impedance based on cable type
- Distribution of houses (loads and PV systems) over various phases
  - Balanced distribution over phases
  - Unbalanced/random distribution

5.2. Scenario simulation and analysis of problems

In this section, various scenarios are modeled and simulated in DEMKit. For each scenario, the grid violations that occur and the influence of various parameters are analyzed.

5.2.1. Scenario 1

Scenario 1 represents a lengthy rural feeder with 9 houses consisting of various types of PV systems connected to different phases of a three phase feeder.

This scenario is designed to show the over-voltages and difference in voltage at each node. Further, all houses in the feeder have the same PV capacity, azimuth angle, altitude angle and efficiency of PV system. So, this scenario can be used to verify the working of the algorithms under various challenging conditions. Complete information about this scenario is given in Table 3 and Figure 6.

Table 3: Scenario 1 description

Parameters	**Information**
Type of feeder	1200 m rural feeder with houses spaced 130m apart
Type of PV systems	Mixture of various types of PV systems with an area of 24 m^2 and an efficiency of 20%
Load conditions	No load conditions
Direction of panels	Facing azimuth 249° (approx. south-west direction), and a tilt angle of 36°
Cable information	Feeder cable: 120 mm^2 Al cable of impedance (0.253+0.08j) Ω/km Service cable: 35 mm^2 Al cable of length 10 m and impedance (0.868+0.08j) Ω/km
Distribution of houses	Unbalanced distributed over phases with many houses connected to phase 1

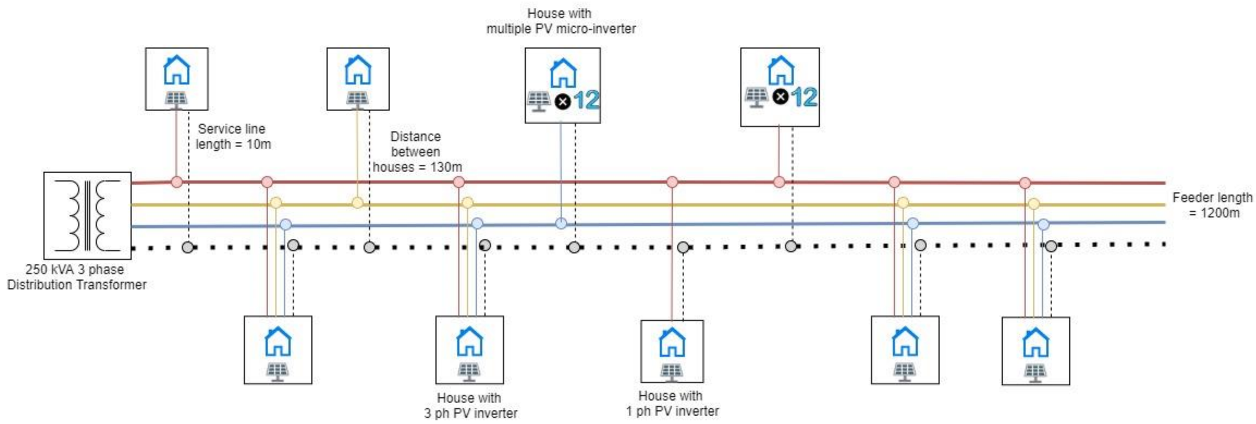

Figure 6: Model of Scenario 1 in DEMKit

The simulation is done for June 11, 2020, as this is the day with the highest PV production for a panel facing south-west direction using the irradiance data available in DEMKit (KNMI data of Twenthe weather station). By simulating this scenario, the following grid violations occur and the influence of parameters is analyzed.

1. Length and cross section of cables

The length and cross sectional area of cables is one of the major factors that affect the impedance of cables. Rural feeders like the feeder shown in Figure 6 are longer in length due to the sparse distribution of houses and a smaller cross sectional area due to the limited number of houses it serves. The feeder cable used in this scenario has an impedance of (0.253+0.08j) Ω/km length and a maximum current carrying capacity of 150A. In a simple network with a load connected to a feeder, the voltage drop at the node can be calculated by,

$$Voltage\ drop\ (in\ V)\ = 2 * length\ (in\ km) * \left(\frac{impedance}{km}\right) * current(in\ A)$$

Due to the usage of the same conductor for the neutral line, the voltage drop is calculated for twice the length of the cable. It is also due to the length of the cables that the inverters connected far away from the transformer experience a higher voltage than the ones that are near to the transformer. Figure 7 shows the voltage at PCC of different houses connected to phase 1. It can be observed from Figure 7 that, the voltage at House 8 is higher than that of House 0 and 3 during PV production hours. The voltage at every node in a feeder is calculated by using load flow analysis. Here, the forward-backward sweep load flow analysis [28] which is available in DEMKit is used.

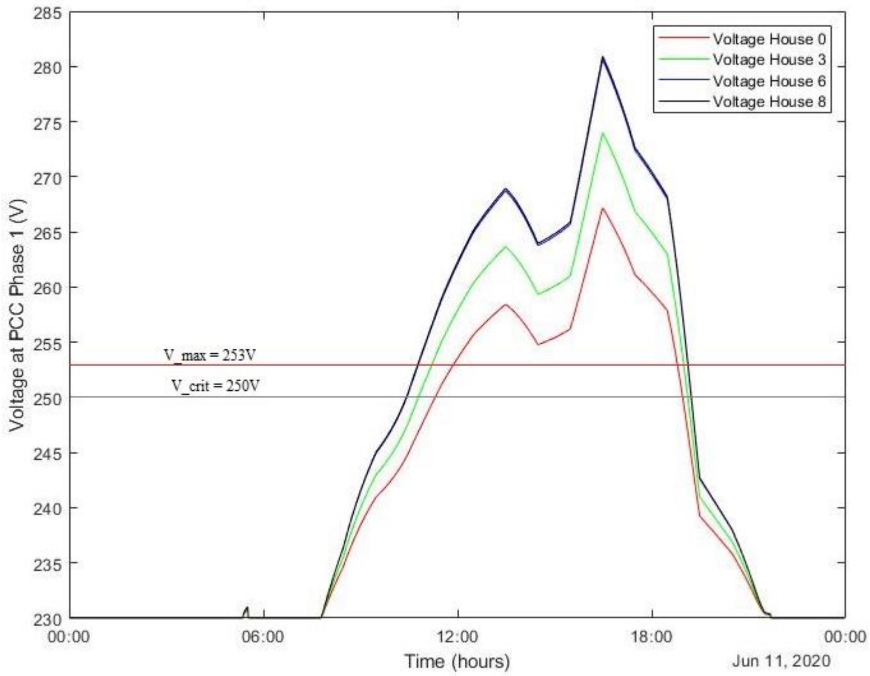

Figure 7: Voltage at PCC of different houses

2. Direction of PV panels

For the Netherlands, the optimal tilt angle for PV panels is around 36° facing the south direction. However, not all houses have a roof facing perfectly south. In this case, an azimuth angle of 249° is assumed i.e. the panels are approximately facing south-west direction. The direction in which panels are facing can have a significant effect on over-voltage situation. For example, if the PV systems of all houses connected to a feeder have exactly the same azimuth angle as in this case, there is a peak power generation during the same time of the day. This can cause a very high over-voltage issue. Figure 8 shows the PV power output of different PV systems. All PV systems here are considered to have the same azimuth angle and hence they all produce their peak power at 16.30 hours.

3. Scale and type of PV system

In this scenario, rural houses are assumed to have a solar installation of 4.8kW (or 24m^2) with an efficiency of 20%. The capacity of a PV installation with a given installation area and efficiency can be calculated by:

$$PV\ Installtion\ capacity\ (in\ kW) = Standard\ irradiance\ \left(\frac{1000W}{m^2}\right) * Area\ of\ panel\ (in\ m^2) * Efficiency\ of\ panels$$

Further, different types of PV inverters including single phase, three phase and micro-inverters are considered. Figure 8 shows the PV power production for all the 3 types of PV systems. The three phase inverter in House 3 feeds 1.6kW to phase 1. House 6 has 12 micro-inverter systems each of size 2 m^2 (0.4kW). Figure 8 shows the power production of one such micro-inverter system.

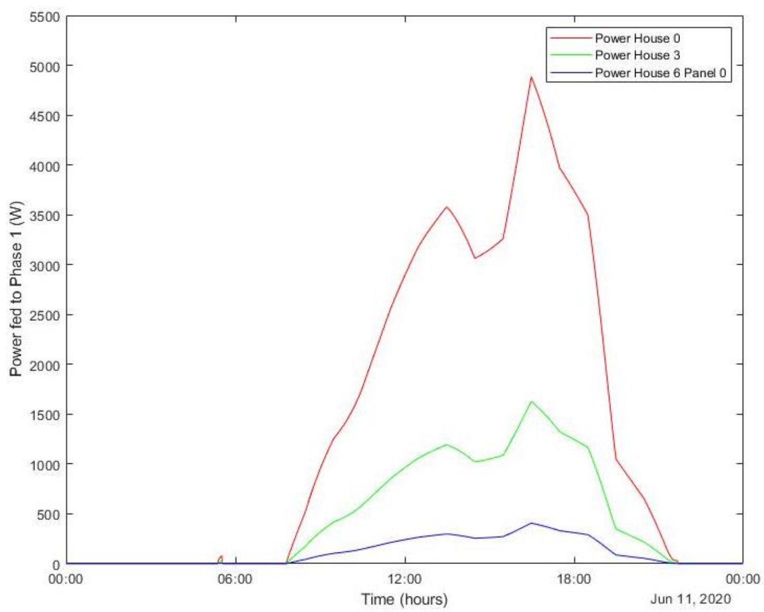

Figure 8: Power fed by different types of PV systems to Phase 1

4. Overvoltage problems

In addition to the above discussed factors, load conditions and distribution of houses over phases can also be the cause for an over-voltage situation. An over-voltage is most likely to occur when there is a high production of PV and very low load in the grid which creates an unbalance in supply and demand. In this scenario, a worst case situation with no load situation is simulated.

Due to the connection of many houses to phase 1 an higher over-voltage is seen in phase 1 compared to the other phases as seen in Figure 7. The shift in the voltage peak is due to solar panels not facing perfectly south but slightly towards south-west direction. During these over-voltages the PV systems of the houses connected to phase 1 would trip and disconnect from the grid.

At the time, where the highest voltage peak occurred (16.30 hours), the voltage at the various nodes/point of coupling is shown in Figure 9. It is seen that the voltage at PCC increases as the distance from the transformer increases. This also means that even smaller PV power peaks during the entire day would probably cause over-voltage at the end of the feeder. This would cause the farthest PV systems to trip more often leading to an unfair energy yield among PV owners.

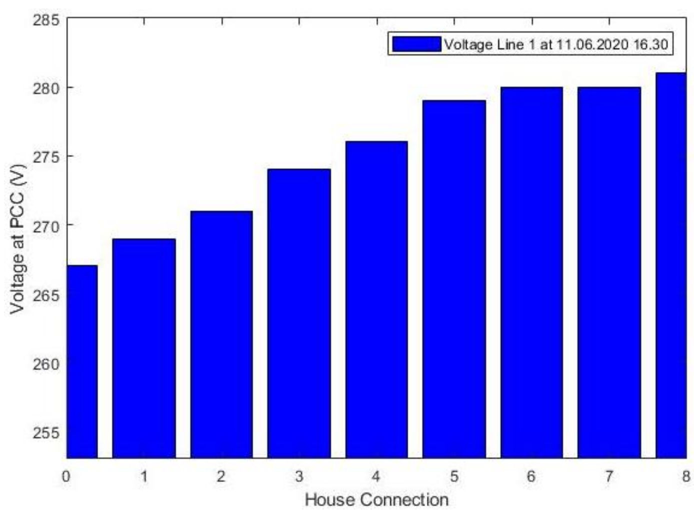

Figure 9: Voltage at PCC of different houses during the highest voltage peak

5. Voltage unbalance problems & neutral point shift

In the given scenario, many houses are connected to phase 1 compared to the other two phases. This result in a higher over-voltage in phase 1 compared to phase 2 and 3. Due to this unbalanced voltage and power distribution, a neutral point shift occurs in this scenario. A shift in neutral point will result in the neutral line not being at ground potential which results in a voltage between the neutral and the ground. As seen from Figure 10, a voltage of up to 17 V occurs between the neutral and the ground at the end of the feeder.

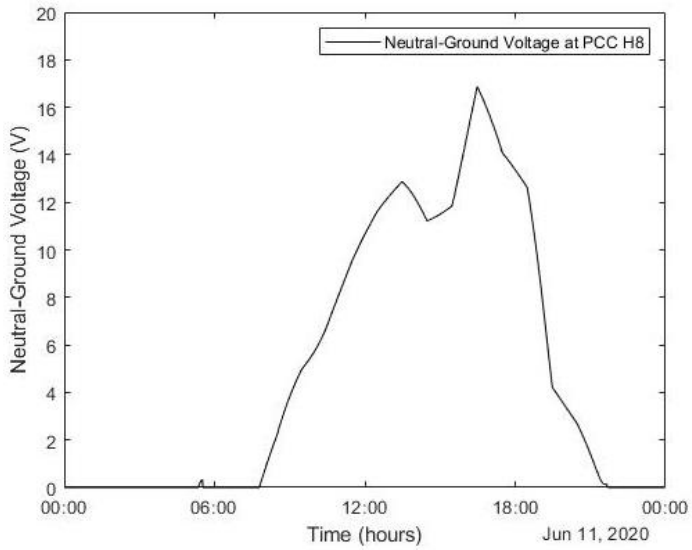

Figure 10: Neutral-Ground voltage at the end of feeder

5.2.2. Scenario 2

Scenario 2 represents a lengthy rural feeder with 9 houses consisting of various types of PV systems connected to different phases of a three phase feeder.

This scenario consists of PV systems of various sizes which are facing different directions and where base-load is added. The effect of east/west facing panels can be investigated in this scenario. The simulation was carried out for a week in summer to observe the voltage response during different days. Complete information about this scenario is given in Table 4 and Figure 11.

Table 4: Scenario 2 description

Parameters	**Information**
Type of feeder	1200 m rural feeder with houses spaced 130m apart
Type of PV systems	Mixture of various types of PV systems with an area ranging from 23 to 25 m^2 and an efficiency ranging from 19-20%
Load conditions	Base load conditions
Direction of panels	Azimuth angle ranging from 110° to 249° and

	altitude angle ranging from 33° to 37°
Cable information	Feeder cable: 120 mm^2 Al cable of impedance (0.253+0.08j) Ω/km Service cable: 35 mm^2 Al cable of length 10 m and impedance (0.868+0.08j) Ω/km
Distribution of houses	Unbalanced distributed over phases dominantly phase 1 and 2

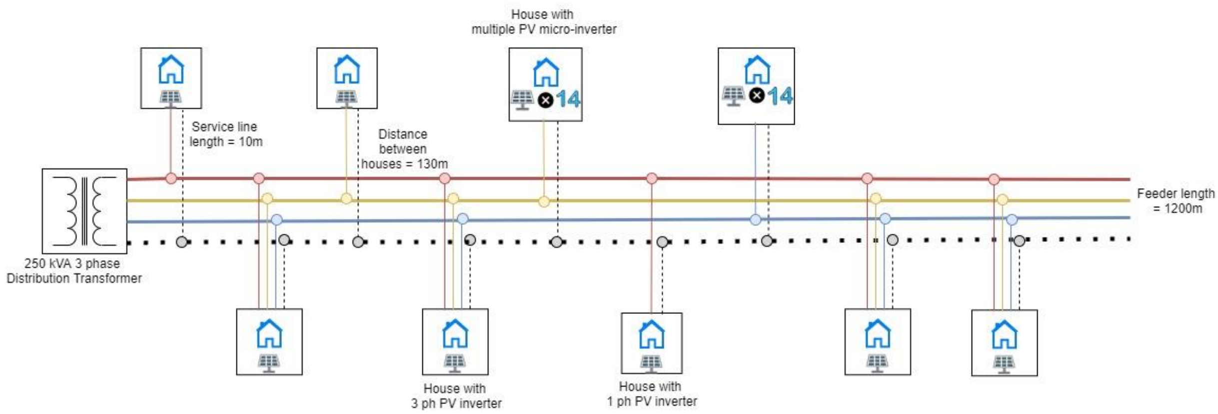

Figure 11: Model of Scenario 2 in DEMKit

The following grid violations are analyzed for this scenario.

1. Length and cross section of cables

The length and cross section of cables remain the same as in Scenario 1. Hence, the level of over-voltage caused due to length and cross section of cables remains the same.

2. Direction of PV panels

To simulate a real life situation, PV systems of different sizes and directions are considered in this scenario. PV panels facing different direction generate their peak power during different times of the day. Figure 12 shows the PV production of PV systems in three houses namely House 1, 7 and 8 which have their azimuth angles as 120°, 182° and 249° respectively. The overvoltage situations can occur in different time of the day due to such scenarios.

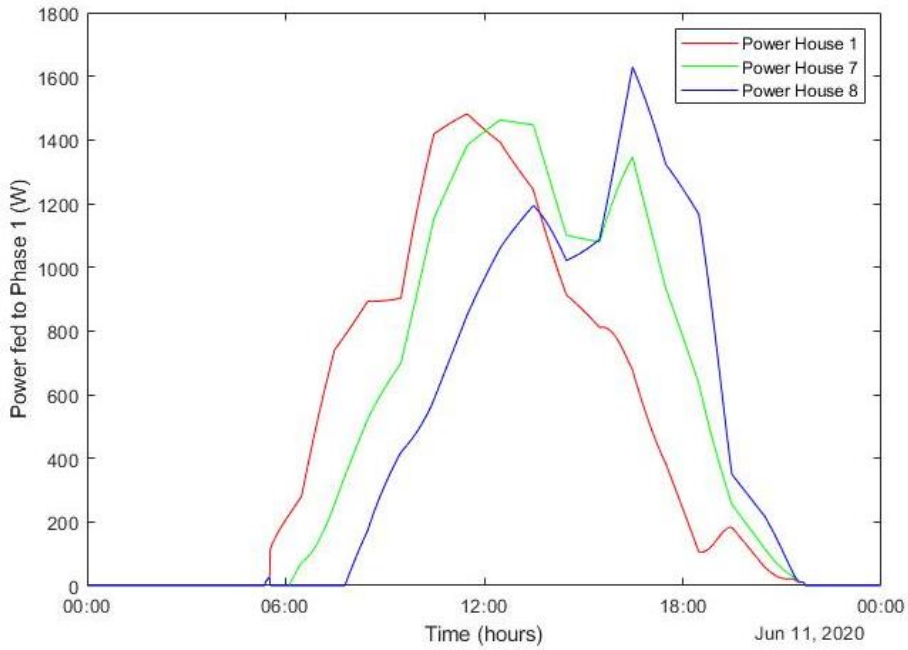

Figure 12: Power fed by PV systems with different azimuth angle to phase 1

3. Scale and type of PV system

Different types of PV systems including single phase, three phase and micro-inverters are considered in this scenario. House 4 and 6 have 14 micro-inverter systems each of size 1.7m^2. House 1, 3, 7 and 8 have three phase inverters and the remaining houses have a single phase central inverter system. The connection scheme to different phases can be seen in Figure 11. The size of PV systems connected to the feeder range from 23m^2 to 25m^2 with efficiencies of 19-20%.

4. Over-voltage problems

The voltage response in this scenario is not only affected by the PV generation conditions but also due to the base load conditions in the feeder. Figure 13 shows the voltage at PCC of house 8 in phase 1 and 2 for 7 days. From the voltage response it is seen that day 1 has a high PV power production during which over-voltage situations occur. Day 5 is a cloudy day with low irradiance. The voltages at PCC of houses connected to phase 1 and 2 are compared for day 1 in Figures 14 and 15. The over-voltage situations occur in both the phases but during different times of the day.

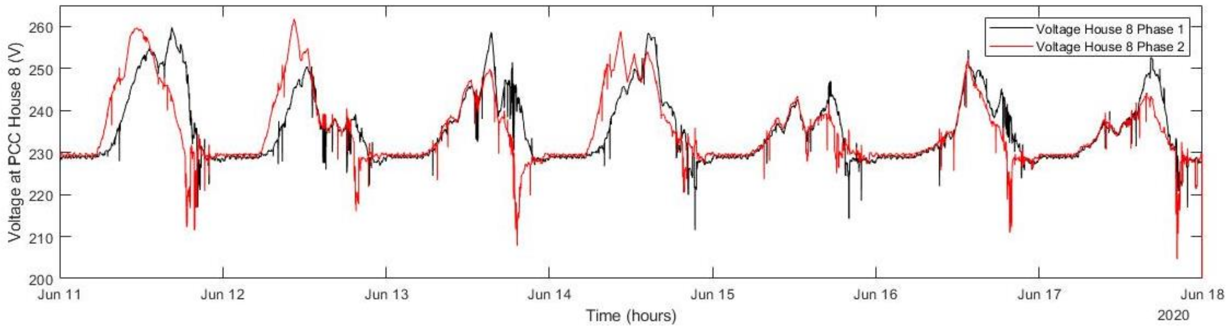

Figure 13: Voltage at PCC of House 8 in phase 1 and 2 for a week

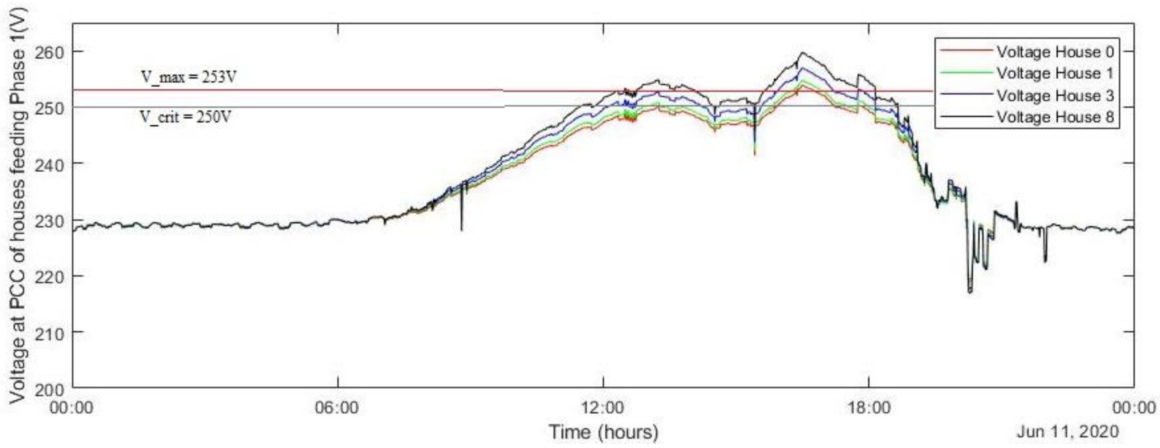

Figure 14: Comparison of voltage at PCC of houses connected to phase 1

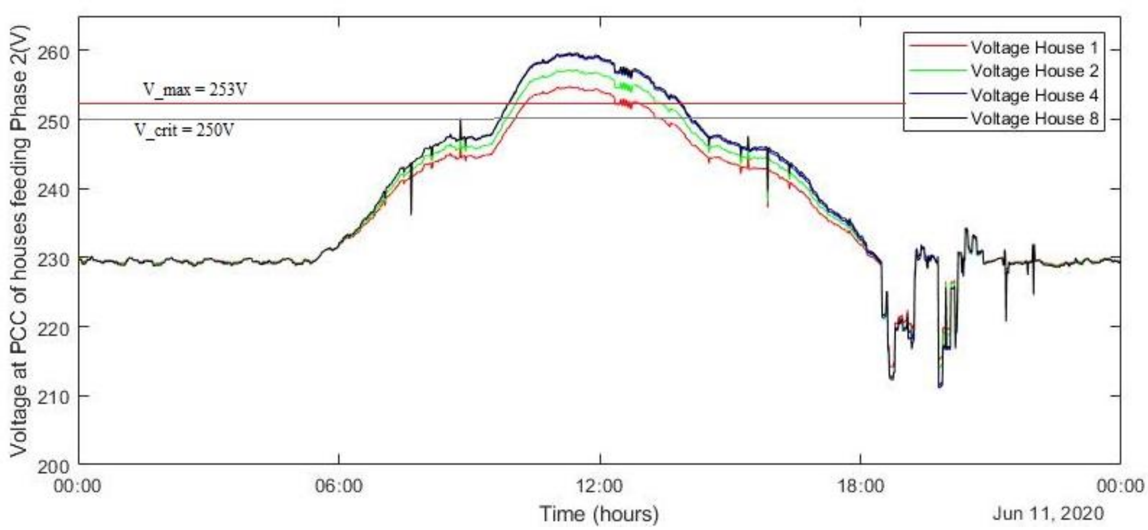

Figure 15: Comparison of voltage at PCC of houses connected to phase 2

The voltage at phase 1 and phase 2 reaches up to 260V during day 1 but during different times of the day due to the direction of panels connected to the two phases. The voltages below 230V during the evening hours around 18.00 are due to the increase in loads in houses during the evenings.

5. Base load conditions

The base load of three houses is shown in Figure 16. It can be seen that the base loads are almost constant throughout the day except during the evenings when they increase to a high value. Since house 1 and 3 have a three phase connection, the loads are distributed to all the three phases whereas house 5 has its entire load connected to phase 1.

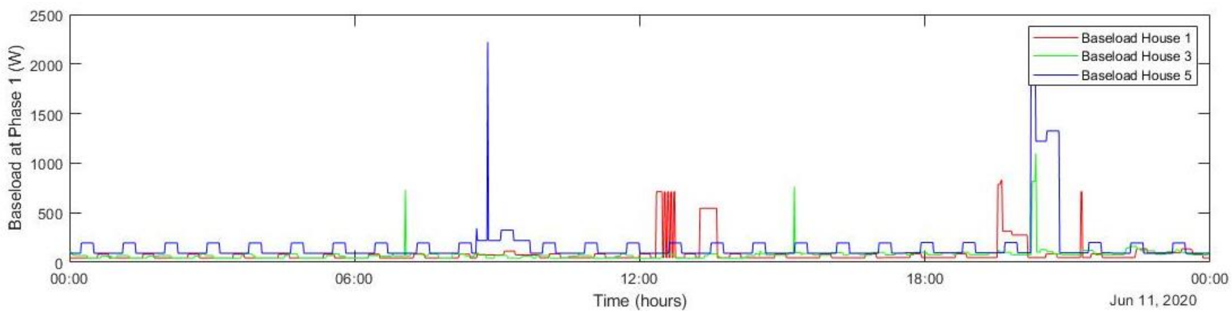

Figure 16: Base load of houses connected phase 1

5.2.3. Scenario 3

Scenario 3 represents an urban feeder of length 450m with 40 houses connected to a three phase distribution feeder. Out of 40 houses, 35 houses have grid connected PV systems. In this scenario, the effect of shorter and thicker cables on the over-voltage levels is investigated. The scenario also consists of PV systems of various sizes facing different directions. Complete information about this scenario is given in Table 5.

Table 5: Scenario 3 description

Parameters	**Information**
Type of feeder	450 m rural feeder with houses spaced 5m apart
Type of PV systems	Mixture of various types of PV systems with

	an area ranging from 16 to 25 m^2 with an efficiency ranging from 15-20%
Load conditions	No load conditions
Direction of panels	Azimuth angle ranging from 159° to 249° and altitude angle ranging from 32° to 38°
Cable information	Feeder cable: 150 mm^2 Al cable of impedance (0.206+0.08j) Ω/km Service cable: 70 mm^2 Al cable of length 10 m and impedance (0.443+0.07j) Ω/km
Distribution of houses	Unbalanced distributed over phases dominantly phase 1 and 2

The following grid violations are analyzed in this scenario.

1. Length and cross section of the cable

The length and cross section of the feeder cables play a very important role in deciding the voltage levels. In comparison to Scenario 1 and 2, this scenario has shorter and thicker cables because urban feeders are shorter in length with a high density of house connections. Due to the high number of customers it serves, the cables are also thicker than the rural cables. This leads to a lower impedance and hence a lower over-voltage with the same current flowing through the feeder.

2. Direction and size of PV systems

PV systems of various sizes ranging from $16m^2$ (3.2kW) to $25m^2$ (5kW) are assumed which includes a mixture of detached, semi-detached and terraced houses. Different values of azimuth and altitude angles were taken to simulate a real life situation. The PV power of three phase PV systems in house 1, 15 and 35 fed to phase 1 is shown in Figure 17. PV systems in house 1, 15 and 35 have the same size of $24m^2$ and azimuth angle of 249° with a system efficiency of 20%, 20% and 18% respectively.

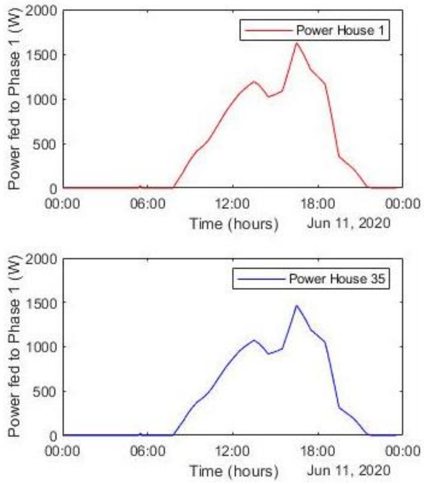

Figure 17: Power fed by three phase PV inverters to phase 1

3. Overvoltage and voltage unbalance problems

The voltage at PCC of house 1, 15 and 35 connected to phase 1 is shown in Figure 18(a). It is seen that the voltage exceeds 253V only during the peak generation hours in the late afternoons. The PV systems in house 1, 15 and 35 have PV systems of size 24m^2 which is the same as the houses in the rural feeder in Scenario 1 discussed in Section 5.2.1. However, in comparison to the over-voltage scenarios in rural feeders, not much over-voltage issues occur in urban feeders due to the shorter length and thicker cables used.

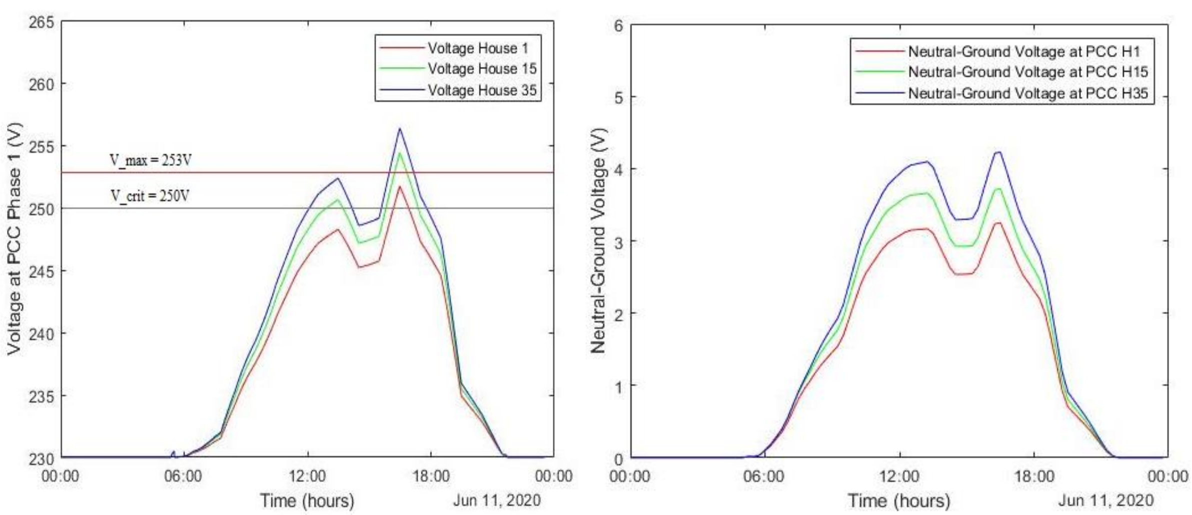

Figure 18: a) Comparison of voltage at PCC of houses connected to phase 1

b) Comparison of neutral to ground voltage at PCC of houses connected to phase 1

Due to the unbalanced distribution of houses over phases, a neutral point shift occurs as shown in Figure 18(b). A neutral-ground voltage of up to 4V can be seen at houses in the end of the feeder. A non-zero neutral-ground voltage would affect the voltages and controls in other phases even if only one phase is loaded with PV panels.

Grid and PV systems parameters like length of feeder, size of PV systems, connection of houses to different phases, loading conditions and direction of panels contribute to voltage issues in the feeder. In general, grid violations like over-voltages and voltage unbalances occur due to the increased penetration of PV in a low voltage feeder. On comparing Scenario 1 and 3, it is observed that problems are more severe in rural feeders than in an urban feeder.

6. CONTROL ALGORITHMS

The problems and grid violations occurring in the scenarios described in Section 5.2 need to be tackled with suitable control algorithms. The control algorithms achieve grid compliance by curtailing the energy fed by PV systems to the grid. The algorithms must be able to maintain compliance to grid code during worst case situations. During such a control execution, it is also desired to avoid unfair curtailment situations at the end of the feeder.

The grid compliance achieved by control algorithms can be specified and evaluated by the voltage profiles of each house and the grid as a whole. But in order to measure the fairness achieved, it is first important to define fairness. There is no standard definition for fairness, and therefore the term ‘Fairness during curtailment’ might have multiple interpretations. To get a clear framework, in this work fairness is said to be achieved in a scenario when:

“Every house connected to a certain phase feeds the ***same percentage*** of its maximum energy to the grid ***instantaneously or over a period of time*** during ***overvoltage situations*** in the particular phase”.

The maximum energy refers to the amount energy that the PV system would have fed to the grid when no voltage limits are given. By this definition, it means that fairness is achieved phase-wise. i.e. fairness is not achieved between houses connected to different phases of the low voltage grid. An attempt to achieve fairness among PV systems connected to different phases would result in curtailing a PV system that is connected to a phases that is not facing any over-voltage issues. This can result in creating problems in other phases and also leads to curtailment of huge amount of PV power. Due to these reasons, we aim to achieve fairness phase-wise and not throughout all houses in the feeder which is a trade-off between renewable energy feed-in and fairness. Further, the definition of fairness is applied only during over-voltage situations.

6.1. Working of control algorithms

In this Section, the working of four curtailment algorithms is presented. The control algorithms are designed to tackle the problems that occurred in scenarios discussed in Section 5.2. The following four PV curtailment algorithms are explained:

1. ON/OFF Control algorithm

2. Unfair droop control algorithm
3. Distress signal control algorithm
4. Centrally controlled droop algorithm

In general to analyze a curtailment event, the following terminologies are used.

- V – Instantaneous line-neutral voltage at any node in the grid. Node voltages are measured at PCC.
- V_crit – Critical voltage represents the voltage at which curtailment starts (here 250V)
- V_max – Maximum voltage represents the highest voltage that is allowed to occur at any point in the grid (253V). In practice, an instantaneous voltage equal to V_max is considered a grid emergency and the inverter connected to the particular node is disconnected from the grid.
- P - Instantaneous power output of a grid connected PV system
- P_MPPT – Maximum power output of a PV system when no voltage limits are given.

6.1.1. ON/OFF control algorithm

The ON/OFF control can be seen more as a safety feature in a grid connected inverter rather than as a control algorithm. This method is a local control strategy, where each inverter functions only based on measurements at its own node, independent of other inverters.

According to IEEE 1547-2018 standard [14] all grid connected inverters have to disconnect from the grid immediately when a voltage of V_max (253V) is sensed at its node. For voltages less than 253V, the PV inverters continue to feed their maximum possible power to the grid. This leads to the following calculation of the power output of the PV system.

$$P = \begin{cases} P\_MPPT\ , & V < V\_max \\ 0, & V \geq V\_max \end{cases}$$

Due to the control operation based only on local voltage measurement, this algorithm leads to unfair power curtailment. The houses towards the end of the feeder would more often measure a voltage greater than 253V at their nodes and hence disconnect from the grid more often than the houses in the feeder closer to the transformer. In this method, the inverters do not participate in the voltage regulation process. Further, the abrupt disconnection of PV inverters from the grid causes a high voltage flicker and fluctuations that can even be dangerous to the grid and the loads connected to it. The standard for such allowed voltage fluctuation in a power system is defined by IEEE Standard 1453-2015 [34].

6.1.2. Droop control algorithm

Droop control algorithm is also a local control strategy where the control of an inverter is entirely dependent on the voltage measured at its PCC. In contrast to the previous algorithm, the control actions of the inverters here are based on the V_crit (250V) measured at the PCC. The same critical voltage is set for all inverters connected to the feeder.

Figure 19 shows the working of droop control algorithm. Initially, the operating point of the inverter is set to its maximum power. i.e. $P = P\_MPPT$. The control action occurs simultaneously for all the inverters connected to the feeder for every time period of operation. First, the voltage at the PCC is measured and compared to V_crit. If the voltage at PCC is less than V_crit, then the inverters continue to operate with output P. If the voltage is equal to or greater than V_crit, then the output power of the inverter is reduced by a droop factor (N). This process is repeated until voltage at PCC is within limits. The droop factor N represents the percentage of curtailment taking place per iteration of the algorithm for every time period of operation.

In this method, the algorithm curtails only a certain amount of power that is enough to bring the voltage to less than the critical voltage. Also the inverters never disconnect from the grid, but instead stay ON and vary their output to regulate voltage. This avoids causing any voltage fluctuation or flickering. On the other hand, as different nodes in a feeder sense different voltages, there is still an unfair curtailment between houses in this method.

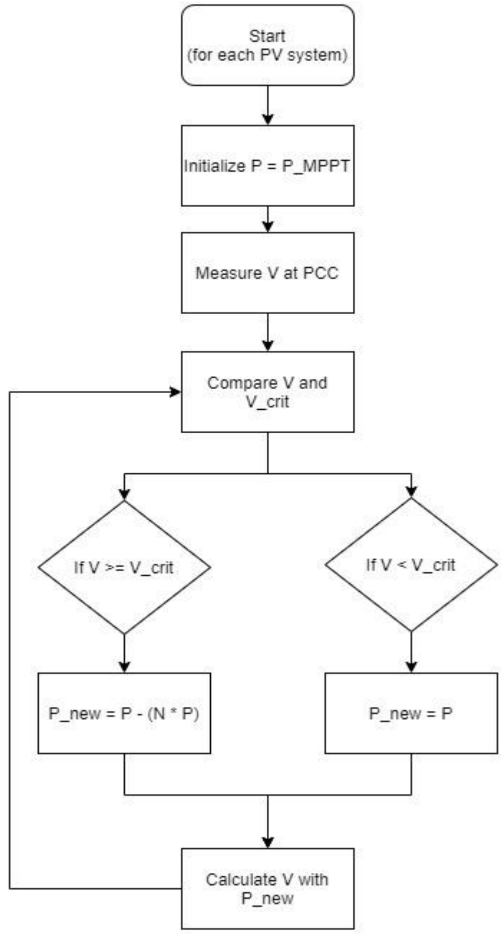

Figure 19: Working of a Droop control algorithm

6.1.3. Distress signal control algorithm

Distress signal control is a distributed control strategy where any inverter connected to a phase can act as a controller for all the inverters in the same phase depending on the over-voltage situation. The distress signal algorithm is also executed on a local level, but there exists a communication between inverters connected to the same phase.

In this method, when an inverter senses a $V >= V\_crit$ at its node, it sends out a distress signal to all the inverters connected to the same phase and as a result all the inverters that receive a distress signal start to curtail their power output by a droop factor N until the distress signal is withdrawn. Hence, already when one house in a particular phase has a voltage at PCC greater than the critical voltage, all the houses in the same phase curtail their power. The curtailment of power happens by all the inverters connected to the same phase until the voltage at PCC of every house is less than 250V. This is in contrast to the droop control algorithm, where only the inverter(s) which measure an over-voltage is/are curtailed. Due to this reason, the total amount of energy curtailed in a particular phase to solve the overvoltage problem is greater than the droop control strategy.

This method of curtailment is capable of maintaining a fair curtailment among PV systems connected to the same phase at every instant of time but this comes at the cost of curtailing more energy than the droop control method in order to solve the same over-voltage and the need to set up communication between inverters. Figure 20 shows the working of the distress signal control algorithm.

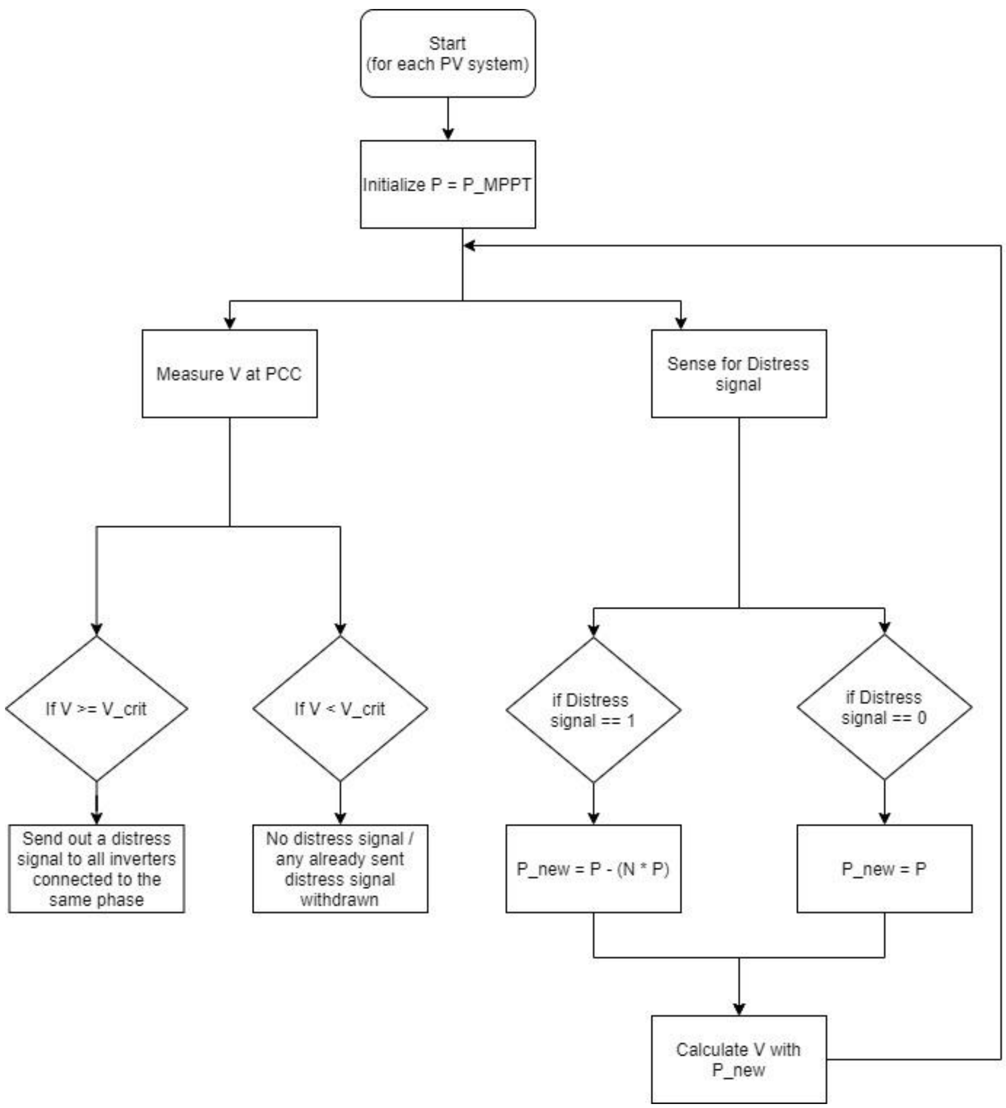

Figure 20: Working of distress signal control algorithm

Although the droop factor N is constant for all houses connected to a phase, N is multiplied with the instantaneous power P of the particular inverter when the distress signal is set to 1. This results in the same percentage of power being curtailed and not the same amount of power.

6.1.4. Centrally controlled droop algorithm

In the central control strategy, the inverters are controlled by a centralized controller. The aim of this algorithm is to maintain fairness and at the same time reduce the total amount of energy curtailed during over-voltage situations. In order to achieve this, time is used as a trade-off factor, i.e. the algorithm ensures fairness of curtailment over a period of time instead of maintaining fairness at every instant of time. It is this trade-off that results in lower total energy curtailed than the distress signal control algorithm. Figure 21 shows the working of centrally controlled droop algorithm.

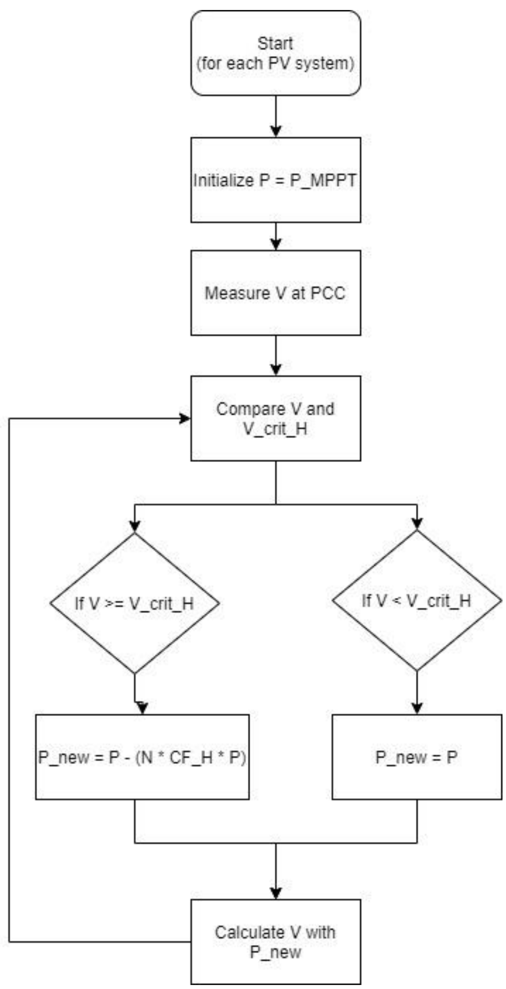

Figure 21: Working of centrally controlled droop algorithm

The working of the algorithm is similar to the droop control strategy, except that it includes two additional factors namely:

V_crit_H – Critical voltage specific to a house H obtained by the sensitivity (ΔP/ΔV) at each node. The critical voltage for each house is specific to the particular scenario being simulated and is obtained by measuring the voltage at PCC of other houses when the last house in the feeder measures a voltage of 250V at its PCC in a situation without any control.

CF_H – Curtailment factor which is calculated by the central controller based on the history of curtailment for the house H.

Each inverter records its percentage of curtailment for each time period of operation with the central controller. The central controller keeps a record of the summation of the curtailment percentages for each house. This is called the Curtailment history.

$$Curtailment\ history\_H = \sum CF\_H * N$$

The $Avg\_curtailment$ is the average of the curtailment history of all the houses connected to the same phase. With these parameters, the central controller calculates the CF for every house during each iteration based on the equation below.

$$CF\_H = \begin{cases} 1 + (Avg\_curtailment - Curtailment\ history\_H), & Curtailment\ history\_H > 0 \\ 1, & otherwise \end{cases}$$

The houses which have a curtailment history greater than the average curtailment, curtail less during the next interval and vice versa.

6.2.Control algorithms in a real-life situation

The working of control algorithms discussed in Section 6.1 represents the way in which algorithms are simulated in DEMKit in a discrete time environment. However, this is not the case in a real-life scenario which is in a continuous time environment. In practice, a PV inverter will work with very small discrete time steps to emulate a continuous time environment. A control action happens when an over-voltage is sensed at the PCC. Then, the decision to execute the next control action is taken by measuring the voltage at PCC during the next time step and not by a calculation of voltage. During the next control action, the resultant P from the previous control action is used and not P_MPPT. The algorithm will increment P until P_MPPT is reached when there is no overvoltage situation and curtail P until zero when an over-voltage situation occurs.

7. EVALUATION OF ALGORITHMS

Each scenario discussed in Section 5.2 is tested with the control algorithms discussed in Chapter 6. The results are compared for their grid compliance, fairness, and total energy fed to the grid during over-voltage situations. Grid compliance is measured from the voltage profile at the PCC of all houses in the feeder. The voltage at PCC should never reach 253V. Fairness is measured by the comparison of the total energy fed by each house in a particular phase according to the definition of fairness described in Chapter 6. The total energy fed to a particular phase is obtained by the sum of all energy fed by all houses during over-voltage situations.

7.1. Scenario 1

Scenario 1 introduced in Section 5.2.1, represents a three phase rural feeder of length 1200m with 9 houses connected to it. Further, the results of this scenario executed with the control algorithms are presented.

7.1.1. ON/OFF control algorithm

When evaluating the power fed by PV systems in house 0, 3 and 6, the PV system at house 6 is the first one to cease production and also the last house to begin production after the over-voltage does not occur anymore. On the other hand, House 0 is connected to the grid for a longer period of time compared to other houses. It should be noted that the houses with higher numbers are located further away from the transformer. This unfair curtailment situation is seen in Figure 22.

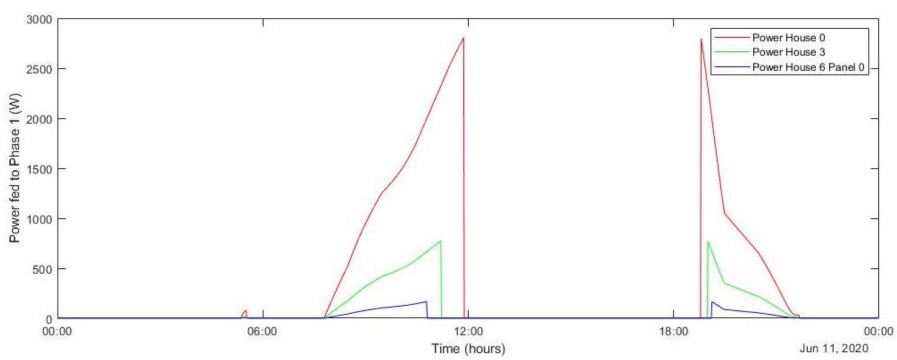

Figure 22: Power fed to Phase 1 by various types of PV systems

The voltage curve for this fluctuating power is shown in Figure 23. The sudden ON and OFF operation of PV inverters leads to severe voltage fluctuations and under-voltage situations.

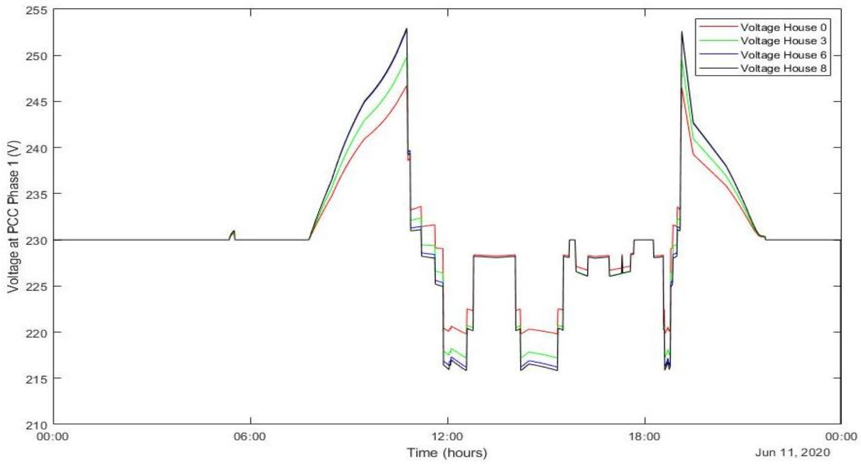

Figure 23: Voltage fluctuation due to ON/OFF control algorithm

7.1.2. Droop control algorithm

It can be observed from Figure 24(a) that the droop control algorithm ensures compliance to the grid code by limiting the voltage rise to less than 253V and limiting voltage fluctuations. Figure 24(b) shows the neutral to ground voltage at house 8 after the implementation of droop control algorithm. It can be seen that the neutral-ground voltage has reduced significantly while it reaches a near zero during peak production hours. However, Figures 25 and 26 show variation in the amount of power fed to the grid by different houses, which means that the algorithm is unfair in its curtailment strategy. Houses that are located towards the end of the feeder (House 5 and 8) curtail more power than the houses that are located nearer to the transformer (House 0, 1), although they have the same amount of installed capacity.

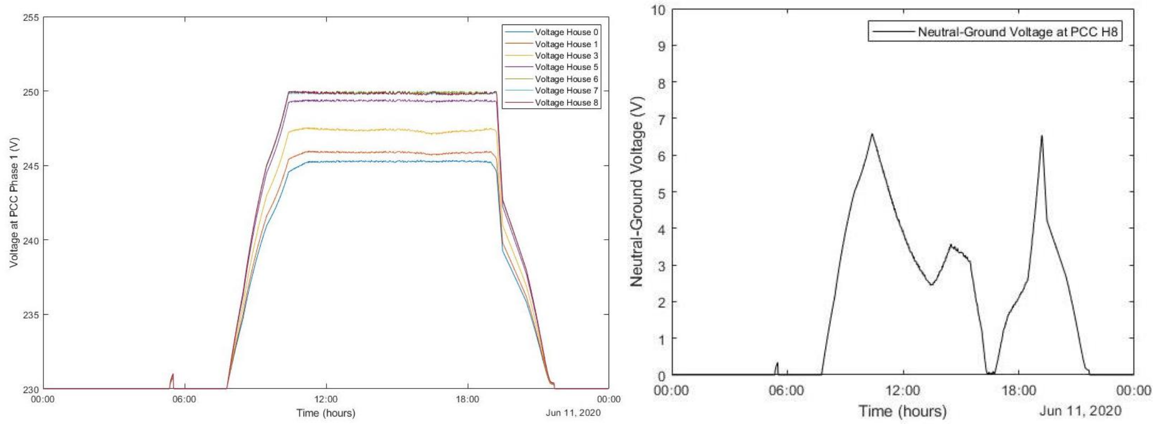

Figure 24: Voltage profile at PCC after droop control b) Neutral-Ground voltage at PCC of House 8 after droop control

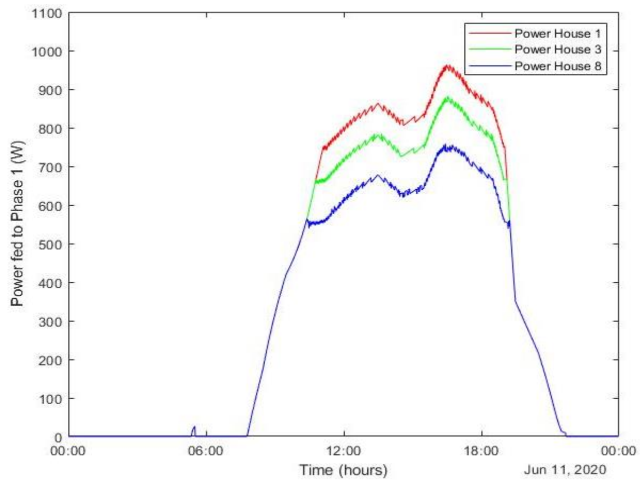

Figure 25: Power fed by three phase PV systems to Phase 1

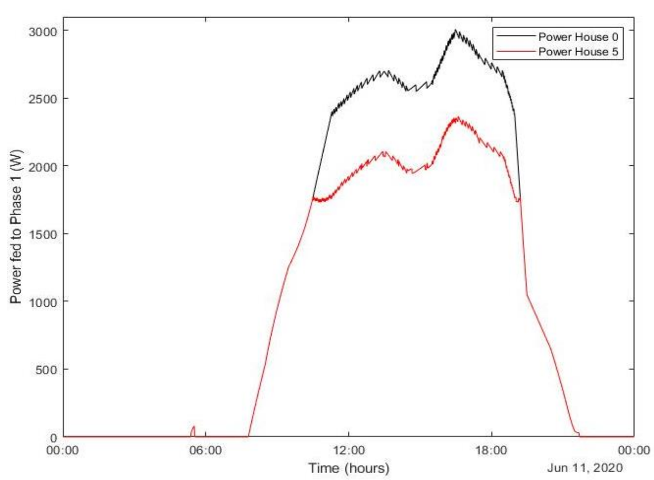

Figure 26: Power fed by single phase inverter to Phase 1

During this curtailment situation from 10:26 to 19:14, the summation of energy fed to the grid by all the houses connected to phase 1 is found to be 83.426 kWh. Table 6 shows the energy fed by different houses due to unfair curtailment.

Table 6: Comparison of energy fed by different houses during curtailment situations over the day

House	**% of MPPT energy fed during curtailment event**	**House**	**% of MPPT energy fed during curtailment event**
Single phase PV systems		*Three phase PV systems*	
H0	78.03	H1	74.877
H5	60.99	H3	68.148
H6	58.47	H7	58.889
		H8	58.723

From this table, the unfair curtailment of power among houses connected to the same phase can be observed.

7.1.3. Distress signal control algorithm

In this method, it is seen from Figure 27 that the phase voltages are within the limits. Also, all the houses connected to the same phase feed the same amount or percentage of power at every point of time. As seen from Figure 28 and 29, all the houses (House 1, 3 and 8 for example) curtail until House 8 stops experiencing an over-voltage, thereby achieving the same percentage of curtailment.

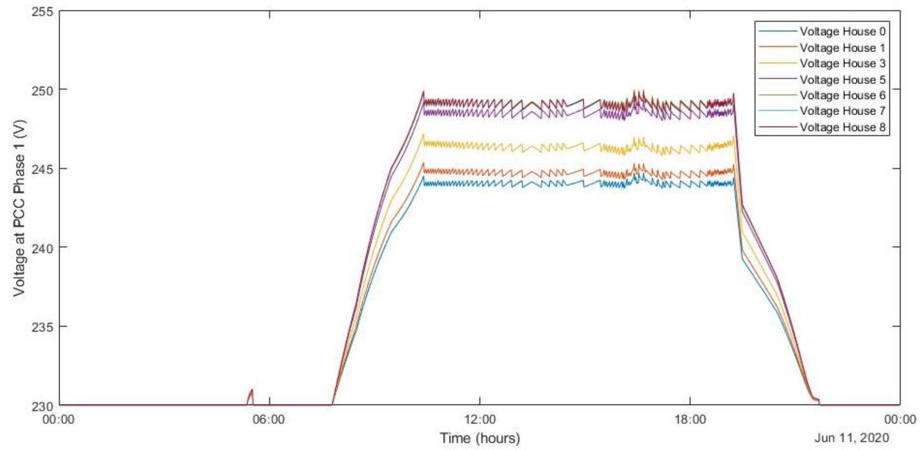

Figure 27: Voltage profile at PCC after distress signal control

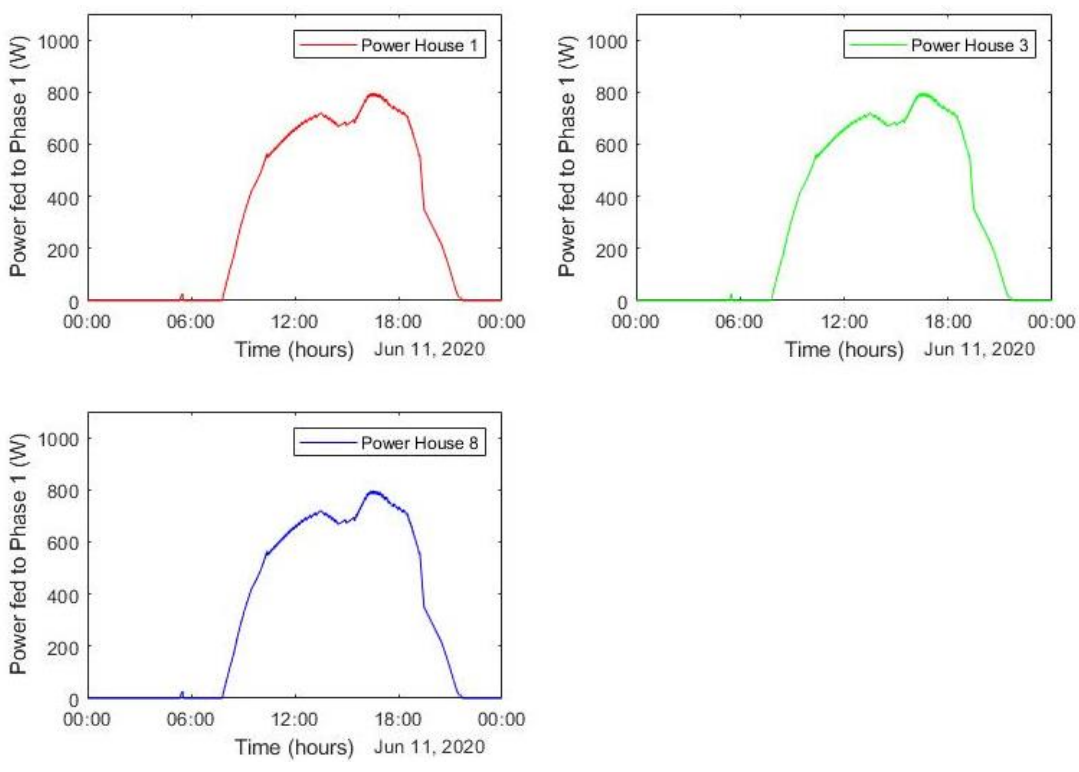

Figure 28: Power fed by three phase inverter to Phase 1

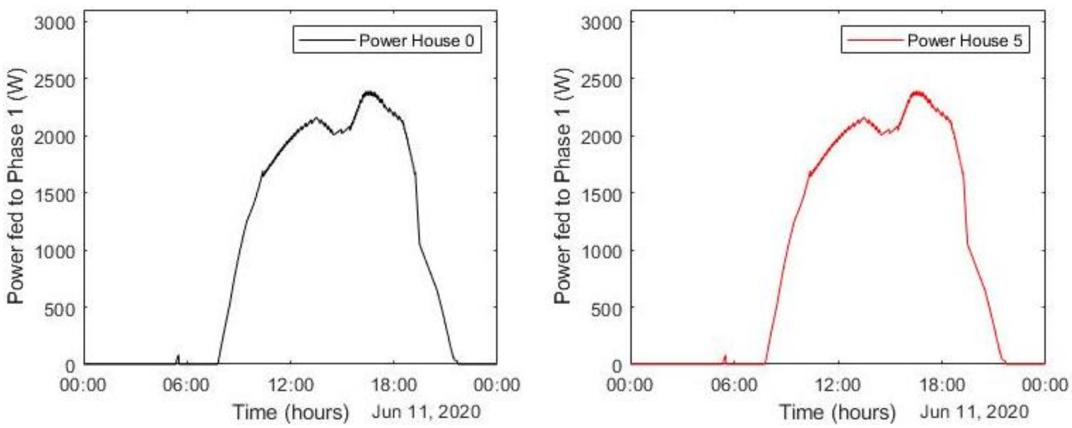

Figure 29: Power fed by single phase inverter to Phase 1

In this case, fairness is achieved at every time instant but the total energy fed to the grid by all houses connected to phase 1 during the curtailment situation is found to be 79.34 kWh which is less than in the droop control case. Table 7 shows the same percentage of energy fed by different houses during over-voltage situations.

Table 7: Comparison of energy fed by different houses during curtailment situations over the day

House	% of MPPT energy fed during curtailment event	House	% of MPPT energy fed during curtailment event
Single phase PV systems		*Three phase PV systems*	
H0	62.41	H1	62.41
H5	62.41	H3	62.41
H6	62.41	H7	62.41
		H8	62.41

7.1.4. Centrally controlled droop algorithm

In the centrally controlled droop strategy, each house curtails a different percentage of power during various times depending on their curtailment history and converges to an equal curtailment history over a period of time. The power fed by three phase and single phase inverters in response to this algorithm is shown in Figure 30. From Figure 31 which shows the power fed by single phase inverters during the curtailment situation, it is seen that the power fed by house 0 and 5 are alternating their maximum production during various times of the day. Although the difference in power fed during each time period is very small, the total energy fed by house 0 and 5 has increased by 0.2kWh each as seen in Table 8, as compared to distress signal control algorithm. Moreover, the change in power fed can be increased by increasing the value of droop factor *N*. However, such an increase in droop factor would lead to sudden changes in voltage levels.

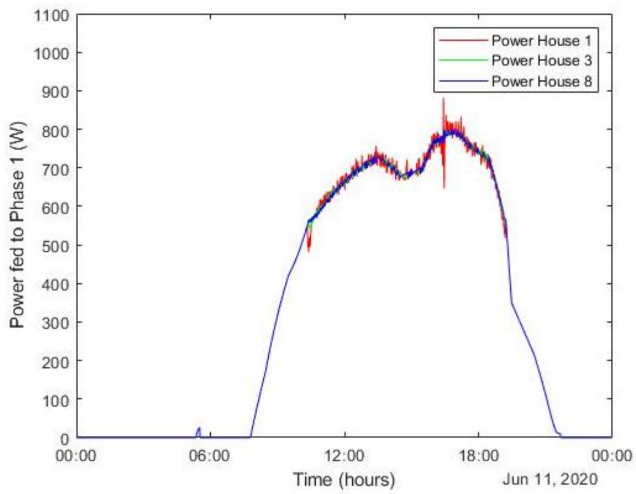

Figure 30: Power fed by three phase inverter to Phase 1

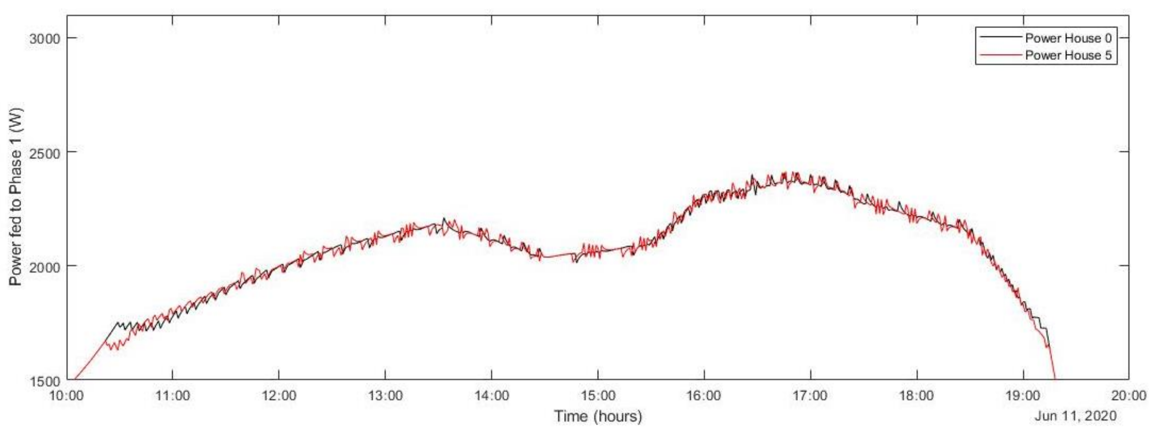

Figure 31: *Power fed by single phase inverter to Phase 1 during the curtailment situation*

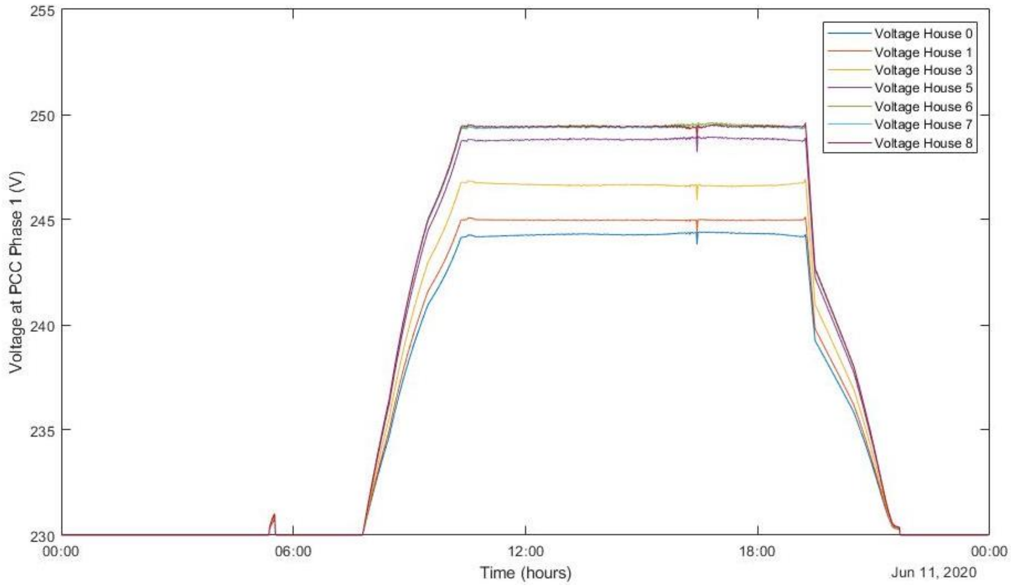

Figure 32: Voltage profile at PCC after centrally controlled algorithm

The voltage at PCC profile obtained as a result of this implementation is also in compliance with the grid code as shown in Figure 32. To analyze the convergence of this algorithm for fairness over the day, the percentage of energy fed by various houses connected to phase 1 during the over-voltage situation is compared in Table 8.

Table 8: Comparison of energy fed by different houses during curtailment situations over the day

House	% of MPPT energy fed during curtailment event	House	% of MPPT energy fed during curtailment event
Single phase PV systems		*Three phase PV systems*	
H0	63.08	H1	63.10
H5	63.07	H3	63.065
H6	63.07	H7	63.067
		H8	63.067

All the houses have fed approximately equal amount of power over the day, although the algorithm has not fully converged yet.

7.1.5. Comparison and discussion

A comparison of grid compliance, fairness and total energy fed for the three algorithms during curtailment events is shown in Table 9.

Table 9: Comparison of results

Algorithm	**Voltage level (V)**	**Fairness**	**Total energy fed to Phase 1 during curtailment (kWh)**
ON/OFF control	< 253 always, but with frequent voltage fluctuations	Unfair	8.8026
Droop control	< 253 always	Unfair	83.426
Distress signal control	< 253 always	Fair	79.34
Centrally controlled droop	< 253 always	Fair over a period of time	80.134

The maximum amount of energy that can be fed to phase 1 without any control is 127.118 kWh. The droop control creates an unfair opportunity among the houses but at the same time it has enabled a maximum amount of energy of 83.426 kWh fed to phase 1 during the over-voltage situation. The other two algorithms ensure fairness among houses connected to the same phase 1 instantaneously or over a period of time. The distress signal control algorithm has curtailed the most amount of energy (47.778 kWh) compared to droop control (43.692 kWh) and centrally controlled droop algorithm (46.984 kWh). The centrally controlled algorithm has curtailed lower energy of 46.984 kWh compared to distress signal control algorithm by using time as a trade-off between fairness and energy curtailment. In real-life, the grid operator can also choose to implement an unfair droop control strategy to avoid curtailing a lot of renewable energy and instead compensate the prosumers for their loss in energy. However, financial compensation cannot be sustained over many years due to the increasing number of prosumers and hence the grid operator needs to consider implementing a technical solution like centrally controlled droop algorithm to make a trade-off between fairness and total energy curtailed.

7.2. Scenario 2

Scenario 2 discussed in Section 5.2.2 represents a three phase rural feeder of length 1200m with 9 houses with different types and sizes of PV systems connected to it. Further, the results of this scenario executed with the control algorithms are presented.

7.2.1. ON/OFF control algorithm

Figures 33 and 34 shows the power fed by 3 phases inverters in house 1, 7 and 8 fed to phase 1 and 2 respectively. PV systems in house 1, 7 and 8 have their azimuth angles as 120°, 182° and 249° respectively. Since the peak power is occurring at different times of the day, more frequent connection and disconnection of inverters from the grid can be seen. However, the level of over-voltage and thereby the curtailment occurring in phase 1 and 2 are different.

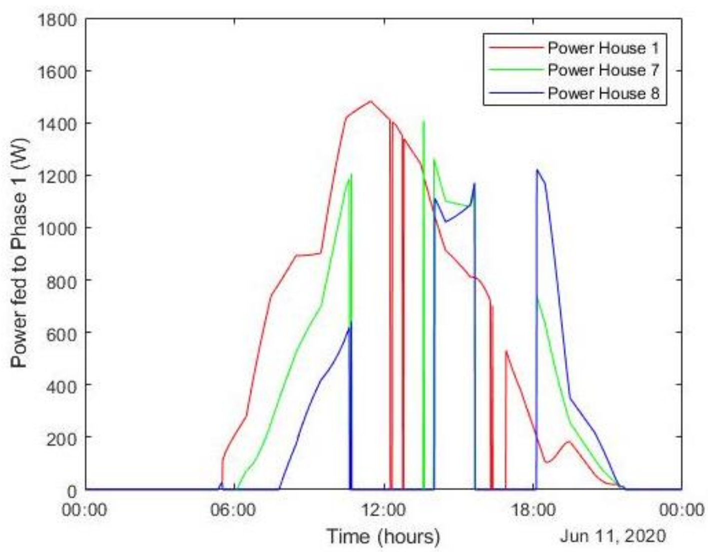

Figure 33: Power fed to phase 1 by PV systems in House 1,7 and 8

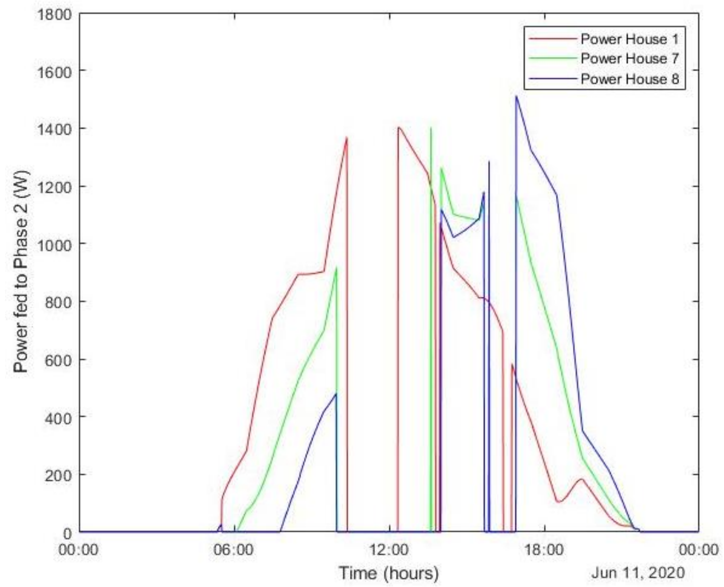

Figure 34: Power fed to phase 2 by PV systems in House 1,7 and 8

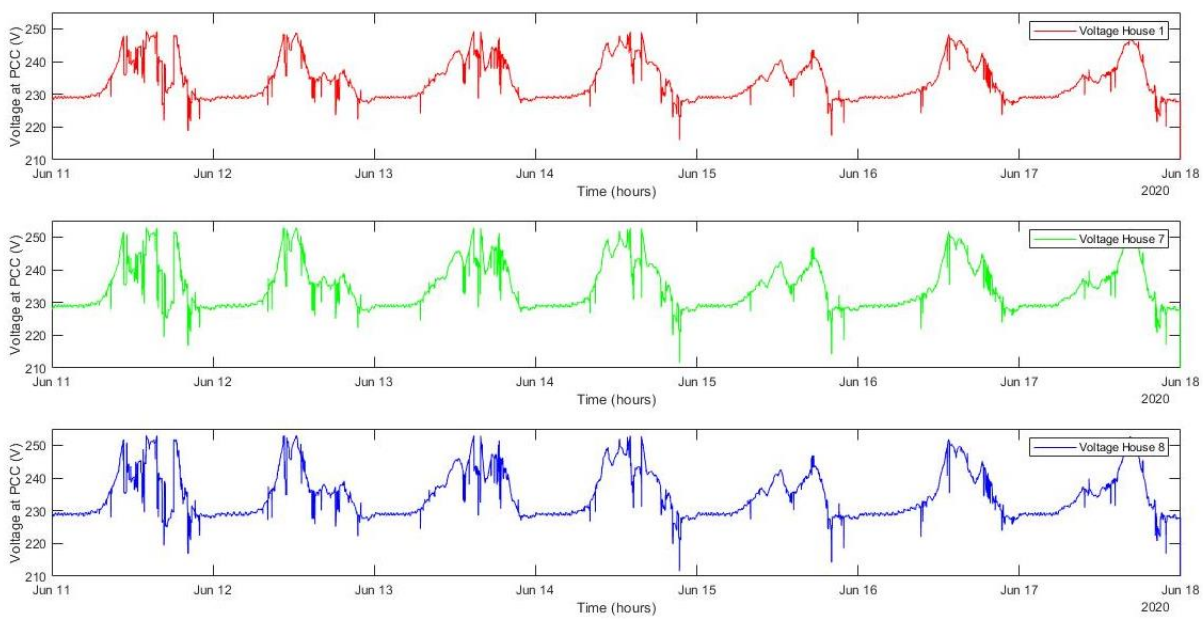

Figure 35: Voltage response to ON/OFF control algorithm for a week

Figure 35 shows the voltage at PCC of houses 1, 7 and 8 in phase 1 for all the 7 days. Sudden drop and rise of voltages are seen due to frequent connection/disconnection of inverters from the grid and fluctuating loads. No over-voltage occurs in day 5 due to low PV generation. The unfair curtailment of the algorithm can also be seen from comparing the power curves of house 1 and house 8 in Figures 33 and 34 where House 8 faces a lot curtailment compared to house 1.

7.2.2. Droop control algorithm

The voltage at PCC of houses 1, 7 and 8 in Figure 36 shows compliance to grid code by maintaining voltage at PCC less than 253V. However, the voltage compliance is achieved by unfair curtailment of PV systems. Since PV systems have varying size and azimuth angles in this scenario, the power curves after curtailment are shown with their MPPT power plots in Figure 37.

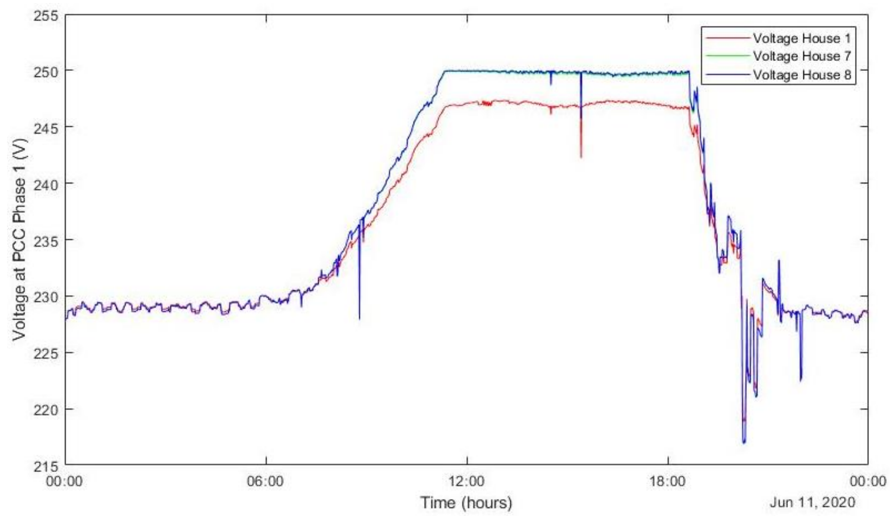

Figure 36: Voltage at PCC of houses connected to phase 1

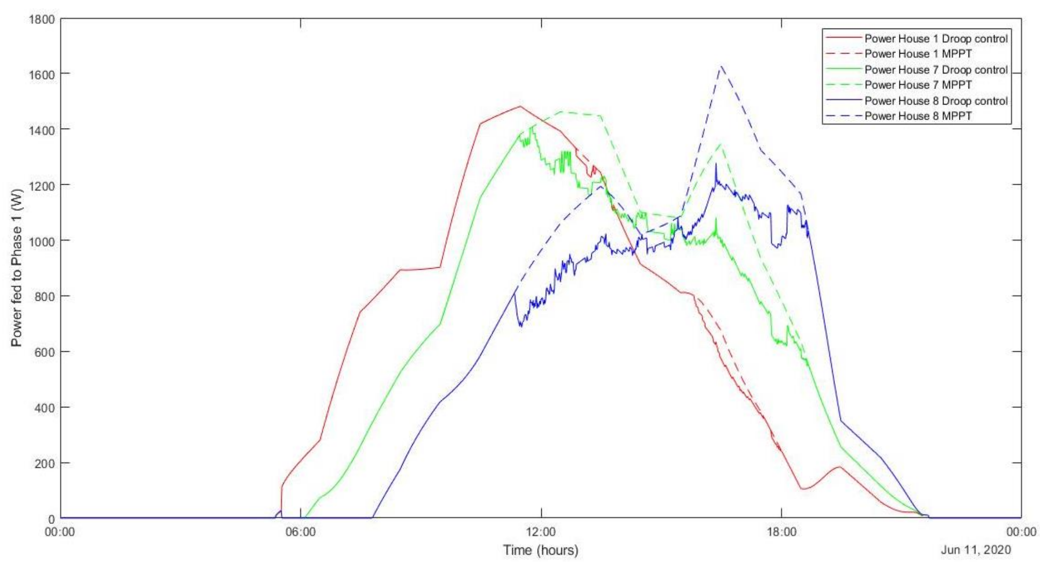

Figure 37: Power fed by houses to phase 1 with droop control in comparison to MPPT power

In such situations, it is difficult to understand and compare the levels of curtailment of various houses with PV systems of various sizes and azimuth angles. However, plotting the power fed by inverters to the grid in terms of their MPPT power gives a clear picture. Figure 38 shows the percentage of MPPT power fed to phase 1 by different inverters. From here, it is clearly seen that houses connected closer to the transformer feed in higher power to the grid than the houses far away from the transformer when droop control algorithm is used.

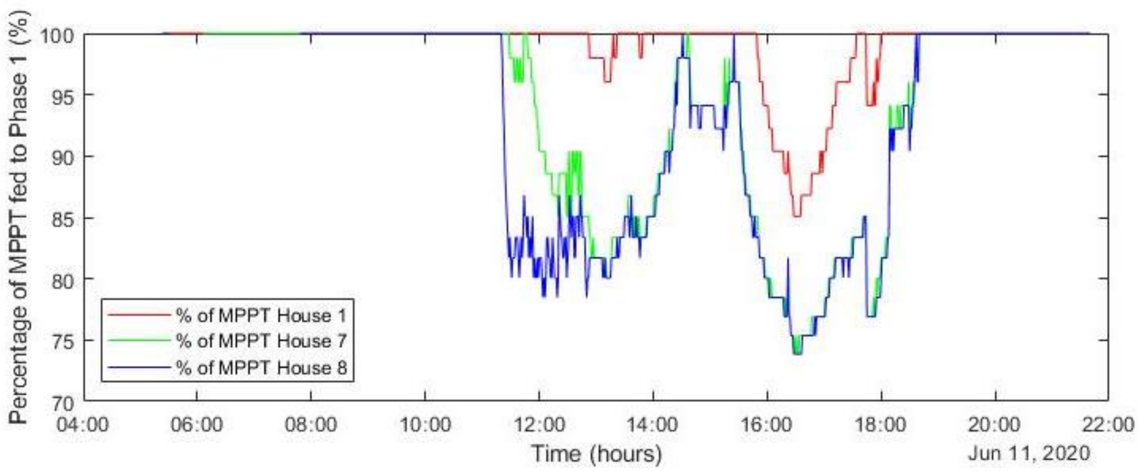

Figure 38: Percentage of MPPT power fed to phase 1 by different houses

The total amount of energy fed to phase 1 after 1 day of simulation during over-voltage situations is 71.4482 kWh. Table 10 shows the percentage of maximum energy fed to the grid by various houses which shows that the droop control strategy is unfair in curtailment.

Table 10: Comparison of energy fed by different houses during curtailment situations

House	% of MPPT energy fed during curtailment event after 1 day
H1	98.06%
H7	86.02%
H8	84.15%

7.2.3. Distress signal control algorithm

The voltage at PCC of House 1, 7 and 8 is shown in Figure 39. The voltages are maintained within the maximum limit of 253V. With the distress signal control, same percentage of their maximum power needs to be fed at every instant of time. In Figure 40, a comparison is made between the MPPT power and the power fed after curtailment. On comparing, Figure 40 to the power fed during droop control (Figure 36), it is seen that PV system in house 1 also starts to curtail power when house 8 starts to curtail which results in achieving same percentage of curtailment. Figure 41 shows the percentage of MPPT power fed by each PV system to phase 1 and it is observed that all 3 PV systems feed the same percentage of power to the grid during overvoltage situations.

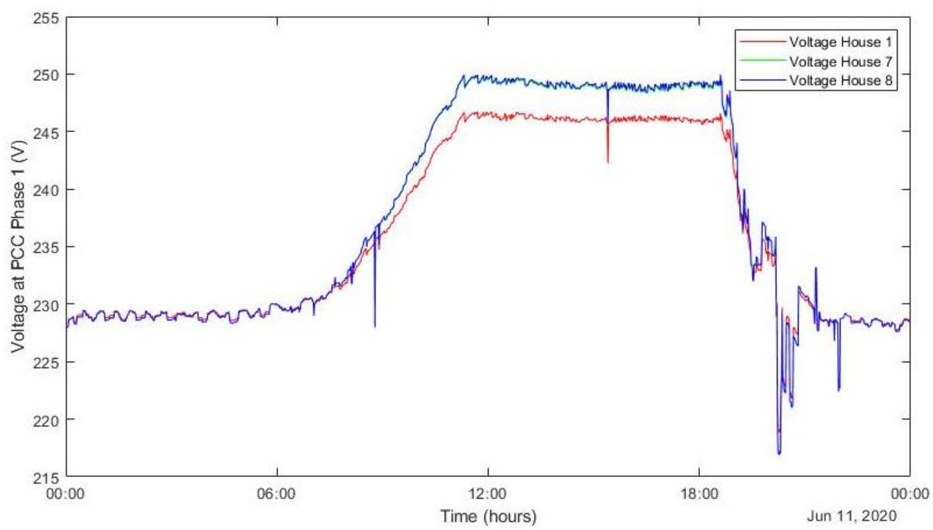

Figure 39: Voltage at PCC of houses connected to phase 1

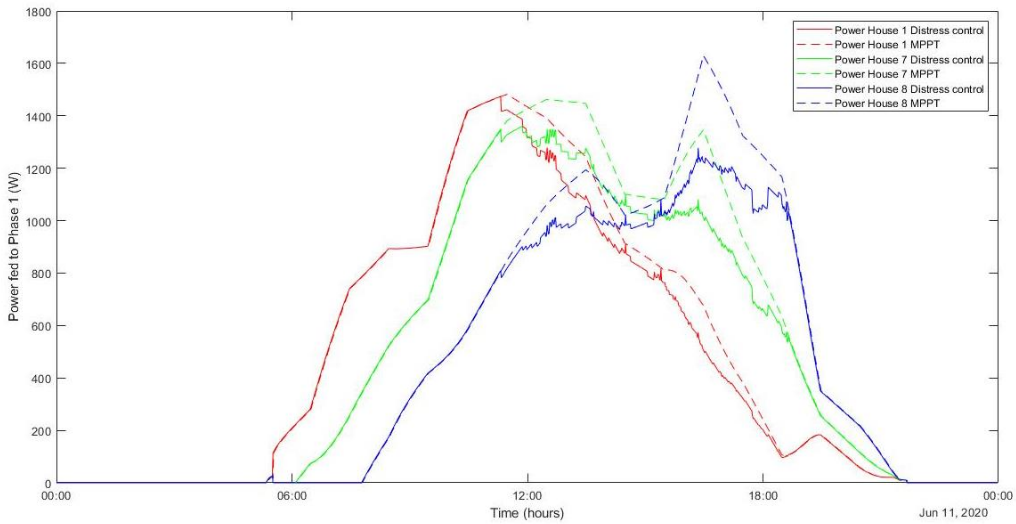

Figure 40: Power fed by houses to phase 1 with distress control in comparison to MPPT power

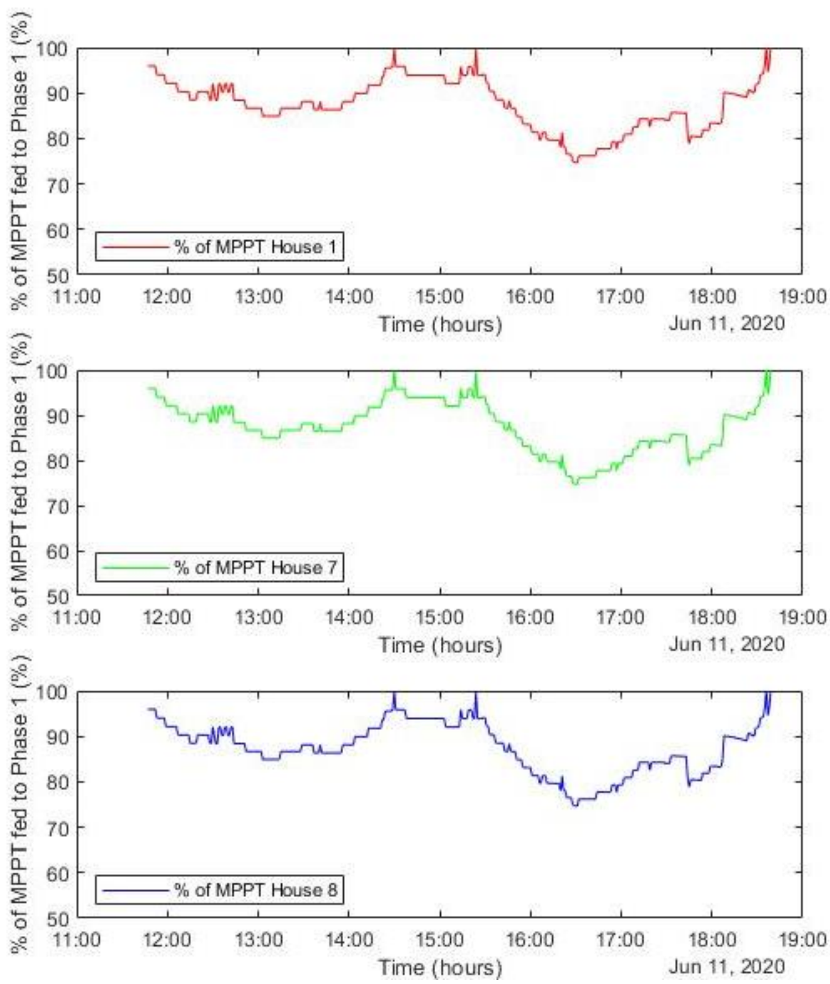

Figure 41: Percentage of MPPT power fed to phase 1 by different houses

The total amount of energy fed to phase 1 after 1 day of simulation during over-voltage situations is 68.847 kWh. Table 10 shows the percentage of maximum energy fed to the grid by various houses which shows that the distress signal control algorithm is fair during curtailment.

Table 11: Comparison of energy fed by different houses during curtailment situations

House	**% of MPPT energy fed during curtailment event after 1 day**
H1	88.25%
H7	88.25%
H8	88.25%

7.2.4. Centrally controlled droop algorithm

Figure 42 shows the voltage at PCC and power fed by houses 1, 7 and 8 to phase 1. Based on the curtailment history and voltage levels, the houses curtail a different percentage of power at any instant of time, but the percentage of power curtailment becomes fair over a period of time.

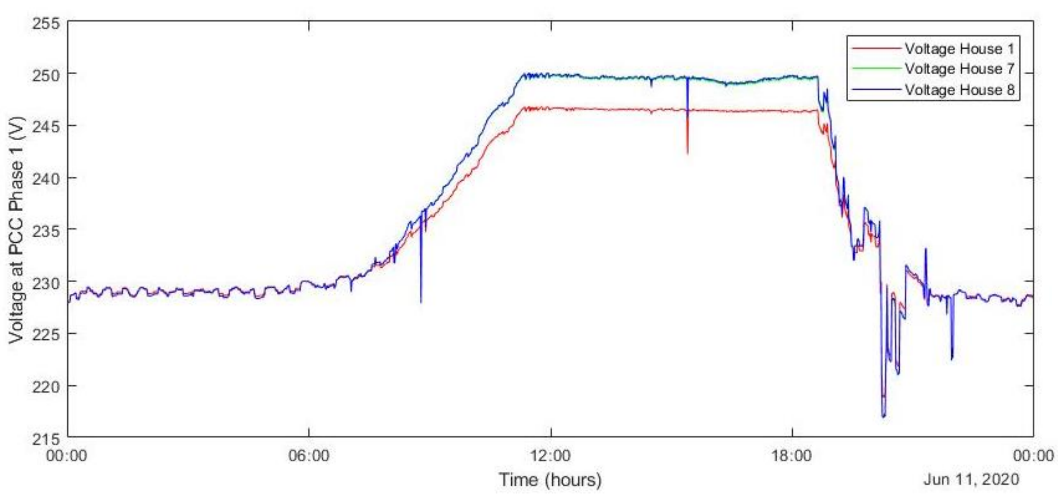

Figure 42: Voltage at PCC of houses connected to phase 1

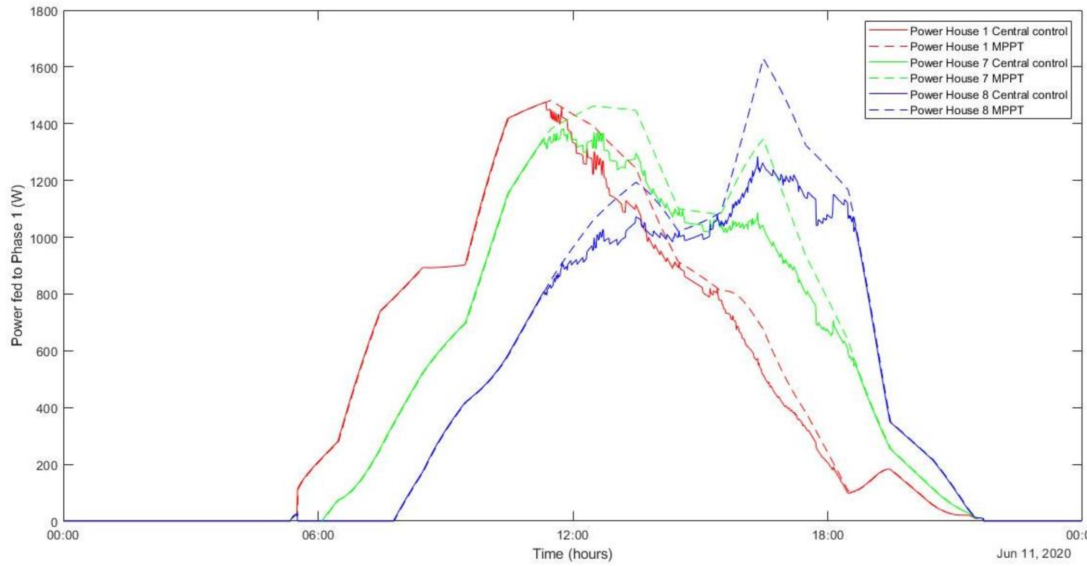

Figure 43: Power fed by houses to phase 1 with distress control in comparison to MPPT power

The comparison power fed by different houses to phase 1 is shown in Figure 43. The percentage of power of different houses varies alternatively based on the history of curtailment as shown in Figure 44 towards achieving a fair curtailment over a longer time period.

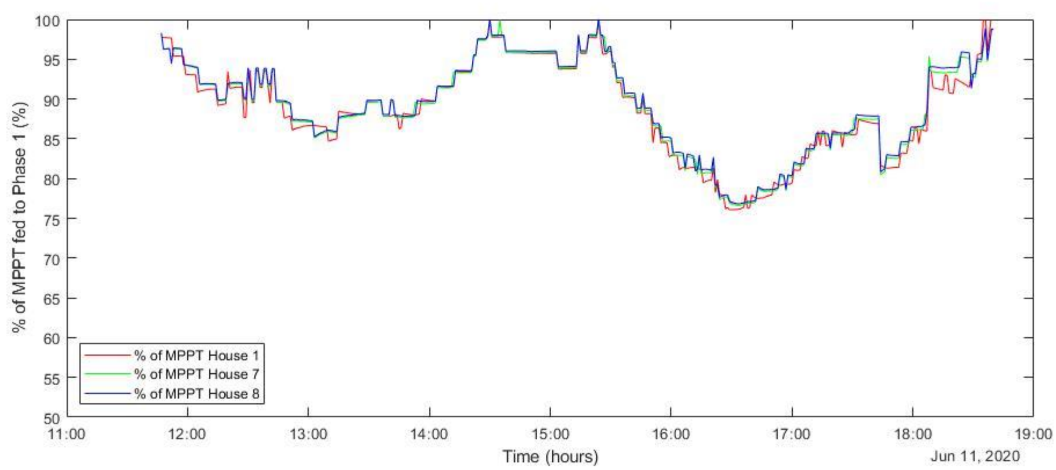

Figure 44: Percentage of MPPT power fed to phase 1 by different houses

To analyze the convergence of this algorithm for fairness, the percentage of energy fed by various houses connected to phase 1 during the over-voltage situation is compared in Table 12. The algorithm has achieved a reasonable amount of fairness over time with percentage feed in reaching a close range of 88.5% to 89.5%. The normalized values with respect to house 1 shows the convergence of the algorithm towards a fair scenario, although the time required to achieve complete convergence can vary on a case to case basis depending on a many factors like irradiance, load conditions, and voltage levels.

Table 12: Comparison of energy fed by different houses during curtailment situations

House	**% of MPPT energy fed during curtailment event after 1 day**	**Normalized MPPT energy fed after 1 day**	**% of MPPT energy fed during curtailment event after 3 days**	**Normalized MPPT energy fed after 3 days**
H1	89.48%	1	89.37%	1
H7	88.90%	0.9935	88.81%	0.9937
H8	88.54%	0.9894	88.46%	0.9898

7.2.5. Comparison and discussion

A comparison of grid compliance, fairness and total energy fed for the three algorithms during curtailment events is shown in Table 13.

Table 13: Comparison of results

Algorithm	**Voltage level (V)**	**Fairness**	**Total energy fed to Phase 1 during curtailment after 1 day (kWh)**
ON/OFF control	< 253 always, but with frequent voltage fluctuations	Unfair	7.666
Droop control	< 253 always	Unfair	71.448
Distress signal control	< 253 always	Fair	68.847
Centrally controlled droop	< 253 always	Fair over a period of time	69.835

The droop control algorithm is unfair in its curtailment strategy but has curtailed the least amount of energy compared to other algorithms. While the distress signal control algorithm allows less feed in of energy of 68.847 kWh while maintaining fairness at every point in time. The centrally controlled droop algorithm makes a time trade-off to maintain fairness over a period of time and curtails less energy than the distress signal control algorithm.

7.3. Scenario 3

Scenario 3 discussed in Section 5.2.3 represents a three phase urban feeder of length 450m with 40 houses with different types and sizes of PV systems connected to it. Further, the results of this scenario executed with the control algorithms are presented.

7.3.1. ON/OFF control algorithm

The response of three phase inverters in house 1, 15 and 35 connected to phase 1 is analyzed. The voltage at the PCC of house of house 15 and 35 crosses 253V only during the late afternoon hours. However, inverter in house 1 does not sense any overvoltage during the entire day. From Figure 45 it can be seen that inverters in house 15 and 35 trip during these overvoltage times.

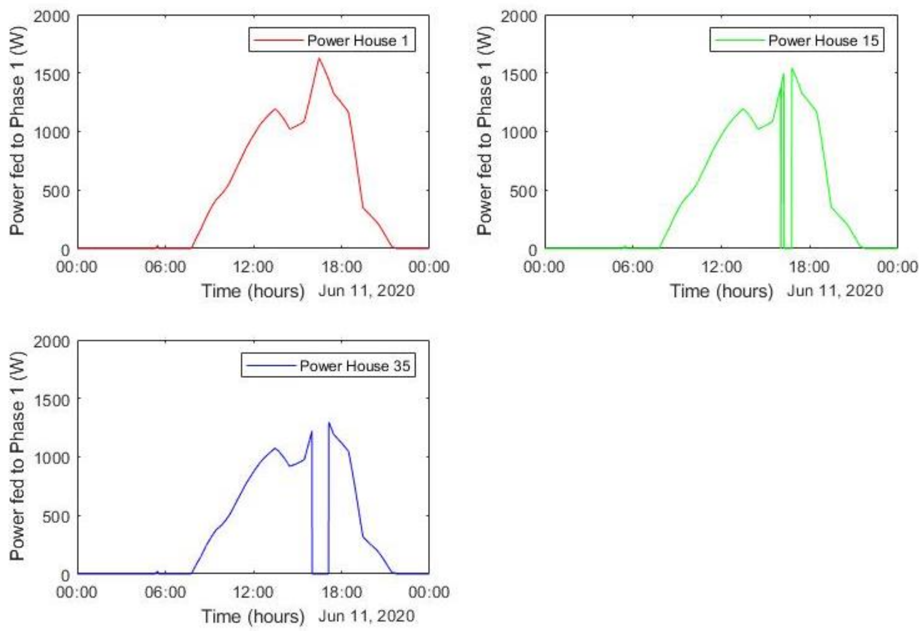

Figure 45: Power fed by house 1, 15, and 35 to phase 1

Due to the disconnection of inverters from phase 1 during peak power generation hours, a sudden dip in voltage could be seen in Figure 46.

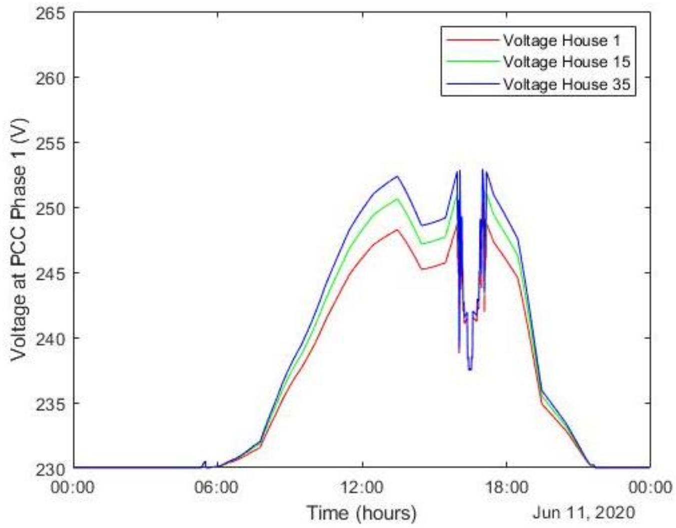

Figure 46: Voltage at PCC of house 1, 15, 35 at phase 1

7.3.2. Droop control algorithm

When evaluating the simulation results of the droop control algorithm for this scenario, an increased curtailment of PV system in house 35 is seen compared to PV systems at house 15 and 1 as shown in Figure 47. Also, during the afternoon hours when the voltage at PCC of houses 15 and 35 increases beyond 250V, only PV system of houses 15 and 35 gets curtailed whereas PV systems in house 1 does not face any curtailment.

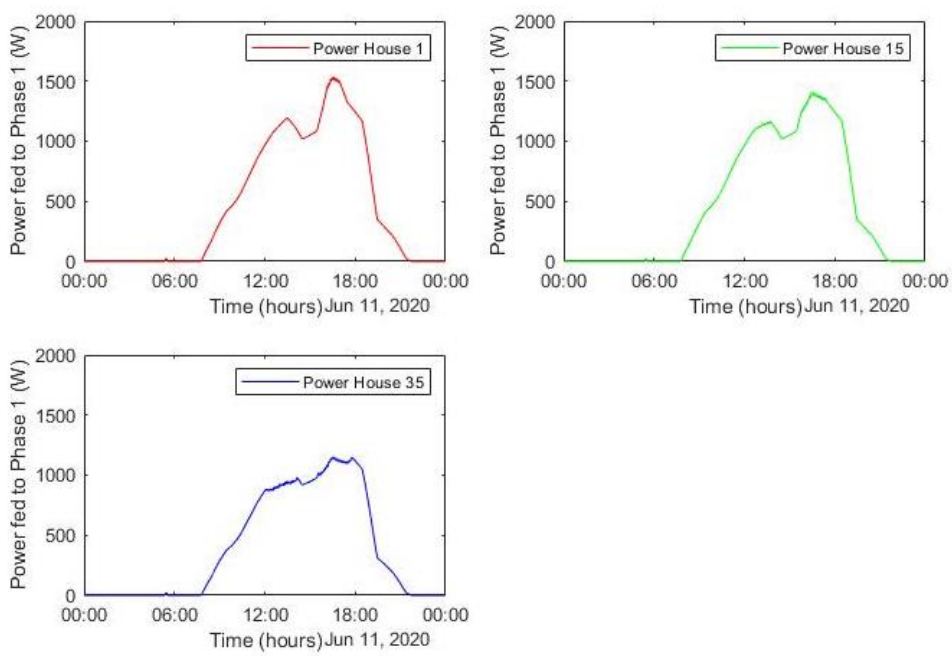

Figure 47: Power fed by house 1, 15, and 35 to phase 1

However, a smoother voltage curve is achieved as a result of this unfair curtailment of power among the PV systems. Figure 48(a) shows the voltage at PCC of house 1, 15 and 35. Table 14 shows the comparison of percentage of MPPT energy fed to phase 1 by PV systems in house 1, 15 and 35 during the over-voltage situations.

Table 14: Comparison of energy fed by different houses during curtailment situations

House	**% of MPPT energy fed during curtailment event after 1 day**
H1	99.27%
H15	95.94%
H35	88.14%

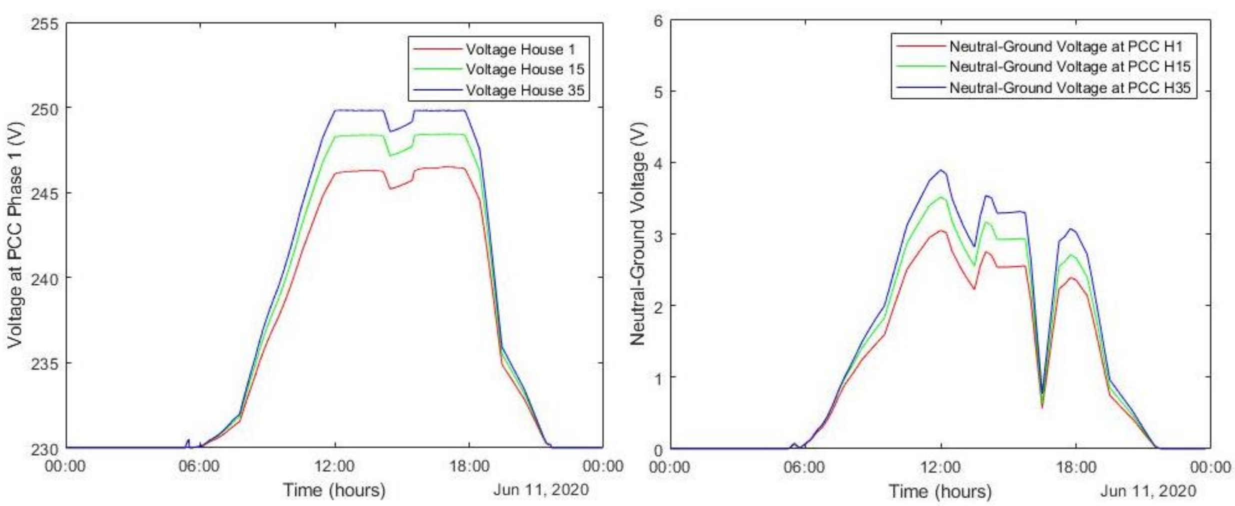

Figure 48: a) Voltage at PCC of house 1, 15, 35 at phase 1 b) Neutral-Ground voltage at PCC of house 1, 15 and 35

Figure 48(b) shows the neutral to ground voltage after the implementation of droop control algorithm. It is seen that the neutral to voltage is lower after the implementation of droop control, however a zero neutral-ground voltage cannot be achieved due to the inherent unbalanced distribution of houses.

7.3.3. Distress signal control algorithm

With the distress signal control algorithm, curtailment of energy is seen in all the three PV systems during the over-voltage situations during the afternoons (12:00 hours) and late afternoons (18:00 hours). A comparison of output power of PV systems in house 1, 15 and 35 is shown in Figure 49.

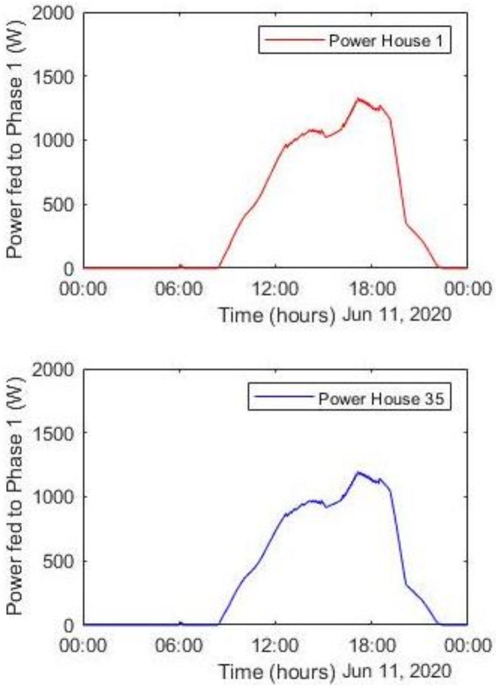

Figure 49: Power fed by house 1, 15, and 35 to phase 1

The voltage compliance to levels below 253V can be seen in Figure 50(a). In this case, the same percentage of curtailment is seen in all the three houses which represent fairness among houses achieved at every point of time. Figure 48(b) shows the neutral to ground voltage after the implementation of distress signal control algorithm. Table 15 shows the same percentage of power being fed to phase 1 during the over-voltage situations, although every houses feeds in less power compared to the droop control scenario.

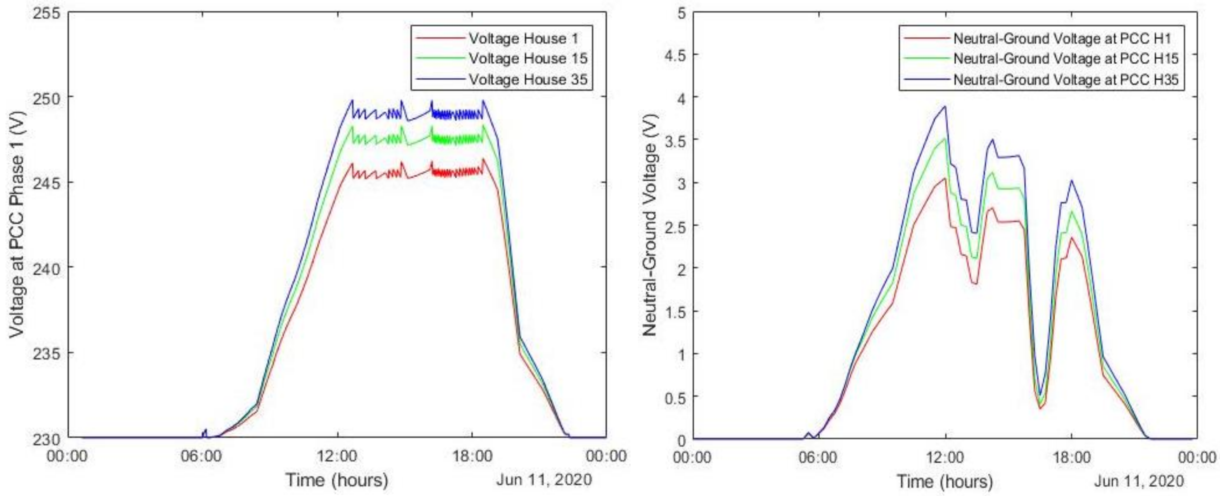

Figure 50: Voltage at PCC of house 1, 15, 35 at phase 11 b) Neutral-Ground voltage at PCC of house 1, 15 and 35

Table 15: Comparison of energy fed by different houses during curtailment situations

House	**% of MPPT energy fed during curtailment event after 1 day**
H1	86.07%
H15	86.07%
H35	86.07%

7.3.4. Centrally controlled droop algorithm

The implementation of centrally controlled droop algorithm ensures grid compliance as shown in Figure 51(a). Figure 51(b) shows the neutral to ground voltage after the implementation of central control algorithm. Figure 52 shows the power fed by house 1 and 15 are high alternatively during different times.

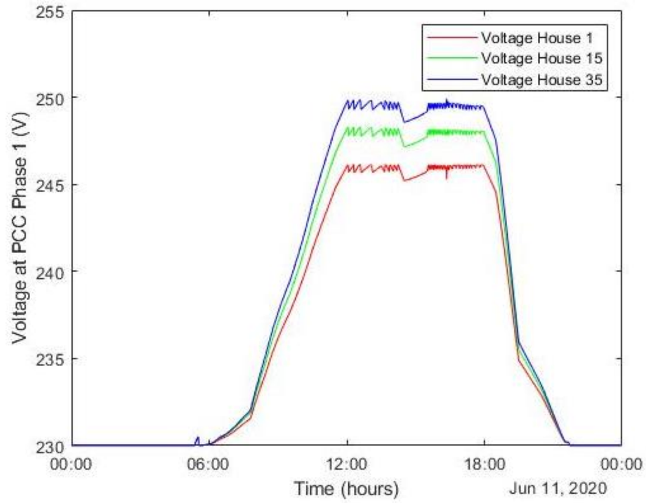

Figure 51: Voltage at PCC of house 1, 15, 35 at phase 1 b) Neutral-Ground voltage at PCC of house 1, 15 and 35

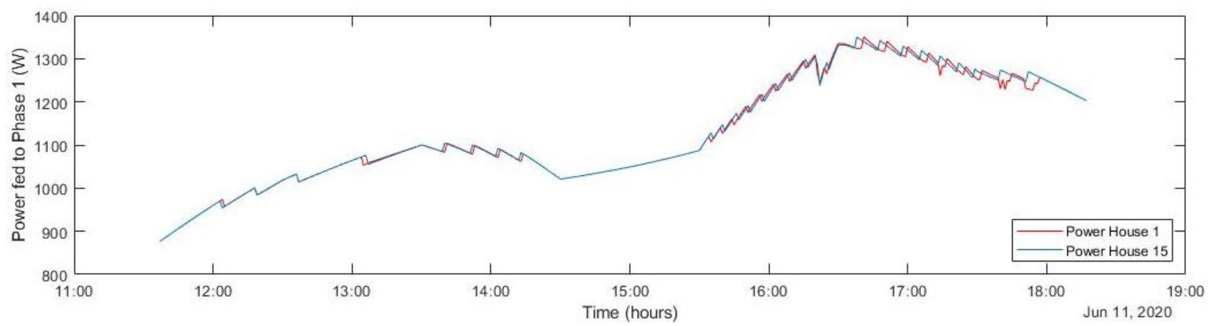

Figure 52: Power fed by house 1 and 15 during the over-voltage situation

A comparison of energy fed by house 1, 15 and 35 during curtailment situations is shown in Table 16. Although the percentage of energy fed is not exactly same, the algorithm is close to achieving a fair curtailment. The overall percentage of energy fed with the centrally controlled droop algorithm is higher than the distress signal control case.

Table 16: Comparison of energy fed by different houses during curtailment situations

House	**% of MPPT energy fed during curtailment event after 1 day**
H1	91.46%
H15	91.52%
H35	91.64%

7.3.5. Comparison and discussion

The level of over-voltages seen in the urban feeder scenario is very less compared to lengthy rural feeders. A similar behavior of algorithms is seen in the urban feeder scenario with the centrally controlled droop algorithm achieving a reasonable fairness over time and curtailing less energy compared to the distress signal algorithm.

8. CONCLUSIONS AND DISCUSSION

Firstly, in the literature survey the low voltage grid structure, grid regulations due to the addition of DERs like PV in the grid, types of PV inverters are discussed. Further, existing PV curtailment algorithms are discussed briefly. Case studies and problems due to increasing PV penetration in different countries are also analyzed.

This work is focused on implementing fair PV curtailment algorithms for a three phase distribution grid using various scenarios of PV systems, loads and distribution of houses over phases that can occur in the grid. The main focus of the work is to design a PV curtailment strategy that can not only maintain fairness among PV owners but also reduce the total amount of energy curtailed.

Initially, different components like the feeder and types of PV systems are modeled in DEMKit. Various grid scenarios are created using varied combination of parameters including number of houses, size and direction of panels, length of feeder, cable impedances and load conditions. These scenarios are simulated without any control to understand the problems and grid violations that could occur in such situations. Furthermore, four PV curtailment algorithms of various types including unfair, fair, distributed control and central control algorithms are discussed. Each scenario is tested with these control algorithms and the grid compliance, fairness and total energy curtailed are compared. From the results it is clear that the distress signal control algorithm and centrally controlled droop algorithm are able to maintain fairness at every instant of time and over a period of time respectively. However, only the centrally controlled droop algorithm is able to achieve both fairness and reduced energy curtailment.

In conclusion, a brief reflection on the research questions is presented.

How can a heterogeneous set of PV inverters be controlled to curtail power in a fair way while respecting grid limitations?

Sub-questions:

- *How should fairness be defined?*

  Throughout this work, fairness during curtailment is achieved phase-wise in a three phase distribution system. i.e. houses connected to the same phase curtail the same amount of power during an over-voltage situation. So fairness is defined as – "Every house connected to a certain phase feeds the same percentage of its maximum energy to the grid (fed energy/maximum possible energy) instantaneously or over a period of time during overvoltage situations in the particular phase"

- *What is a realistic scenario with different types of PV inverters and which problems are expected in such scenarios?*

  Grid scenarios are designed based on parameters obtained from [28-30] which are specifically focused on cases in the Netherlands. On simulating each scenario, problems like over-voltages, voltage unbalances, neutral point shift are analyzed. Most of these problems occurred during afternoons when the PV generation is the highest. More severe over-voltage problems are seen in rural feeders compared to urban feeders.

- *Which control algorithms can tackle these problems in an effective and fair manner?*

  The droop control algorithm, distress signal control and centrally controlled droop curtailment algorithms are capable of achieving grid compliance in such situations. However, only the distress signal control and centrally controlled droop curtailment algorithms are able to maintain fairness during curtailment instantaneously or over a period of time.

- *How and which trade-offs can be made between minimizing energy curtailment and maximizing fairness among PV owners?*

  Time is the factor used to achieve a trade-off between minimizing energy curtailment and fairness among PV owners. The centrally controlled droop algorithm is able to reduce the total energy curtailed compared to the distress signal control with a trade-off that fairness is achieved over a period of time and not at every point in time.

9. RECOMMENDATIONS

The following recommendations are made for future works on curtailment algorithms.

In this work, fairness is achieved only among houses connected to the same phase. Ideally, a prosumer would expect fairness to be maintained among all prosumers connected to the same feeder. Implementing fairness across phases with the current algorithms would lead to a large amount of curtailment of renewable energy. Hence, strategies to achieve fairness across PV systems connected to different phases could be investigated.

Although this work is only focused on curtailment algorithms for PV systems connected to the grid, the algorithms can also be extended to other sources. The algorithms are basically inverter controlled algorithms and hence can be applicable to other DERs like micro-wind turbines. However, in a grid scenario that has a combination of PV systems and wind turbines, maintaining fairness among these sources is not always possible with these algorithms. This is due to the fact that the power generation hours of these two sources are not the same. For example, a wind turbine could produce energy during the night hours. If over-voltage situations occur during these hours then it is obvious that fairness could be achieved only among wind turbines and not among PV systems. Future works could focus on scenarios with a combination of multiple DERs. Further, a combination of source and demand side management could be analyzed. Such a case would not only include generation control but also demand side controls like load shedding, load shifting and many more.

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