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Theme

Load Shedding Strategies in Power System Distrubition in the Presence of Renewable Energy

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الملخص

الانقطاعات الكهربائية واسعة النطاق، تحدث غالبًا نتيجة لعدم استقرار الجهد في شبكات التوزيع، والذي ينجم عادةً عن حالات تحميل زائدة كبيرة. ولتفادي العواقب الخطيرة، يصبح من الضروري تفعيل أجهزة الحماية من خلال استراتيجية تقليل الأحمال. تهدف هذه الدراسة إلى تطوير منهجية جديدة لتقليل الأحمال عند انخفاض الجهد(UVLS) ، مع ضمان تحسين معيارين أساسيين في الاستراتيجية وهما: كمية الأحمال التي يتم تقليلها وأولوية الحمل، وذلك للحفاظ على استقرار الشبكة في وجود أو غياب التوليد الموزع (DG). تكمن المساهمة الرئيسية لهذا البحث في تطبيق آلية تقليل أحمال تكيفية تعتمد على خوارزمية المنطق الضبابي. في ظل السياق المتزايد لامركزية الشبكات، يصبح تحديد مواقع فعالة لتقليل الأحمال أمرًا بالغ الأهمية، حيث يُستخدم مؤشر استقرار الجهد (VSI) لتحديد العقد الأكثر عرضة لانهيار الجهد، مع السعي لتقليل كمية الأحمال المقتطعة وتعظيم قيم الجهد في العقد الحرجة، وذلك ضمن القيود التشغيلية والأمنية للشبكة.

الكلمات المفتاحية: الانقطاع الكهربائي، شبكات التوزيع، التحميل الزائد، تقليل الأحمال عند انخفاض الجهد (UVLS)، التوليد الموزع (DG)، تقليل أحمال تكيفي، المنطق الضبابي، ، مؤشر استقرار الجهد (VSI).

ABSTRACT

Large-scale power outages, commonly referred to as blackouts, often occur due to voltage instability within distribution power systems, typically triggered by significant overload conditions. To prevent severe consequences, the activation of protective devices through a load shedding strategy is essential. This study proposes a novel approach for Under-Voltage Load Shedding (UVLS) aimed at optimizing two critical aspects of the load shedding strategy: the amount of load to be shed and the prioritization of loads, thereby ensuring power system stability both in the presence and absence of distributed generation (DG). The primary contribution of this research lies in the implementation of an adaptive load shedding mechanism based on a fuzzy logic algorithm. In the context of increasing decentralization, identifying optimal load shedding locations is crucial. This is achieved by utilizing the Voltage Stability Index (VSI) to pinpoint nodes most vulnerable to voltage collapse, while simultaneously minimizing the amount of load shed and maximizing voltage amplitudes at critical nodes, all within the operational and safety constraints of the power system.

keywords: Blackout, Distribution Power Systems, Overload, Under-Voltage Load Shedding (UVLS), Distributed Generation (DG), Adaptive Load Shedding, Fuzzy Logic, Voltage Stability Index (VSI).

RÉSUMÉ

Les coupures de courant à grande échelle, communément appelées blackouts, résultent fréquemment d'une instabilité de la tension au sein des réseaux de distribution, souvent provoquée par des surcharges significatives. Afin de prévenir des conséquences graves, l'activation de dispositifs de protection via une stratégie de délestage s'avère indispensable. Ce travail propose le développement d'une nouvelle méthodologie pour le délestage en tension (UVLS), visant à optimiser deux critères essentiels : la quantité de charge délestée ainsi que la hiérarchisation des priorités de charge, dans le but d'assurer la stabilité du réseau aussi bien en présence qu'en l'absence de génération distribuée (DGs). La contribution majeure de cette étude réside dans l'implémentation d'un mécanisme adaptatif de délestage fondé sur un algorithme de logique floue. Dans un contexte de décentralisation croissante, il est crucial de déterminer des emplacements stratégiques pour le délestage, en exploitant l'indice de stabilité de tension (VSI) afin d'identifier les nœuds les plus vulnérables à un effondrement de la tension, tout en minimisant la quantité de charge délestée et en maximisant les amplitudes de tension aux points critiques, dans le respect des contraintes opérationnelles et sécuritaires du réseau.

Mots-clés: Blackouts, Réseaux de Distribution, Surcharges, Délestage en Tension (UVLS), Génération Distribuée (DGs), Délestage Adaptatif, Logique Floue, Indice de Stabilité de Tension (VSI).

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CONTENTS

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GENERAL INTRODUCTION

The electrical power power system was originally designed and dimensioned to transport electricity generated at production centres to the most remote consumption areas [1].

Typically, an electrical power system is hierarchically organised according to voltage levels and is structured into three principal subdivisions: the transmission power system, the sub-transmission power system, and the distribution power system [2].

The distribution power system is responsible for supplying electricity to all end-users. It is connected to the transmission power system—often referred to as the "infinite power system"—which helps maintain a stable frequency. Due to this connection, the primary concern in distribution becomes the voltage level [1]. Its operation is managed by a Distribution Management System (DMS).

Distribution power systems are generally configured in a radial structure. Unlike meshed structures, a radial configuration significantly simplifies the protection system, as power flow is unidirectional—from the primary substation (HV/MV) to the secondary substations (MV/LV) and ultimately to the end-users [3].

A distribution power system operates under normal conditions when the voltage remains within its stability margins. The occurrence of a fault or an overload can lead to power system instability, characterised by voltage deviations beyond acceptable limits.

To ensure service continuity and maintain power system reliability [4], the implementation of several defensive procedures becomes essential in response to major disturbances that compromise the normal operation and stability of the electrical grid [5].

In general, the stability of electrical power systems can be defined as their ability to maintain equilibrium under normal operating conditions following a disturbance, while keeping key parameters (frequency and voltage) within prescribed limits [6].

For a radial distribution power system connected to an infinite transmission system, as previously stated, the frequency remains stable. Therefore, the stability analysis focuses solely on voltage. This characteristic is a key feature of radial power systems, which are also particularly prone to significant voltage drops and frequent disturbances that may destabilise the system [7].

When defensive procedures fail or prove insufficient, an emergency solution known as *load shedding* is applied to restore system stability and avoid total system collapse (blackout) [8].

Load shedding is a management procedure within a power distribution system that involves the deliberate interruption of electricity supply for short periods. Several load shedding approaches aim to minimise the amount of load curtailed and to do so at optimal locations. These include conventional techniques, adaptive techniques, intelligent methods, and strategies based on stability indices [9].

This dissertation aims to examine a load shedding strategy within a radial distribution power system, with the goal of identifying the most optimal approach. The study compares two techniques—conventional and adaptive—while taking into account the magnitude of disturbances, the load to be shed at each threshold level, and the minimum voltage achieved following the shedding operation [10].

Renewable energy sources, referred to as distributed generations (DGs), are integrated into the studied power system and are optimally located in terms of both quantity and placement. The presence of DGs contributes to enhanced distribution power system stability, as these sources can compensate for energy supply deficits. Consequently, load shedding becomes unnecessary in cases of minor overloads, whereas it remains essential under severe overload conditions. Therefore, the overall amount of load to be shed is mitigated by the presence of DGs [8].

The structure of this dissertation is divided into four chapters:

- **Chapter One** presents a literature review outlining the general characteristics of electrical distribution power systems. It also addresses the impact of integrating renewable energy sources into these power systems, followed by an introduction to the concept of stability in distribution systems and, finally, emergency control mechanisms, particularly load shedding and its various types.
- **Chapter Two** provides a detailed overview of the different load shedding techniques proposed in the literature, concluding with a comparative analysis of these methods.
- **Chapter Three** proposes a methodology for adaptive load shedding. It is divided into two main parts: the first part addresses the formulation of the proposed problem, while the second focuses on the implementation of the proposed approach. This chapter also includes a discussion of simulation results that reflect how the electrical distribution power system behaves during voltage variations, in the presence of DGs, under certain conditions. We present a comparative study to validate the effectiveness of the proposed adaptive load shedding approach against the conventional technique.

This work concludes with a general conclusion that summarises the key findings and outcomes of the dissertation.

CHAPTER 1

GENERALITY ABOUT BLACKOUTS

1.1 Introduction

Currently, with the increase in the interconnection of electrical power systems, the competitive aspect linked to deregulation, as well as the difficulty of building new works linked to environmental problems, the safety margins of electrical power systems are decreasing, and their operation is becoming more and more complex. Indeed, the triggering of a major transmission line or a generator can lead to the appearance of major failures in electrical power systems (blackouts). These blackouts have considerable economic and social consequences. To improve the security of electrical power systems, it is therefore interesting for the electricity power system manager to develop new techniques in order to operate the power system more efficiently and more safely. In this first chapter, a brief history of some blackouts that have affected electrical power systems in recent years is presented. Subsequently, these blackouts' impacts, phases, and development mechanisms will be presented in detail. At the end of this chapter, we present some of the means currently used worldwide to improve the security of electrical power systems.

1.1.1 Electrical distribution power systemes

DPSs constitute the most important energy infrastructure in the energy system system, as it is the final interface leading to most electricity consumers. consumers. They are generally larger and denser than the transmission power systems, which feed them via source substations. HV/LV source substations.

1.1.2 Structure of distribution power systems

Distribution power systems are organised into two parts depending on the voltage level. A distinction is made between medium-voltage power systems - known as HV power systems - and low-voltage power systems - known as LV power systems.[11].

- Medium-voltage power systems

  The medium-voltage power system can be either overhead or underground. This power system is operated from 1 kV up to 50 kV or less in some cases (according to French standard NF C 15-100)[12] and is generally tree-lined, looped, but operated radially except in the event of a fault on the main supply diagram. It is connected to the transmission power system via source substations. These are transformer substations that lower the voltage. The source substations also provide control of the voltage, power system protection, metering, etc. ...

- Low-voltage power systems

  The low-voltage power system is operated at 400 V and is generally radial and not looped. The outgoing feeders on the low-voltage power system are shorter than those on the medium-voltage power system. It is connected to medium-voltage power systems via distribution substations, which lower the voltage, generally from 20 kV to 400 V. [13]

Figure 1.1 shows the structure of the distribution power system.

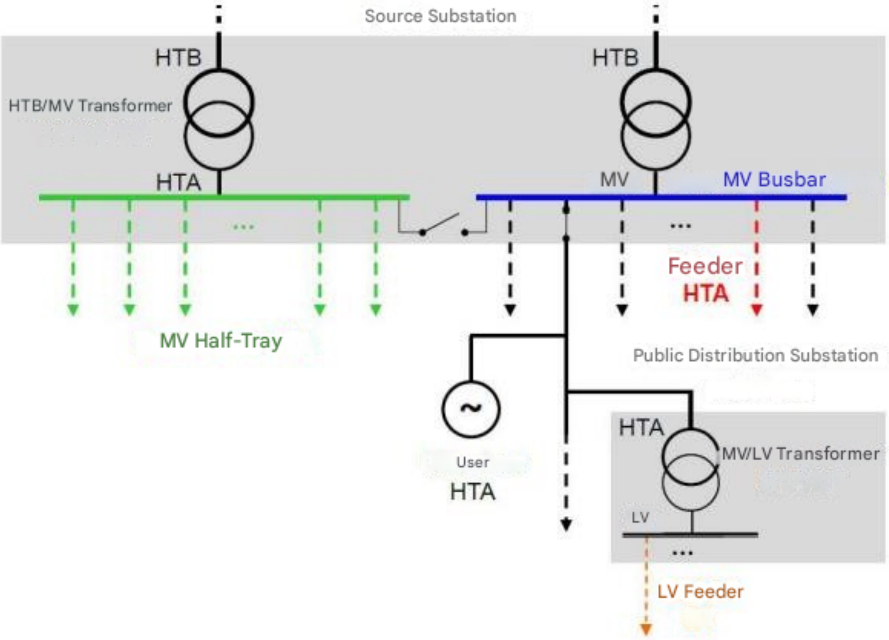

Figure 1.1: The structure of the distribution power system

1.1.3 Stability of distribution power systemes

Researchers and power system engineers claim that only voltage stability is required for distribution power systems connected to the transmission power system (infinite node). Frequency is kept stable by the transmission power system [14]. The work in this thesis is in line with this line of research on distribution power system voltage stability. Voltage stability is the ability of an electrical system to maintain node voltages at acceptable levels during normal operation or after a disturbance [15]. Voltage instability results from the inability of the generation-transmission-distribution system to : -Supply the power demanded by a heavy load, -Withstand a short-circuit, -Meet a high reactive power demand. The system becomes unstable if a disturbance causes a progressive and uncontrolled drop in voltage. This generally takes the form of a monotonic decrease in voltage. Voltage collapse leads to a very low voltage in part or all of the power system, which causes a cascade collapse of the power system, without causing the loss of synchronism between generators.

1.2 Electrical blackouts

The term 'blackout' refers to a large-scale power cut affecting several regions or even an entire country. entire country. When a large-scale blackout occurs, it can cause significant economic damage. damage, and it also affects other important infrastructures that provide essential services such as services such as communications, internet, transport, water and emergency services. At the last two decades, several major power outages have been experienced in different countries around the world. The table below provides a brief overview of some of the major blackouts blackouts that have affected the world since the 2000s, for which we have obtained relatively detailed information (Table 1.1) [16].

Table 1.1: Main blackouts affecting the world in recent years.

Blackouts	**Year**
Algeria	03/02/2003
Italy	28/09/2003
Sweden/Denmark	23/09/2003
North East United States and Canada	14/08/2003
Greece	12/07/2004
Europe	04/11/2006
Nord et à l'Est de l'Inde	30 and 31 July 2012
Turkey	31/03/2015

In this section, we attempt to describe some of the root causes and mechanisms of these major of these major failures taken from the published literature on these failures [16, 17].

1.2.1 Impact of blackouts

Generally speaking, electricity blackouts cause huge economic losses and plunge millions of people into total darkness in a very short space of time. millions of people into total darkness in a very short space of time, as shown in (Table 1.2).

Table 1.2: Impacts of electrical blackouts.

Blackout	Population Affected	Lost load
Algeria	25 million	4476 MW
Italy	56 million	177 GWH
Sweden/Denmark	1.6 million in Sweden and 2.4 million in Denmark	4700 MW to Sweden 1850MW in Denmark
North East United States and Canada	50 million people	62000MW
Greece	5 million	4500 MW
Europe, Germany and North Western Europe	15 million	14GW
North and East India	620 million	48000MW
Turkey	76 million	33 450 MW

1.2.2 Blackout evolution phases

According to the results of the analysis of some blackouts, the phases in the evolution of electrical blackouts can be described in the figure below [18]

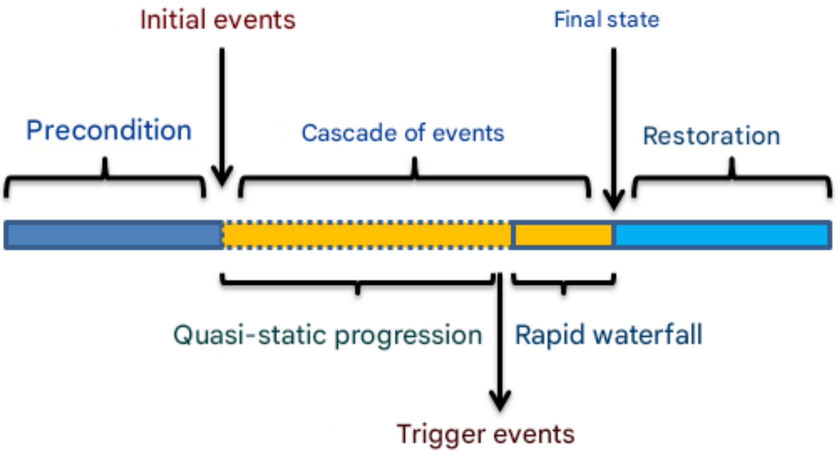

Figure 1.2: Phases in the evolution of electrical blackouts.

The development phases of a blackout are pre-conditions, initial events, cascade of events and recovery. cascade of events and recovery. The cascade of events can be further subdivided into two phases in the process of certain blackouts: the quasi-static progression and the rapid cascade as shown in (Figure 1.2). In the quasi-static progression period, the progression of the cascade of events is slow, and the system can maintain a balance between production and consumption. consumption. In the period of rapid cascade, it is generally too late for the grid operator to take corrective action. for the grid operator to take remedial action, as the blackout generally progresses very quickly. is generally very rapid. The(Table 1.3)summarises the period of each phase of the blackouts analysed.

Table 1.3: Duration of each phase of the blackouts analysed

Country	Slow cascade	Fast cascade	Recovery Duration
Algeria	Without	15 seconds	06 hours
Italy	24 min	2.5 minutes	18- 24 hours
Sweden/Denmark	5 min	90 seconds	6 hours
North East United States and Canada	1 h 05 min	03 minutes	24 hours
Greece	13 min	02 minutes	3 hours
Europe	-	19seconds	02 hours
North and East India	-	15 seconds 1 min 36 s	16 hours for 30 July 2012 21:30 for 31 July 2012
Turkey	-	15 seconds	7 Hours and 18 Minutes

The initial events in various blackouts are diverse and varied. These events may directly cause the blackout or aggravate the conditions of the power system that may indirectly lead to it. Short circuits, overloads, and protection failures are the usual initial events. Other events, such as the loss of a generator, can sometimes also be the initial events. The initial blackout events analysed here are shown in Table 1.4.

Table 1.4: Initial blackout events analysed

Country	**Initial Events**			
	Short Circuit	**Surcharge**	**Protection Failure**	**Generator Loss**
Algeria		*		*
Italy	*	*	*	
Sweden/Denmark				*
North East United States and Canada	*			
Greece	*			*
European interconnected power system		*		
North and East of India		*	*	
Turkey		*		

1.2.3 Blackout development mechanisms

The mechanism or chain of events leading to electricity blackouts is directly linked to the processes of directly linked to the loss of stability of electricity power systems. This loss of stability manifests itself mainly through four types of phenomena [18]:

- cascades of overloads
- voltage collapse
- frequency collapse
- synchronism failures

Based on the available data, we have identified the main phenomena that lead to the blackouts analysed:

Table 1.5: Analysis of Blackout Development Mechanisms

Country	**Voltage Collapse**	**Frequency Collapse**	**Overload Cascade**	**Loss of Synchronism**
Algeria		*	*	
Italy		*	*	
Sweden/Denmark	*		*	
North East United States and Canada	*		*	
Greece	*			
Europe			*	*
North and East India			*	
Turkey		*	*	*

1.3 Ways of improving the safety of electricity power system

In order to guarantee quality of service to their customers, electricity companies have developed planning and operating rules to ensure that the electricity power system is able to cope at all times with common contingencies, such as the loss of one or more transmission or power generation facilities or a poor estimate of the consumption profile. In fact, these measures alone may not be sufficient to protect the power system from hazards with serious consequences, such as poorly eliminated short circuits [19]. In practice, to improve the security of electricity power systems, power companies are adopting other means that complement the current planning and operating rules. In this section we present some of the methods used.

1.3.1 Defence plan

A defence plan is a set of coordinated automatic measures designed to ensure that electricity power systems are protected against disturbances involving unforeseen events. The defence plan is therefore the ultimate barrier for protecting the power system in the event of a major incident, when all other measures, such as protection systems and generator control devices, have failed to stop the chain of incidents and limit their consequences[20]. The aims of a defence plan are to:

- detect that the power system is in a degraded state;
- take appropriate remedial measures to stop incidents spreading to the rest of the power system:
- by sacrificing the supply of non-priority customers if necessary;
- by organising the breakdown of the power system in order to save the healthy parts;
- to enable a rapid return to a healthy power system situation;
- to promote, as a last resort, the subsequent reconstitution of the system.

Generally, a defence plan is made up of two lines of defence, the scope of which is not covered by the planning and operating rules[21]. The first line of defence is made up of a certain number of measures taken by power system operators in control centres during incidents, when the dynamics of the phenomenon allow it. The measures taken enable the power system to be restored to a viable situation as soon as possible. In general, these measures are [22]:

- Changing the active and/or reactive generation setpoints of the generating units: The generating units are asked to produce as much active and/or reactive power as possible, in order to maintain the voltage of the transmission system as much as possible;
- manual load shedding of part of the load.

1.3.2 Integration of renewable energies into distribution power systems

- **General information on renewable energy sources**

Installations producing electricity from renewable sources, known as decentralised or distributed generation, with a capacity of between 1 and 10 MW, are often connected to the distribution power system. They include: wind, hydroelectric, solar, geothermal, biofuel power plants (biomass from forestry, agriculture and wood processing, biogas from agricultural crops and organic residues and waste from the agricultural and agri-food industries, as well as industrial waste), fuel cells, or power plants using other renewable sources (waves, tides, etc.)[23]. It should be noted that a 10 MW plant can be directly inserted into the transmission grid.

- **Impact of renewable sources on distribution power systems**

The connection of distributed generation transforms a passive unilaterally fed distribution power system into an active dual-fed power system (the source itself and the infinite node (transmission power system)). The main impacts of sources on such a power system are [24] :

- Changes to the power system voltage profile (Figure 1.3)
- The appearance of transients when sources are switched on and off,
- Increased short-circuit currents,
- Changes in losses as a function of production and consumption,
- Congestion on individual lines,
- Impact on the quality and reliability of the power supply,
- Protection plan malfunctions,
- The need for protection coordination.

The growing demand for security, reliability and quality of supply places new demands on planning and development. The integration of distributed generation is a challenge in itself in terms of power quality, grid stability, system balance, voltage regulation, protection, outages (isolated mode) and reliability. A variety of renewable sources is the most important characteristic that defines their operation, in terms of uncertainty in predicting available power, the magnitude of changes in power output and the rate of change [25].

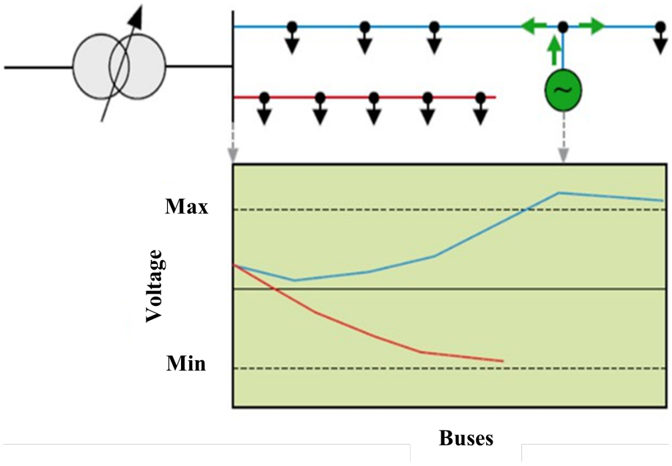

Figure 1.3: Impact of the presence of distributed generators on the voltage profile.

1.4 Conclusion

The aim of this chapter is to provide a general overview of load shedding in distribution power systems. We began with a general introduction distribution power systems, explaining voltage levels and their limits. Then we mentioned the various faults and protections. We then defined an essential point of our work, which is load shedding, citing the different types. We then looked at the integration of renewable energies into distribution power systems and the impact of this integration on several levels: voltage, protection and power quality.

The next chapter will give a detailed presentation of the different load shedding techniques and the proposed technique (adaptive technique), the aim of which is to carry out a comparative study.

CHAPTER 2

LOAD SHEDDING TECHNICS

2.1 Introduction

Electricity power system operators around the world are proposing ways of maintaining the stability of the electricity power system following severe disturbances. A drop in voltage or frequency is an indication of power system instability. A variety of load shedding techniques are adopted by system operators to avoid major outages and blackouts [26, 27]. The aim of this chapter is to present the different load shedding techniques frequently discussed in the literature: conventional, adaptive, intelligent and techniques based on stability indices.

2.2 Load shedding techniques

Different load shedding techniques are introduced, as described in Figure 2.1 [28], which have advantages, disadvantages and applicability in the power system. Conventional technique is limited in achieving optimal load shedding due to the inability to estimate the exact amount of power imbalance in systems, it can control frequency and voltage simultaneously. Intelligent techniques have proved to be the best because of their robustness and flexibility in handling complex non-linear and high-power systems. However, their use slows down the system during simulation because several steps have to be carried out beforehand, such as: faults in the electrical power system, instabilities in the power system, testing of each component, etc. The technique best suited to controlling load shedding is adaptive, thanks to its ability adjust decision criteria, autonomous behaviour, etc.[29]

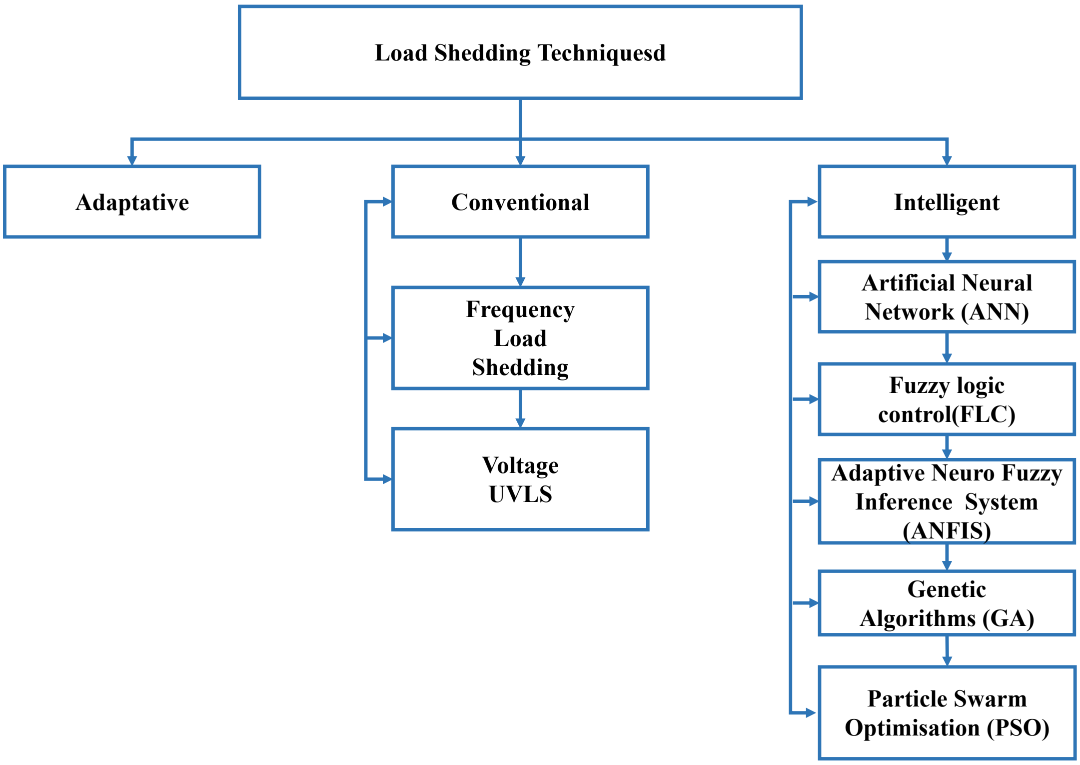

Figure 2.1: Different load shedding techniques.

2.2.1 Conventional

The conventional approach to load shedding is a simple technique for eliminating the effects of overloading in the power system [30]. There are two types of conventional technique: conventional frequency load shedding (UFLS) and conventional voltage load shedding (UVLS)

2.2.2 Conventional frequency load shedding (UFLS)

Frequency load shedding is applied in the event of a serious fault, a more rapid drop in frequency due to the loss of generators. According to the standards of the Institute of

Electrical and Electronics Engineers (IEEE) [28], frequency load shedding must be carried out quickly to stop the frequency from dropping. by reducing the load on the electricity system to match available generation capacity". To this end, certain frequency threshold values are set to start frequency load shedding. The minimum acceptable frequency depends on the system equipment, such as the type of generator, its auxiliary device and the turbine. The UFLS relay is initialised to shed a fixed amount of load in predefined steps when the frequency falls a certain predefined threshold in order avoid a blackout[27]. The European power system of Transmission System Operators for Electricity (ENTSOE) has recommended following steps for frequency load shedding

- The first stage of automatic load shedding must be initiated at 49 Hz.
- At 49 Hz, at least 5% of the total consumption must be shed.
- 50% of the rated load should progressively disconnected using underfrequency relays in the 49.0-48.0 Hz frequency range.
- At each stage of load shedding, it is advisable not to disconnect more than 10% of the load.
- The maximum disconnection delay must be 350 ms including circuit breaker operating time. [31]

UFLS relays still fail to achieve the optimum load shedding scheme, because they shed a fixed amount of load at certain frequency thresholds. This scheme is notorious for its unreliability in shedding the right amount of load and can cause frequency overshoot. In the event of a major overload, the relay setting cannot ensure the load-shedding procedure. In addition, this technique lacks the flexibility to deal with different types of instability (frequency and voltage instabilities). Due to the increasing number operations on modern power grids[28], this technique has become increasingly popular.

2.2.3 Conventional voltage load shedding (UVLS)

UVLS schemes are implemented to protect the power system voltage collapse. The major power outages that have occurred in the world have been caused by voltage instability problems, which generally occur due to forced generator shutdown, line loss or overload.

In this situation, the demand for reactive power increases in the electrical system and the margin of stability is reduced. decreases. A conventional UVLS is performed when all defensive measures have been exhausted. [28] In 1998, UVLS were introduced based on decentralised voltage protection relays at local nodes. UVLS use fixed voltage thresholds, fixed time delays and fixed quantities of loads to be shed. However, this always results in either too much (over-delivering) or too little (under-delivering) in the power system. Figure 2.2 shows the flowchart of conventional UVLS . [28] . Previously, conventional UVLS is incorporated in a stepwise approach. First, the total amount of load to be discharged is a predetermined percentage of the total load that will be discharged as a unit load [32]. The voltage drops to the first threshold, a first predefined percentage of the total load is shed. If the voltage continues to decrease and reaches the second threshold, another predefined percentage of the total load is shed. This process will repeat until the voltage rises above its permissible limit. However, conventional UVLS is limited in providing optimal load shedding. UVLS has been proposed taking into voltage instability in local systems or distribution power systems [28] . Table 2.1 shows an example of conventional voltage load shedding.

Table 2.1: Example of conventional voltage load shedding

Step	**Voltage threshold (pu)**	**timer(s)**	**Load shedding (%)**
1	0.90	0.5	6
2	0.85	0.5	6
3	0.80	0.5	6
4	0.75	0.5	6
5	0.70	0.5	6
6	0.65	0.5	6
7	0.90	10	5

2.2.4 Limits of conventional load shedding techniques

Conventional load shedding techniques are limited by their inability to provide optimal load shedding . They simply follow a preset rule whereby a fixed amount of load is shed

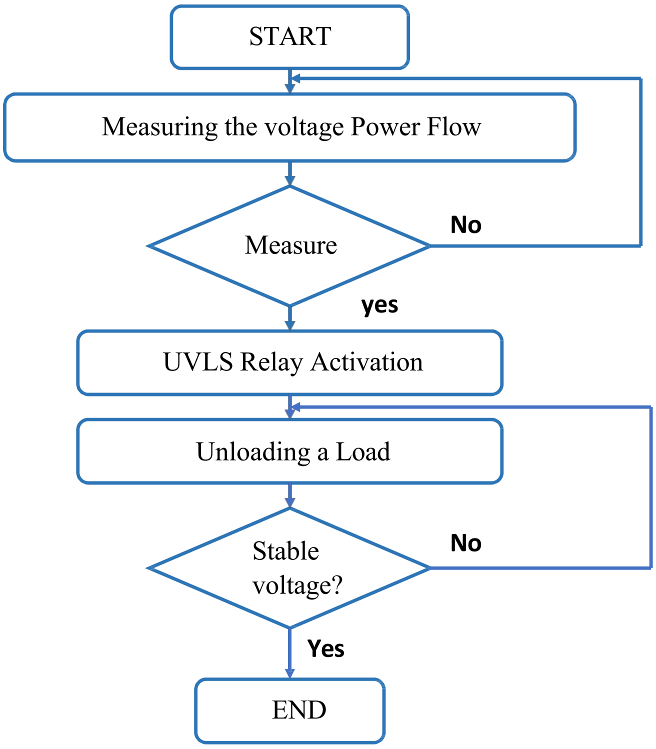

Figure 2.2: Flow chart summarising the principle of conventional Voltage load shedding.

when the frequency/voltage deviates from the nominal value. The main disadvantage of this method is that it does not allow the exact amount power imbalance to be estimated. The result is either excessive load shedding, which affects power quality, or insufficient load shedding [31].

2.3 Intelligent techniques

Computational intelligence techniques are a set of techniques applied to human intelligence [28] and include artificial neural power systems (ANNs), fuzzy logic control (FLC), genetic algorithms (GAs) and particle swarm optimisations (PSOs). They offer additional advantages over conventional techniques in solving non-linear problems and can easily solve multi-objective power system problems that cannot be solved by conventional methods with desired speed and efficiency. Smart techniques have also been applied for load shedding approaches[31] .

The following table (Table 2.2) lists some of the advantages and disadvantages of intelligent techniques[30] .

Table 2.2: Advantages and disadvantages of smart techniques .

Technical	Benefits	Disadvantage
Artificial Neural Network (ANN)	ANN has the capacity to provide an optimal amount of load shedding.	The ANN can provide satisfactory results for known cases only and may not predict accurate results for unknown or variable cases.
Fuzzy Logic Control (FLC)	The FLC can be used as a load shedding application on any size power system.	FLC membership parameters require prior knowledge of the system. Otherwise, it may not provide optimal load shedding.
Adaptive Neuro Fuzzy Inference System (ANFIS)	FLC parameters are optimised using ANN, which can lead to accurate load shedding.	It can only work with Sugeno systems.
Genetic Algorithms (GA)	GA is a global optimisation technique for solving non-linear multi-objective problems. GA ensures minimum load shedding.	GAs take a long time to determine the amount of load shedding. This relative slowness limits their use for online applications.
Particle Swarm Optimisation (PSO)	The PSO calculation is simple and has the ability to find the optimum value.	it takes a long time to determine the amount of load shedding. This relative slowness limits their use for online applications.

2.3.1 Adaptive technique

Conventional methods of system load shedding are too slow and cannot effectively calculate the correct amount of load to shed. This is because loads are not constant, as the system load can vary, making it difficult to accurately predict the amount of load to be shed at any given time and location. Another problem is that the connection of distributed generation can lead to excessive or insufficient load shedding[33]. The adaptive load shedding technique is proposed to improve the estimation of the power imbalance and to determine the appropriate location of the load to be shed, which are not efficiently solved by conventional techniques [28] This technique is tuned in real time to the estimated magnitude of one or more disturbances simultaneously[33].

2.3.2 Load shedding based on stability indices

Some research [28, 34] highlights importance of stability indices as an indicator for identifying the stability of the whole system under dynamic conditions. The stability index is widely used in power system problems such as: prediction of contingent line outages, optimal location for DG integration and detection of voltage instabilities. The application of the VSI index is widely used for load shedding in an electrical power system. Optimal load shedding can be introduced to avoid voltage instabilities during emergency situations [28].

However, relatively few contributions are reported on the application load shedding to the distribution power system. This is due to the fact that, compared with the transmission system, distribution power systems have different characteristics, such as a radial structure and a high X/R ratio, which analysis more difficult [33].

Therefore, to improve this barrier, some work has been done to propose VSI-based load shedding for the distribution system [35]. The fast voltage stability index VSI gives priority from the weakest node to the non-vital load load shedding following unstable conditions. [33].

2.4 Comparison of the three main load shedding techniques

In order to better understand the differences between conventional, adaptive and intelligent load shedding techniques, a table (Table 2.3) summarising their characteristics is shown below.

Table 2.3: Comparison between the main load shedding techniques.

Conventional	**Adaptive**	**Semi-adaptive (intelligent)**
No account taken of system inertia or topology	Includes system inertia constant and other real-time responses	Reflects the actual state and load conditions for shedding
No communication between remote protection relays and UF devices	Fibre-optic communication enables fast data exchange	The scheme is defined by the user
Delivers a fixed amount of load based on frequency thresholds. Over/under-shedding may occur.	Stepwise shedding based on rate of frequency decline. Load shedding error may occur.	Minimises shedding based on real-time load status. LS error is minimised.
Waiting time involved. Hence, slow response.	Includes delay. Leads to slow response.	Fast response with minimal delay.
Based on worst-case scenarios.	Depends on the instantaneous frequency decay rate.	Based on real-time dynamic system behaviour.
Complex design with many I/O relays.	Reduced complexity and increased reliability.	Reduced complexity.
Load priority list is not optimal.	Non-critical loads may receive power.	Priorities updated and loads classified into critical/non-critical.
Extensive simulation and transient studies required.	Major simulations not needed.	Major simulations not needed.

2.5 Conclusion

The present chapter reviews several load shedding techniques proposed in the literature, highlighting their distinctions. It has been observed that the effectiveness of one technique over another is generally assessed based on three key criteria: the stability of the distribution power system within its stability margin, the amount of load shed, and the time required for the network to regain stability. The following chapter addresses the problem of load shedding within a distribution power system and presents a description of the multi-agent system and fuzzy logic that will support the proposed method. These tools aim to achieve optimal load shedding with respect to the amount, location, and timing of the shed load. The ultimate objective is to identify the most effective method for achieving optimal load shedding.

CHAPTER 3

METHODOLOGY AND SIMULATION RESULTS

3.1 Introduction

This chapter presents an adaptive load shedding approach based on decentralised UVLS relays controlled by a fuzzy logic system. Unlike the conventional scheme, which relies solely on measured voltage, the proposed method takes into account both voltage levels and load priority at each bus, allowing for improved adaptability to varying power system events.

The chapter is structured in two parts: the first outlines the problem formulation and the proposed methodology, while the second details the simulation process and presents a comparative study between the conventional and adaptive approaches, focusing on voltage stability, minimum voltage levels, and the total amount of shed load.

3.2 Problem Formulation

Whatever the UVLS scheme developed by the researchers, à the main idea is to cut off the supply to some of the consumers to maintain the power system's voltage stability. Equation 3.1 generalises the basic principle of UVLS, also called 'conventional UVLS'.

$$\textbf{If} \quad V_i < V_{i,\text{threshold}} \quad \textbf{for a duration of} \quad t \text{ (s)}, \quad \textbf{then} \quad \Delta P_{L_i} = X_i \cdot P_{L_i} \tag{3.1}$$

Where:

- V_i is the voltage at bus i,
- $V_{i,threshold}$ is the under-voltage threshold for that bus,
- t is the time duration for which the voltage remains below the threshold,
- ΔP_{Li} is the amount of load to be shed, and DP Li represents the fixed shedding amount allocated for bus i.

If there is a further decrement in voltage and it reaches the second threshold point, another preset percentage of the total load is shed. This process will continue until the voltage exceeds its allowable limit [36]. Despite its simplicity, conventional methods are unsuitable for resolving nonlinear and multi-objective problems in large and complex power systems with the preferred precision and speed [37]. Among the causes is the consideration of a single parameter as input of the UVLS relay, the measured voltage, which makes it possible not to differentiate the importance or priority of consumers. Another point occurs during the shedding of a fixed load; this point makes the technique non-adaptive in the face of major events. In this context, finding an intelligent technique that solves the problem by adapting to the surrounding environment and improving the decision-making process to find the best solutions is essential. Among these techniques, we propose FL. FL is an extension of Boolean logic based on its mathematical theory of fuzzy sets, which generalises classical set theory. By introducing the notion of degree into verifying a condition, we allow one condition to be in another state than true or false [38]. FL confers a very appreciable flexibility to the reasoning that uses it, making it possible to account for inaccuracies and uncertainties. Fig.1 shows the main blocs building a FL controller inferred from [39], such as inputs, Fuzzyification, Rule Base, Inference System, Defuzzification, and output. Many authors apply the notion of fuzzy logic to UVLS, as in [40], where the authors consider that the fuzzy logic controller has as input the magnitude of the voltage and an index of instability and as output the load shedding. The type of fuzzy logic used was Sugeno. Fuzzy logic has two types: Mamdani and Sugeno. According to several papers [41], [42], mamdani's limitations are summarized as follows: Output membership function is present, Crisp result is obtained

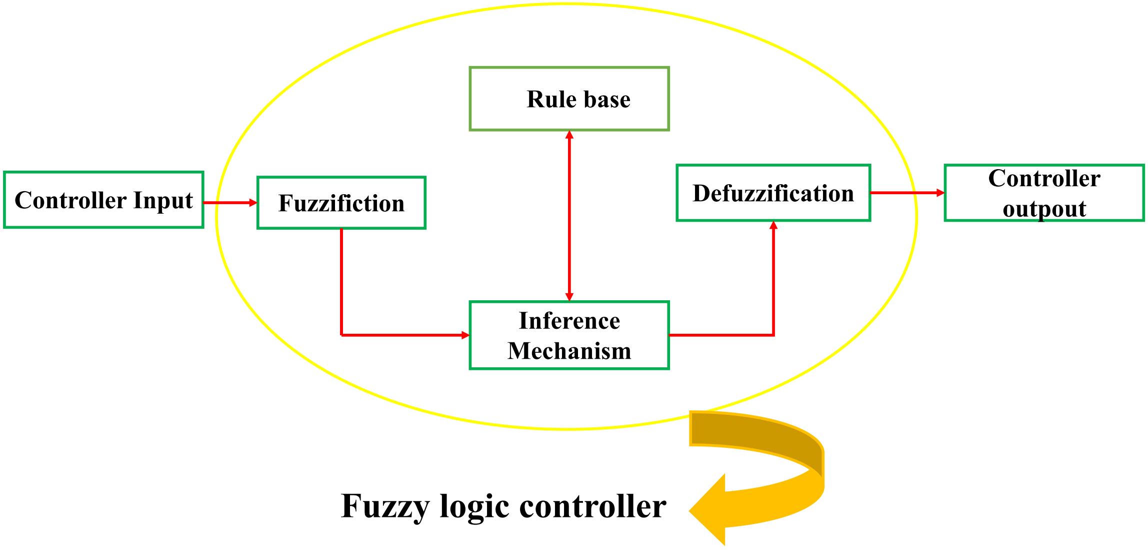

Figure 3.1: Fuzzy logic load shedding controller block diagram

through defuzzification of rules' consequent, Non continuous output ultiple Input Multiple Output) systems, Expressive power and Interpretable rule consequents, Less flexibility in system design, regarding these disadvantages, we propose in this work the sugueno type for UVLS.

3.3 Proposed UVLS Scheme

The current work proposes an application of the Sugeno fuzzy logic controller for a decentralized UVLS to maintain voltage stability in a distribution power system by shedding an amount of load to bring the voltage to its limit. Fig3.2 shows the structure of the Sugeno FIS:

The main idea behind this work is that by optimising the parameters of the Sugeno fuzzy inference system membership functions and output level through an evolutionary algorithm, the fuzzy controller can better adapt to the random nature of the load and output of renewable DGs. In the proposed approach, each bus is equipped with a UVLS relay based on a Sugeno fuzzy controller, where voltage and VSI measured at each bus are selected as inputs. The optimal parameters of the Sugeno FIS are calculated through

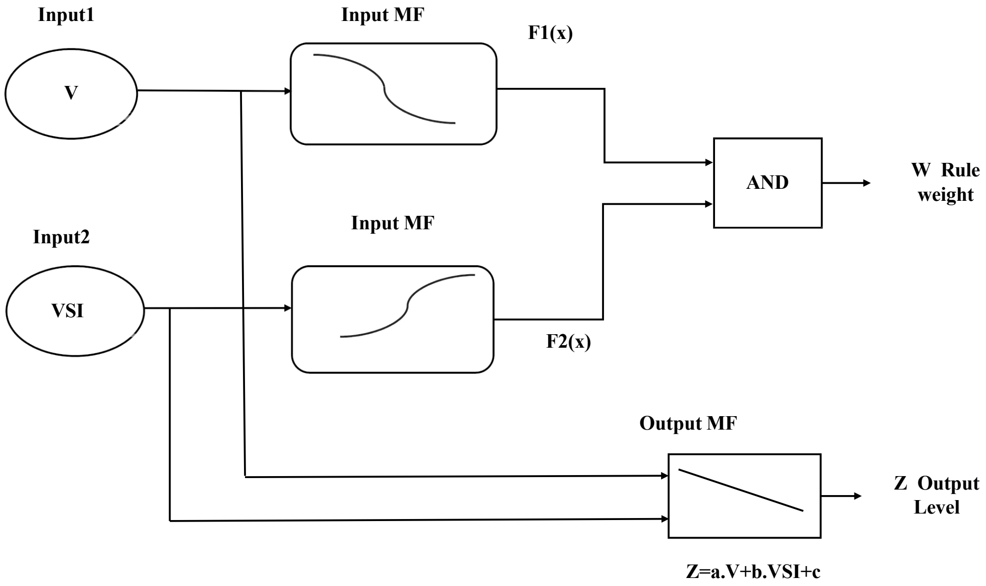

Figure 3.2: Sugeno fuzzy logic blocs for the proposed UVLS

an evolutionary algorithm. The fitness function of each individual xi (i.e., the Sugeno FIS parameters of the ith bus) is calculated over a number of scenarios k = 1, . . . , K, which are generated based on the load profile, the output of Distributed Generators (DGs), and the severity of the event (e.g., overload).

$$\mathrm{fit}(x_i^k) = \sum_{i=2}^{NBS} (w_1(1 - V_i) + w_2 \cdot P_{\mathrm{shed}_i}) \tag{3.2}$$

Where:

- w_1, w_2 are weight parameters that balance voltage deviation and load shedding,
- V_i is the voltage at bus i,
- P_{shed_i} (or DPL_i) is the amount of load shed at bus i,
- NBS is the total number of buses in the system.

Several papers propose that the voltage stability index be used to identify the weakest buses to be shed [1]. These buses could lead to voltage instability when the load increases. In a radial distribution system, each receiving bus is fed by only one sending bus; the value of the VSI is given by:

$$\begin{aligned} VSI(i+1) = |V(i)|^4 - 4\left(P(i+1)\cdot x(j) - Q(i+1)\cdot r(j)\right)^2 \\ - 4\left(P(i+1)\cdot r(j) + Q(i+1)\cdot x(j)\right)\cdot |V(i)|^2 \end{aligned} \tag{3.3}$$

Where:

- VSI is the voltage stability index,
- $V(i)$ is the sending-end voltage at bus i,
- $P(i+1)$ is the active power load at the receiving bus $i+1$,
- $Q(i+1)$ is the reactive power load at the receiving bus $i+1$,
- r_{ij} is the resistance of the line connecting bus i to bus j,
- x_{ij} is the reactance of the line connecting bus i to bus j,

The value of VSI should be maintained at least once for stable distribution system operation. As explained in [43], the bus at which the value of VSI is minimum is more sensitive to the voltage collapse. Therefore, it is concerned with load shedding. We can use fuzzy logic to decide how many buses are classified as the weakest. Figure 3.3 shows the flowchart of the adaptive load shedding method proposed in this work. Evolutionary Algorithms (EAs) are optimization or learning algorithms that have the ability to evolve over time. They are characterized by the following three main features [44]:

- Population-based: EAs maintain a group of solutions, known as a population, which allows them to explore the solution space in parallel. The population serves as the foundation of the evolutionary process.
- Fitness-oriented: Each solution in the population is referred to as an individual. Every individual has a genetic representation (or code) and a performance evaluation, known as its fitness value. EAs prioritize individuals with higher fitness, guiding the optimization and convergence of the algorithm.
- Variation-driven: Individuals undergo various variation operations that mimic genetic mutations and recombination. These operations are essential for exploring the solution space and discovering new candidate solutions.

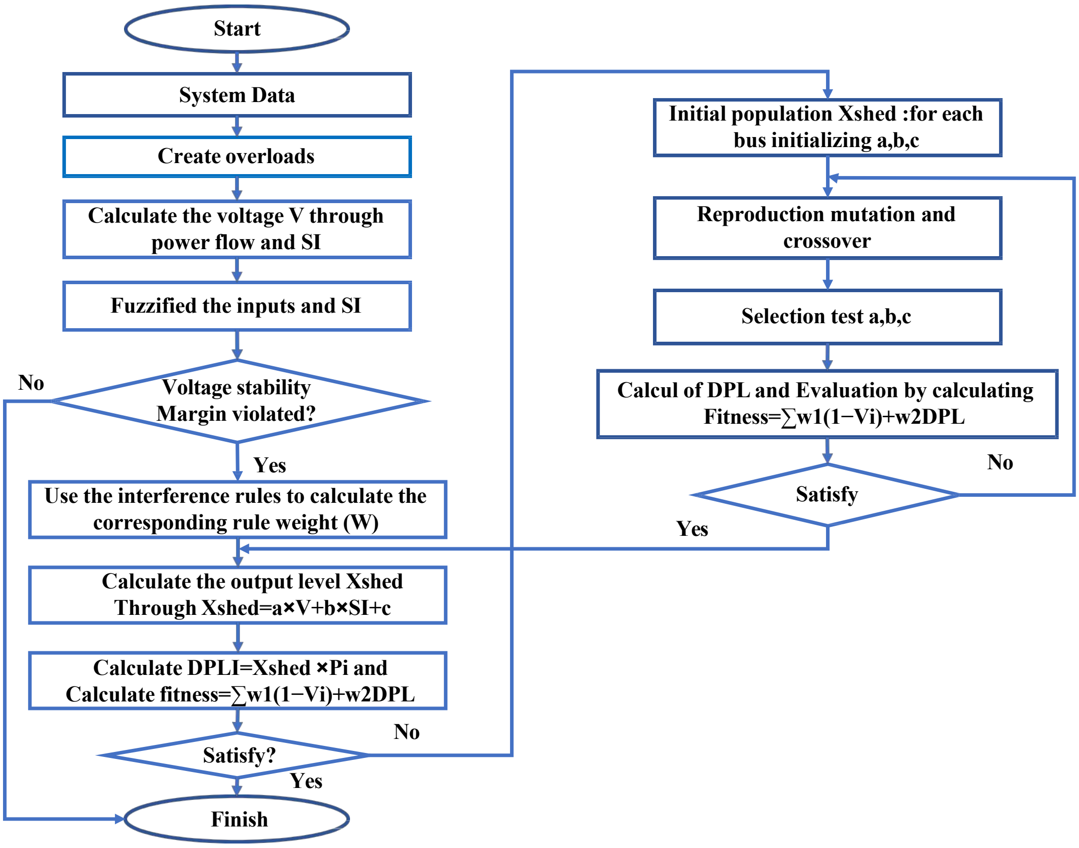

Figure 3.3: Flowchart of the proposed UVLS scheme

3.4 Simulation Results

MATLAB simulations with the MATPOWER toolbox were run on the IEEE 33-bus test system connected to the transmission grid to ensure that the cases examined are realistic as show in Figure 3.4. This power system operates at a nominal voltage of 12.66 kV, with a total demand of 3.715 MW and 2.3 Mvar in normal conditions.

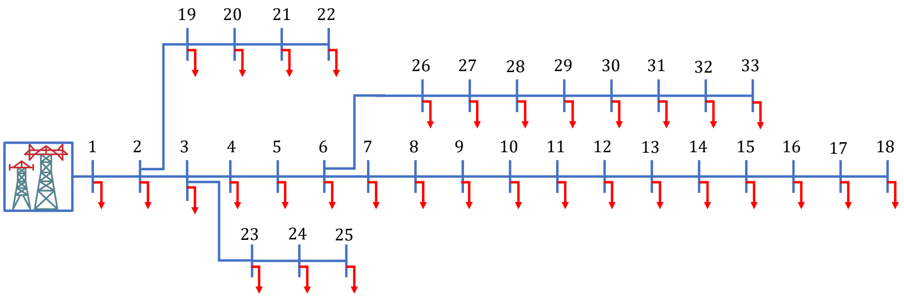

Figure 3.4: IEEE 33 bus system

The IEEE-33 bus distribution power system, including DGs, is studied to test the effectiveness of the proposed approach. The proposed test system's data is taken from [45]. Four event cases are studied: 25%, 50%, 75%, and 100% overload for each case study. The following three cases to study the response of the power system subject to UVLS and its reaction in the presence of DGs for the four overload cases are considered:

- Case 1: base case test system with and without DGs.
- Case 2: Test system under conventional UVLS with and without DGs.
- Case 3: Test system under Adaptive UVLS with and without DGs.

3.4.1 Test system without UVLS

1. **Without DGs**

   Once the distribution power system is subjected to major overloads, the voltage profile decreases as shown in Figure3.5. The voltage profile in this case study drops below its stability margin for all overload cases.

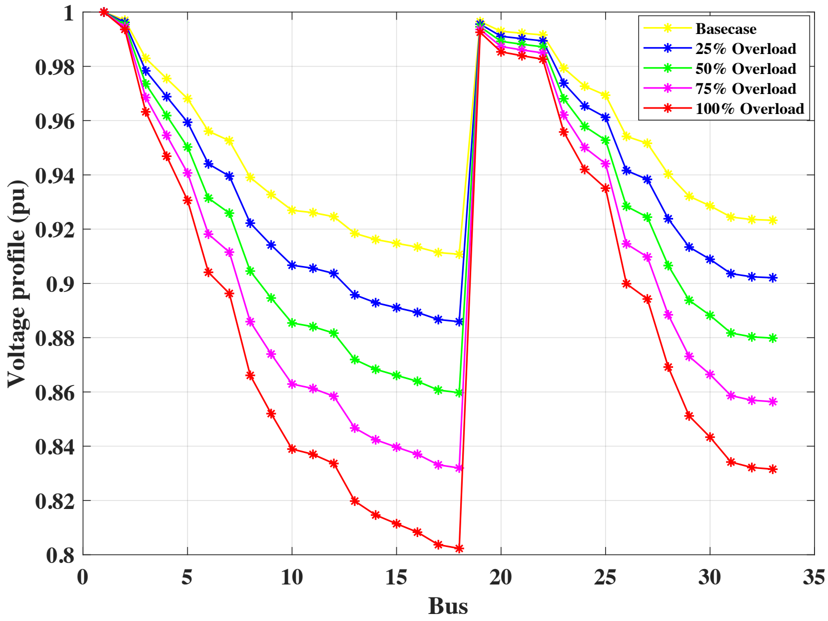

Figure 3.5: Voltage profile without DGs

2. **With DGs**

Figure 3.6 depicts the 33 bus test radial distribution system, which includes DGs connected at buses 18 and 33. In the following simulation, DGs are considered as both active and reactive power sources for each bus. These DGs are configured to supply 30% of the system's total active power (Pg) and 21% of the total reactive power (Qg).

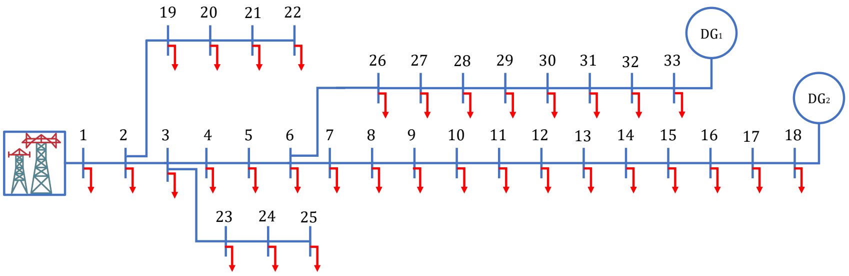

Figure 3.6: IEEE 33 bus system with DGs

Figure 3.7 illustrates a comparison of the voltage profiles with and without the inclusion of DG units, specifically placed at buses 18 and 33. The size and placement of these DGs are fixed based on the specifications provided in [45]. As shown in Fig.5, the voltage profile increases after DG installation but remains below the stability margin for some buses at 75% and 100% overload, which requires load shedding.

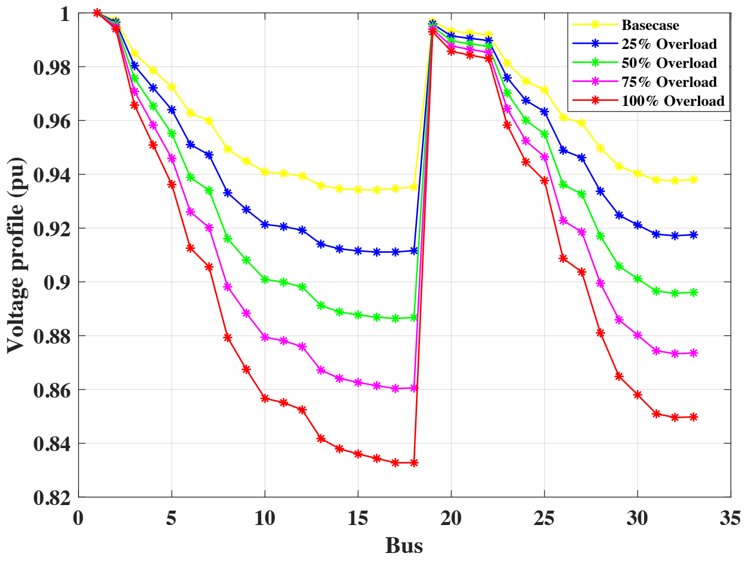

Figure 3.7: Voltage profile without load Shedding in presence of DGs

3.4.2 Conventional UVLS

Table 3.1 presents the conventional UVLS parameters, including the voltage thresholds and the appropriate amount of load to be shed for each bus. The voltage thresholds, as well as the appropriate amount of shed load, are chosen by trial and error while ensuring voltage stability.

Table 3.1: Proposed Conventional UVLS

Voltage Threshold	**Load shedding Amount**
0.90 pu	20 %
0.88 pu	Additional 20%
0.86 pu	Additional 10%

1. **Without DGs**

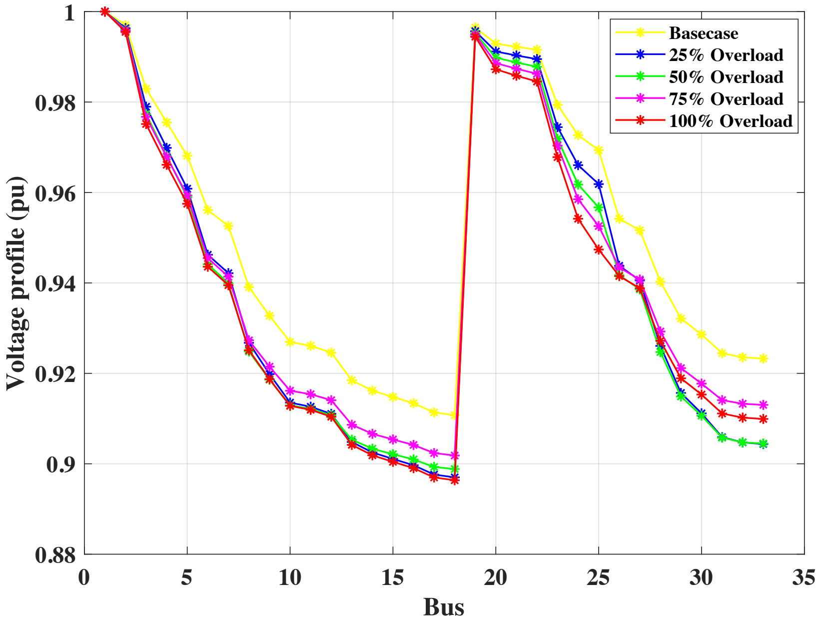

Figure 3.8: Voltage profile with Conventional UVLS without DGs

As shown in Figure 3.8, when the system is overloaded of 80% or 100%, the load system must be relieved. The conventional UVLS offers the possibility for the system to return to its stability margin (V > 0.9 pu) for almost all buses, unlike buses 14 to

18 where the fixed shed amount was not sufficient to maintain the stability margin.

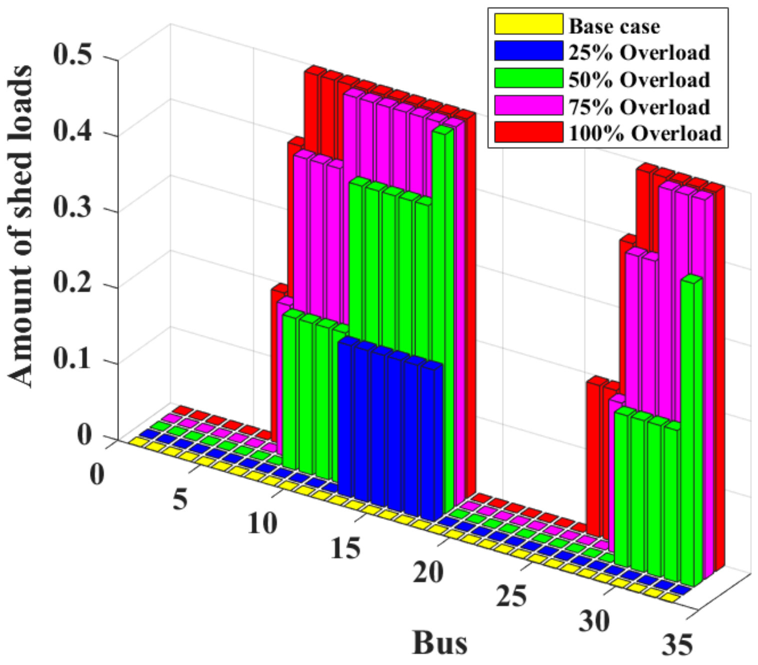

Figure 3.9: Percentage of amount load to be shed with the conventional UVLS in the absence of DG

The figure (Figure 3.9) shows that load shedding increases with the overload level, especially at buses 11–21 and 30–35, in the absence of DGs.

2. **With DGs** The presence of DG helps load shedding to relieve the system against overloads, as shown in Figure 3.10 the voltage profile through the conventional scheme returns the system back to its stability margin for all buses even for 80% and 100% overload.

   Voltage stability requires its minimum value to become at least slightly above or equal the stability threshold which is 0.9 pu, but in this simulation the minimum voltage values jump to almost 0.92pu (for example 100% overload) , that's mean that the shed amount may inevitably be exaggerated. This point called 'overshedding' presents one of the many limitations of the conventional scheme, this problem requires a new UVLS technique which adapts the amount of charge according to several cases of overload.

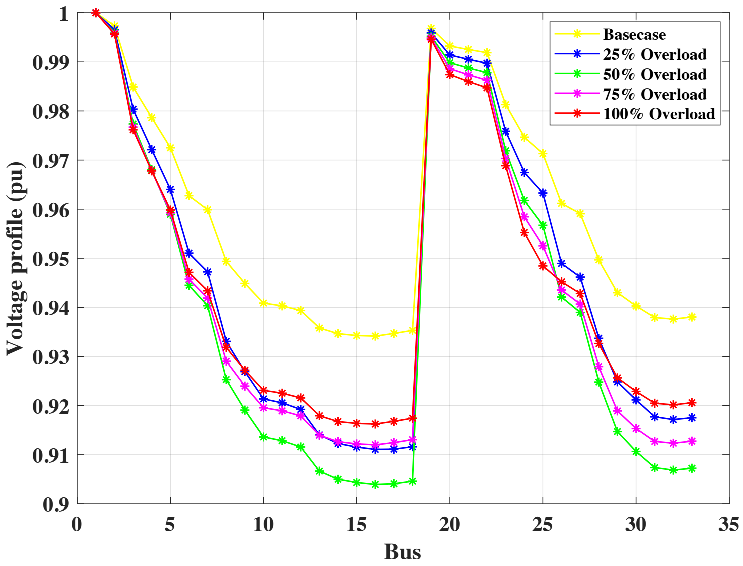

Figure 3.10: Voltage profile with Conventional UVLS with DGs

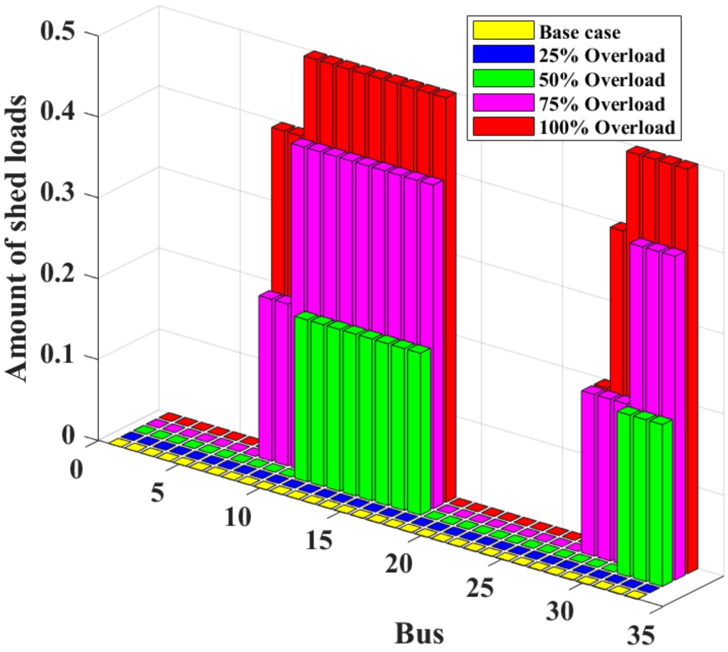

Figure 3.11: Percentage of amount load to be shed with the conventional UVLS in the presence of DG.

The Figure 3.11 shows that, even with the presence of DG, load shedding still increases with overload level—especially at buses 11–21 and 30–35—but to a slightly lesser extent than in the absence of DG. This indicates that DG helps reduce the amount of load shed, though the effect is limited under high overload conditions.

3.4.3 Adaptive UVLS

In order to verify the effectiveness of the proposed approach against the conventional one, the present paper simulate the UVLS relay as a fuzzy logic controller. The FIS Editor displays general information about the fuzzy inference system as shown in Figure 3.12. The fuzzy logic controller is structured as follow:

- Two (02) inputs V and VSI with gauss membership function for both (Figure 3.13 and Figure 3.14)
- One (01) output the load shedding amount with linear function Type (Figure 3.15)

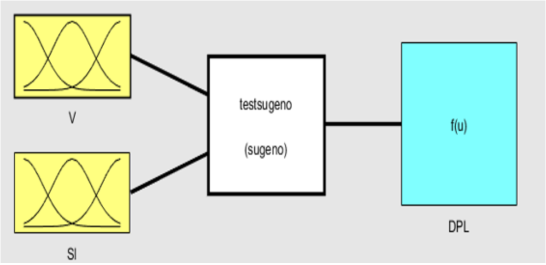

Figure 3.12: Load shedding FIS Editor

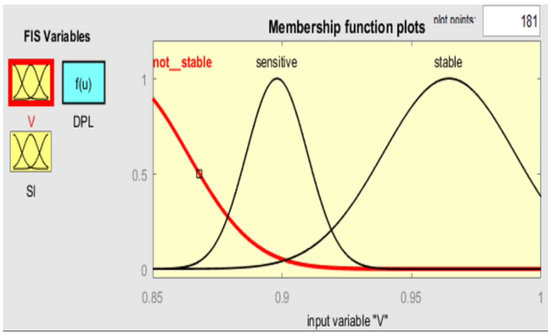

Figure 3.13: The input variable – V membership function

The table 3.2 shows the different rules summarizing the working principle of the proposed fuzzy logic controller. With NLS/ PLS/MLS /HLS represents No load shedding, Poor, medium and high load shedding respectively. As explained above, the proposed UVLS scheme aims to adapt the amount of shed load based on voltage stability by identifying.

The optimal parameters of the Sugeno fuzzy inference system (FIS) are ai, bi, ci, and di. These parameters are tuned to determine the appropriate load shedding level using

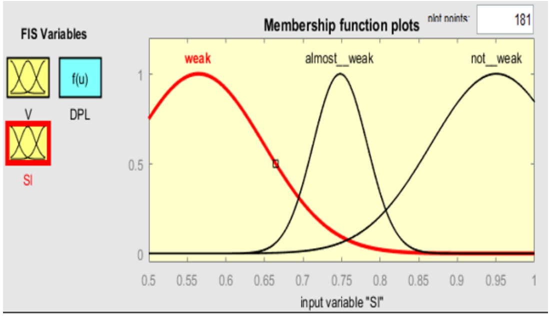

Figure 3.14: The input variable – VSI membership function

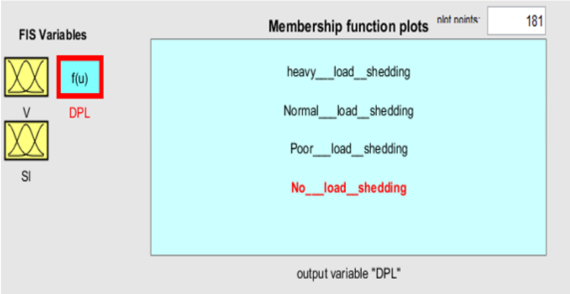

Figure 3.15: The input variable – DPL membership function

Table 3.2: Fuzzy Logic Rules

V(pu) **VSI (pu)**	**Instable**	**Sensitive**	**stable**
Weak	HLS	NLS	NLS
Almost Weak	MLS	PLS	NLS
Not Weak	MLS	NLS	NLS

voltage (V) and stability index (VSI) values, as shown in equations 3.4- 3.7:

$$X_{\text{shed1},i} = a_1 \times V + b_1 \times V_{\text{SI}} + c_1 \tag{3.4}$$

$$X_{\text{shed2},i} = a_2 \times V + b_2 \times V_{\text{SI}} + c_2 \tag{3.5}$$

$$X_{\text{shed3},i} = a_3 \times V + b_3 \times V_{\text{SI}} + c_3 \tag{3.6}$$

$$X_{\text{shed4},i} = a_4 \times V + b_4 \times V_{\text{SI}} + c_4 \tag{3.7}$$

The output in Sugeno type FIS can only be in the range of 0-1 with a linear output value. The threshold 0.9 pu is taken as a common reference to follow the voltage stability behavior.

1. **Without DGs** The voltage profile without DGs obtained is shown in Figure 3.16 The proposed UVLS. forces the system to maintain its voltage stability for each overload even with a high amount of shed load, the presence of DGs is therefore important to relieve the amount of load shedding.

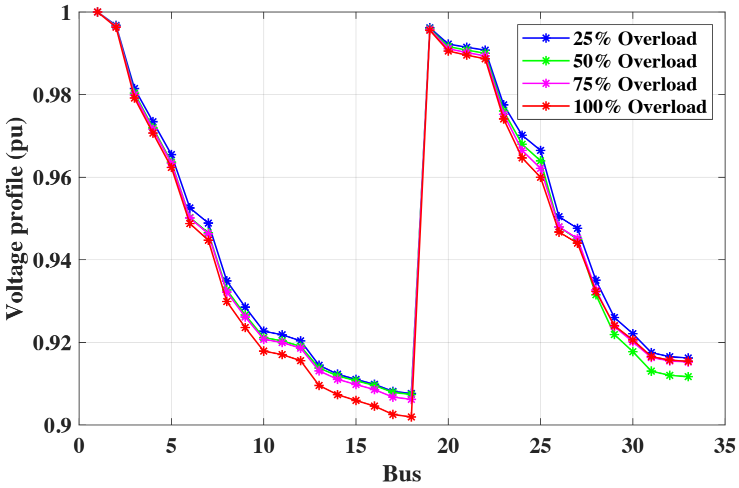

Figure 3.16: Under adaptive UVLS without DGs

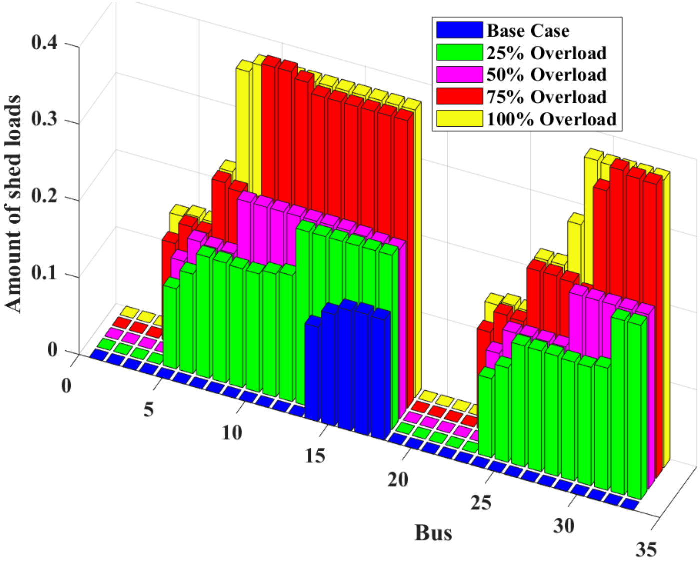

Figure 3.17: Percentage of amount load to be shed with the adaptive UVLS in the absence of DG

Figure 3.17 shows that adaptive UVLS reduces and balances load shedding across buses compared to conventional methods, even without DG. The response is more efficient, especially under high overload conditions.

2. **With DGs**

The voltage profile in the presence of DGs is shown in Figure 3.18. As illustrated, the voltage stability of all buses is maintained across all overload scenarios. The amount of shed load in this case is lower than in the scenario without DGs, as the distributed generation helps mitigate voltage drops.

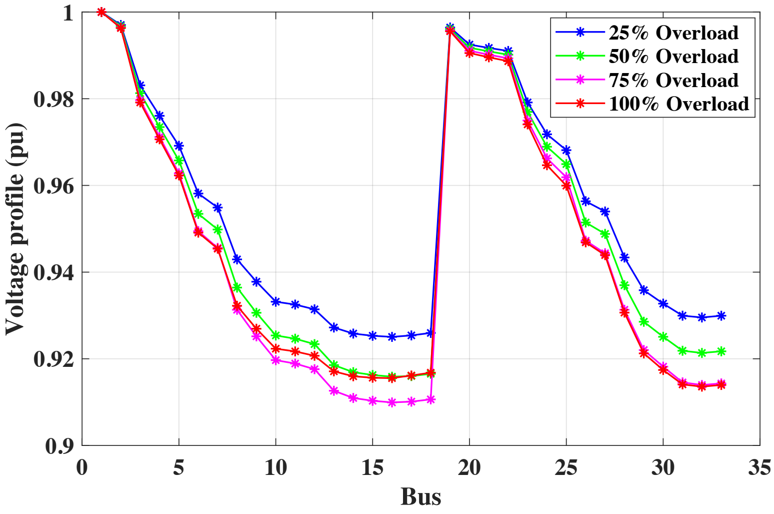

Figure 3.18: Voltage profile under adaptive UVLS with DGs

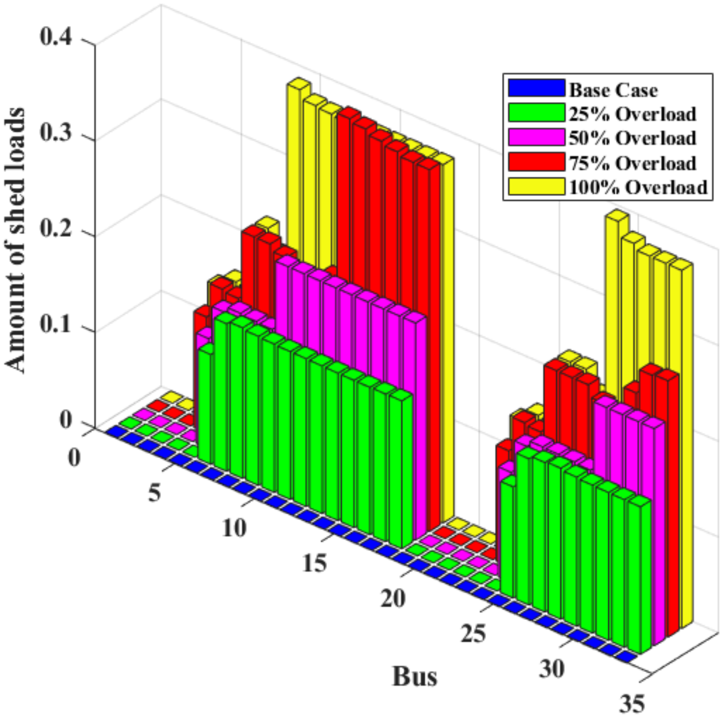

Figure 3.19: Percentage of amount load to be shed in presence of DG.

The Figure 3.19 shows that in the presence of DG, load shedding is further reduced and more stable across buses, even under high overload conditions. Compared to previous cases, the inclusion of DG improves the resilience of the system, leading to lower and more uniform load shedding, especially between buses 5–20 and 30–35.

3.4.4 Results Comparison

To ensure the validity of the proposed UVLS scheme compared to the conventional scheme, the comparison is carried out according to two parameters: the minimum voltage in the system and the sum of the shed load on each bus. The detailed results are summarized in the Table.3.3.

Table 3.3: Summarized results

	Conventional UVLS	
Overload	**Without DGs**	**With DGs**
25%	0.895 pu/ 0.121 MW	0.918 pu/ 0 MW
50%	0.8996 pu/ 0.356 MW	0.904 pu/ 0.206 MW
75%	0.900 pu/ 0.485 MW	0.916 pu/ 0.350 MW
100%	0.896 pu/0.602 MW	0.9 pu/ 0.415 MW

	Adaptive UVLS	
Overload	**Without DGs**	**With DGs**
25%	0.909 pu/ 0.121 MW	0.926 pu/ 0 MW
50%	0.908 pu/ 0.421 MW	0.916 pu/ 0.239 MW
75%	0.906 pu/ 0.514 MW	0.912 pu/ 0.254 MW
100%	0.901 pu/ 0.711 MW	0.91 pu/ 0.297 MW

The results show that the proposed UVLS adapts to system behavior. The amount and location of UVLS depend on the severity of the VSI value index and the voltage drop without overshedding compared with the conventional one.

3.5 Conclusion

This chapter has demonstrated the effectiveness of the proposed adaptive load-shedding approach in maintaining voltage stability within radial distribution power systems, particularly under severe overload conditions. In contrast to the conventional UVLS method, which lacks flexibility, the adaptive strategy, based on multi-agent coordination and fuzzy logic, proved to be more robust and better suited to real-time system behavior.

Moreover, the integration of DGs significantly reduced the need for load shedding by supporting voltage levels at critical nodes. Comparative simulations confirmed that the adaptive approach not only minimizes the amount of load loss but also enhances the overall stability of the power system.

GENERAL CONCLUSION

The main idea behind this final-year project was to present a new decentralised adaptive UVLS load shedding approach for an electrical distribution power system, based on the fuzzy logic algorithm. The objective of adaptive load shedding is to determine a more stable operating point for the power system with a minimal amount of load reduction and to deliver real-time optimal solutions under varying power system conditions.

The location of the shedding action is inherently tied to the power system's architecture and is defined by the position of the node subject to shedding. In this work, the proposed solution takes into account the voltage stability index (VSI) to prioritise the nodes to be shed. Minimising the amount of load to be shed remains the core challenge of any load shedding strategy.

This study focuses exclusively on voltage variation, which also characterises radial distribution power systems connected to an infinite transmission power system, where frequency is maintained stable by the latter.

To determine the most suitable approach for the scenarios under investigation, various load shedding techniques were introduced, along with an explanation of their operating principles. The 33-bus distribution test power system was selected as the application system to evaluate two shedding strategies: the conventional method and the adaptive method based on the fuzzy logic algorithm.

In this study, the performance of the electrical distribution power system is enhanced through the integration of distributed generators (DGs). DGs are capable of compensating for deficiencies in energy supply; thus, under conditions of low overload, load shedding becomes unnecessary, unlike in the case of severe overloads. Consequently, the overall shedding requirement is mitigated by the presence of DGs.

The results obtained in this dissertation demonstrate the effectiveness of the adaptive approach based on fuzzy logic compared to the conventional method. This algorithm enables adaptive load shedding in response to different events, both in the presence and absence of DGs. Without DGs, the distribution power system tends to destabilise even under mild overload conditions. In contrast to conventional load shedding, the adaptive method proved to be more efficient when using the voltage stability index (VSI) in conjunction with voltage drop. It is also evident that the adaptive technique outperforms the conventional one, particularly due to its rapid response in restoring the system to a stable operating point.

Perspectives

- **Dynamic modelling of DG variability:** The current study assumes ideal behaviour of distributed generators. Extending the model to account for real-time variability in DG output—especially from solar and wind sources—would enhance the robustness of the proposed load shedding strategy.
- **Hybridisation with other intelligent techniques:** Combining fuzzy logic with other AI-based approaches such as neural networks or reinforcement learning may improve decision-making speed and adaptability during fast-changing network conditions.
- **Coordination between DGs and UVLS:** Future studies could explore coordinated control strategies where distributed generators and adaptive UVLS schemes operate jointly to maintain voltage profiles and minimise unnecessary load disconnections.

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