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TITRE

Multi-Agent based management of distribution networks

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Abstract

Now, the large-scale integration of renewable energy resources and distribution generations leads to more complex power systems. To deal with this integration, new technologies based on power electronics and information and communication technologies (ICTs) have been explored to manage the new power systems, called active distribution systems.

To facilitate the integration of distributed generation, active distribution networks have emerged. It is always important, at the active distribution networks management center level, to acquire accurate real time measurements to be able to control and take the appropriate decision.

State estimation is an important function in distribution systems in general and active distribution networks in particular. State estimation must be done to ensure the good functioning of the active distribution system. Several authors have proposed some methods to solve the state estimation problem based on the power flow equations. Some methods are numerical like newton method or linear programming and some others based on artificial intelligence.

In this thesis, we will propose a new multi-agent system-based approach. This technique is based on multi agent systems, to split the active distribution network and to manage the resulting sub-networks, and the metaheuristic algorithm ABC to perform the state calculations. Our approach is tested on IEEE 6-bus, 14-bus and 30-bus. The results show a dramatic decrease in the computational burden, thus a faster estimation in large systems can be obtained. This demonstrates the effectiveness of the proposed strategy.

Keywords: Active distribution networks, state estimation, multi-agent systems, artificial intelligence, artificial bee colony.

الملخص

فــي هــذه الأيــام، يــؤدي الــدمج الواســع لمــوارد الطاقــة المتجــددة ومصــادر التوليــد المــوزع إلــى أنظمــة طاقــة أكثــر تعقيــدًا. للتعامــل مــع هاتــه الأنظمــة الجديــدة، تــم استكشــاف تقنيــات جديــدة تعتمــد علــى إلكترونيــات الطاقــة وتقنيــات المعلومــات والاتصالات.

لتســهيل دمــج مصــادر التوليــد المــوزع نشــأت شــبكات التوزيــع النشــطة. لإنــه مــن المهــم دائمًــا، علــى مســتوى مركــز إدارة شــبكات التوزيــع النشــطة، الحصــول علــى قياســات دقيقــة وفعليــة للــتمكن مــن الــتحكم واتخــاذ القــرار المناســب فــي الوقــت المناسب.

تقــدير الحالــة هــو وظيفــة مهمــة فــي أنظمــة التوزيــع بشــكل عــام وشــبكات التوزيــع النشــطة علــى وجــه الخصــوص. يســتوجب علينــا إجــراء تقــدير الحالــة لضــمان حســن ســير نظــام التوزيــع النشــط. اقتــرح العديــد مــن المــؤلفين بعــض الطــرق لحــل مشــكلة تقــدير الحالــة بنــاءً علــى التحليــل بإســتعمال معــادلات تــدفق الطاقــة. بعــض الطــرق الرقميــة مثــل البرمجــة الخطيــة أو الطرق النيوتونية وبعض الطرق الأخرى مثل الذكاء الاصطناعي.

فــي هــذه الأطروحــة، ســوف نقتــرح نهجًــا جديــدًا يعتمــد علــى نظــام متعــدد العمــلاء. تعتمــد هــذه التقنيــة علــى أنظمــة متعــددة العمــلاء، لتقســيم شــبكة التوزيــع النشــطة وإدارة الشــبكات الفرعيــة الناتجــة، وخوارزميــة ABC لإجــراء حســابات الحالــة. تم اختبار نهجنا على الشبكات التمثيلية التالية IEEE 6-bus. IEEE 14-bus IEEE 30-bus.

تظهــر النتــائج انخفاضًــا كبيــرًا فــي العــبء الحســابي، وبالتــالي تقــدير أســرع للأنظمــة الكبيــرة. هــذا يــدل علــى فعاليــة الاستراتيجية المقترحة.

كلمات البحث: شبكات التوزيع النشطة, تقدير الحالات, نظام متعدد العملاء, الذكاء الإصطناعي, خوارزمية خلية النحل.

Résumé

Aujourd'hui, l'intégration à grande échelle des énergies renouvelables et des générations distribués nous a conduit à avoir des systèmes électriques plus complexes. Pour faire face à cette intégration, de nouvelles technologies basées sur l'électronique de puissance et les technologies de l'information et de la communication (TIC) ont été intégrer afin de contrôler et de gérer la nouvelle génération de systèmes électriques, appelés systèmes de distribution actifs.

Pour faciliter l'intégration de la production distribuée, des réseaux de distribution actifs ont vu le jour. Il est toujours important, au niveau du centre de gestion des réseaux de distribution actifs, d'acquérir des mesures précises en temps réel pour pouvoir contrôler et prendre les mesures nécessaires.

L'estimation des états est une fonction importante dans les systèmes de distribution en général et les réseaux de distribution actifs en particulier. L'estimation des états doit être faite afin d’assurer le bon fonctionnement du système de distribution actif. Plusieurs auteurs ont proposé des méthodes pour résoudre le problème d'estimation d'état basé sur les équations de flux de puissance. Certaines méthodes sont numériques comme la méthode de newton ou la programmation linéaire et d'autres basés sur l'intelligence artificielle.

Dans cette thèse, nous proposerons une nouvelle approche basée sur les systèmes multi-agents. Cette technique est basée sur des systèmes multi-agents, pour diviser le réseau de distribution actif et pour gérer les sous-réseaux résultants, et l'algorithme métaheuristique ABC pour effectuer les calculs d'état. Notre approche est testée sur les benchmarks systèmes, IEEE 6-bus, 14-bus et 30-bus. Les résultats montrent une diminution spectaculaire du nombre de calculs, ainsi qu’une estimation plus rapide dans les systèmes de dimension plus importante. Cela démontre l'efficacité de la stratégie proposée.

Mots-clés: Réseau de distribution actif, estimation des états, systèmes multi-agent, intelligence artificielle, algorithme de colonie d'abeilles.

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ICT’s	information and communication technologies
ADN	Active distribution networks
ABC	Artificial bee colony
MV	Medium voltage
LV	Low voltage
MAS	Multi agent systems
PSO	Particle swarm optimization
RESs	Renewable energy resources
DG	Distributed generation
CHP	Combined heat and power
WLS	Weighted least square
DSE	Distributed state estimation
DSSE	Distribution system state estimation
FACTS	Flexible AC Transmission systems
DSO	Distributed system operators
DER	Distributed energy resources
FRIENDS	Flexible, Reliable and Intelligent Electrical energy delivery system
ISO	Independent systems operators
TNO	Transmission network operator
DNO	Distribution network operator
DSM	Demand side management
EMS	Energy management system
PMU	Phasor measurement units
RTUs	Remote Terminal unit
HKF	Hierarchical Kalman Filtering
BDI	Beliefs, desires and intentions
SCADA	Supervisory control and data acquisition
FIPA	The foundation for intelligent physical agents
ACL	Agent Communication Language
KQML	Knowledge Query and Manipulation Language
PEDA	Protection engineering diagnostic agent
CDSE	Completely decentralized state estimation

I. General Introduction

Electrical power systems are considered to be one of the most important energy systems in our modern society. They are spread all over the world, to provide electricity for hundreds of millions of end-users. Currently, power systems do not only provide reliable, available, maintainable and safe energy to the consumers, but have also a good environmental impact. This is why more renewable energy sources (RESs) are integrated into power systems.

Nowadays, large-scale integration of RES and other distributed generations (DG) might lead to extremely complex interactions in power systems. To handle this integration, new concepts and technologies based on power electronics and information and communication technologies (ICTs) have emerged to manage power systems.

Distributed generation has attracted many researchers in power systems. Distributed generation is mainly the introduction of distributed energy resources as micro-turbines, Combined Heat and Power (CHP) installations, small hydro-power plants, wind turbines, photovoltaic systems, fuel cells, or biomass technologies into distribution networks.

Conventionally, electrical energy is transmitted, in one direction, from the power plant (generation layer) to energy consumers through transmission and distribution networks. This is called a vertical power system structure. Power systems are gradually changing from vertical to horizontal structures. This is due to the integration of distributed generation in the distribution system.

To facilitate the integration of DG, active networks, including active distribution networks (ADN), were proposed by Van overbeeke in [1]. The main characteristic of active distribution networks is bidirectional power flow, which means power can go out and in from any network bus. An important feature in ADN is local control areas or cells. In this thesis, we will focus on active distribution networks which are our main application.

It is always important at the ADN management centre level, to have accurate real-time measurements. This way we can manage, control and take the appropriate decision on distribution networks, and deliver desired power to each bus of the system. State estimation is one of the main critical functionalities that must be insured, for the good functioning of the distribution system. In the thesis, our work is focused on state estimation.

In the last decades, several authors presented numerical methods based on power flow equations, to solve state estimation problem. These methods, such as the Newton method [2], linear programming [3] or gradient descent [4], use iterative convergence methods, mostly based on a weighted least square (WLS) estimator [5]. Some other methods, based on Kalman filtering, were also proposed [6–8].

However, these methods present some issues. First, it is assumed that power equations are differentiable and continuous, which is not always the case. Many types of equipment in power systems have non-linear and non-differentiable characteristics. Other drawbacks of classical methods are high oscillations, local minima and non-convergence issues if the choice of initial conditions or linearization step is not appropriately selected.

Artificial intelligence (AI) algorithms are a powerful tool for non-linear optimization, these algorithms do not fall into differentiability and continuity issues. A genetic algorithm for state estimation was first developed by K. Selvi and al [9]. A modified version was also proposed by A. A. Hossam-Eldin and al [10], for small distribution systems. An artificial neural network estimator, based on both synchronized and conventional measurements was presented in [11]. Shabani and al attempt to improve the WLS estimator in [12] using a fuzzy-logic based weight adjustment approach.

Swarm intelligence is an artificial intelligence technique based on the particular behaviour of some animal's swarm. This approach is also used for state estimation. In this process, the individual agents behave collectively in a stochastic manner to reach a global goal [13]. Some research has been performed on state estimation, based on particle swarm optimization (PSO), in a three-bus system in [14] and a six-bus system in [15].

With the emergence of information and communication technologies (ICTs) and their incorporation in power distribution systems, Distributed State Estimation (DSE) has been widely explored [16]. Depending on the way of defining areas in the ADN, different algorithms for solving DSE have been proposed in different works [7, 17-20,34-37].

In this thesis, we will propose a new multi-agent system-based approach for state estimation in active distribution networks which will overcome the drawbacks of the above-proposed methods. In this approach, the state calculations are carried out using ABC swarm intelligence algorithm, since it has proven its efficiency over other algorithms [21]. Besides Multi-agent systems are used to split the system into manageable sub-systems. Our approach can be considered as completely decentralized state estimation.

A Multi-agent system (MAS) is a collection or a community of goal-oriented, smart and autonomous agents, the whole structure works to reach a certain goal. MAS obeys a certain hierarchy when it comes to goal accomplishment, i.e. each agent has its own goal stated as a local goal, but global system goals comes always in priority.

The agent is the fundamental part of MAS, it is considered as a smart entity that can have BDI (beliefs, desires and intentions) and also some knowledge, each agent can have connections to the outside so it can have a view on the surrounding environment. Each agent can interact with other agents of the system, depending on the need of data exchange, when it comes to decision making, following some communication protocol. These agent entities can be implemented as a software or hardware depending on the applications.

The main benefits of the MAS over classical methods (Neural networks, expert systems, artificial immune systems) are the complexity and their limit when it comes to huge systems. It requires also a huge amount of data transmitted and processed, which is of a high cost, not like MAS which require a local view, only on the neighbour agents, which decreases the cost.

Other advantages are the flexibility of the MAS, plug and play and fault-tolerance. For example adding or removing a load will be automatically acknowledged to the system and took into consideration, and MAS will work always to reach the goal.

ABC is an optimization algorithm based on swarm intelligence, inspired by the natural behaviour of honeybee swarms. ABC was first developed by D. Karaboga [22]. The algorithm is simulating the behaviour of real honey-bees, for solving multidimensional and multimodal optimization problems. As stated before, ABC is used to carry out the calculations in the state estimation process. The states in our work are the voltage and the angle at each bus of the active distribution network.

To summarize, in this thesis we will propose a new technique of state estimation in active distribution networks. The technique is based on MAS to split the ADN and manage the resulting sub-networks, and the metaheuristic optimization algorithm ABC to perform the state calculations.

In chapter I, we will give a brief presentation on power systems and how integration of renewable energy resources and other distributed generation gave birth to active power networks. Then, we will describe and give more details on active distribution networks which are the application for the proposed method.

Chapter II is completely devoted to state estimation in power systems. In this chapter, we will present state estimation as a general concept and distribution system state estimation DSSE as a particular one. After that, we will present in details the whole process of state estimation, and focus on parameters state estimation and finally present the concept of distributed state estimation in distribution systems which inspired the proposed technique.

In chapter III, multi-agent systems are presented. We will give an introduction on MAS and present some properties of these systems. We will also introduce some applications of MAS in the different areas including power systems. In the same chapter, the proposed method is presented and explained in details, including also a brief presentation of the metaheuristic algorithm ABC used in state calculations. We will show how multi-agent systems are powerful and efficient when performing state estimation. We will also show how MAS and ABC interact in the proposed method, and how the proposed technique overcomes the drawbacks of classical methods.

In chapter IV, simulations on benchmark systems, the IEEE 6-bus, IEEE 14-bus and the IEEE 30-bus, are carried out to show the efficiency of the proposed method and to confirm all the supposition that have been made. Finally, we will summarize all the research and the obtained results in the general conclusion.

Chapter II: Active Distribution Networks

II.1 Introduction

Electrical power systems are considered one of the most important energy resources for modern society. Conventional power systems can be divided into three main stages: power generation, where the electrical energy is produced in different types of power plants such as coal, hydro, or nuclear power plants. The second stage is the transmission and distribution networks. The third stage is the end-users and consumers. Conventional power systems are characterized by a unidirectional power flow of electricity, starting from the power plant to the consumers.

Conventional power systems are facing many problems such as poor efficiency and environmental pollution. These stated problems led to a new concept which is distributed generation. Distributed generation is the integration of power resources locally as additional energy resources for the network. To overcome the environmental issues, most distributed generations are non-conventional or renewable energy resources like natural gas, biogas, wind power, solar photovoltaic cells, fuel cells, combined heat and power (CHP) systems, microturbines, and Stirling engines.

The integration of distributed generation gives rise a to active networks. Hence, from conventional distribution networks, we ended up with active distribution networks. In this chapter, we will see distributed generation in more details, what are the new challenges for active distribution networks, and the features that these networks offer.

II.2 Distributed generation

Distributed generation is one of the most attractive fields of study in electrical power systems during the last decades. It came up from the introduction of Distributed Energy Resources, like micro-turbines, Combined Heat and Power (CHP) installations, small hydro-power plants, wind turbines, photovoltaic systems, fuel cells, biomass technologies, into the distribution network. The Distributed Generation units supply electrical power for both the

Medium and Low Voltage networks. Renewable energy resources are most of the time based on discrete energy sources because they depend on non-controllable environmental parameters such as wind velocity or solar radiation intensity. So, distributed generations that are based on renewable energies, which is the most spread case, are difficult to control. The increasing integration of distributed generation, therefore, causes both technical challenges and opportunities.

The drawbacks of DG results from the conflicts with the passive and less intelligent distribution system already in service. Technical problems are getting serious and more challenging when the percentage of integration of distributed generation increases. Voltage regulation is one of the biggest problems. When one of the end-user loads is at minimum consumption all the power injectied by the consumer distributed generation flows back to the grid. This issue gives a certain limit to distributed generation penetration in rural distribution networks [23]. Distributed generations based on rotating machines cause a significant increase in the fault current levels of the network. This is not a good initiative in urban areas where the fault current level is approaching the nominal current of end-user equipment. Large-scale penetration of distributed generation affects both the original protection design and the stability of the network.

Besides the technical challenges that come up with the integration of distributed generation, many opportunities arise to make the distribution network intelligent and flexible. Distributed generation prevents power transfer losses from power plants and avoids increasing the distribution and transmission network upgrading. Distributed generations decrease the voltage drop and can be used as redundant power sources to improve reliability. Distributed generation offers also the opportunity to switch to the islanded mode when it is necessary.

II.3 From passive to active distribution networks

As discussed earlier, due to economic pressure, environmental impact, and the increasing demand for electrical power, distributed generation has emerged and its percentage of integration into distribution networks has increased. The conventional power system with unidirectional power flow can not handle this integration and new technology. In [24] Van overbeeke proposed active networks as the backbone networks for the integration of distributed generation. This concept of active network is based on three main characteristics, the first one is the interconnection within the network, which provides the possibility of having a bidirectional power and data between the different areas of the network. The second feature is the local area controls. The third functionality is the ancillary services which provide system stability and is charged to customers.

Active distribution networks are no more than distribution networks with the integration of distributed generation. To be able to perform the features mentioned above we need essential tools to manage and control future distribution networks.

II.3.1 Power electronics

Power electronics is essential hardware and implementation tool for the conventional distribution network and active distribution networks. Flexible AC Transmission Systems (FACTS) play an essential role in future distribution systems and more generally power systems, its major role is to enhance networks. Some of these devices are the distributed static compensator, dynamic voltage reglation, and solid-state transfer switches. It is also very important to study the interface between distributed generation and the utility grid to minimize the drawbacks of renewable energy resources.

II.3.2 Information and communication technology

With the quick development of information and communication technologies (ICTs), it became a permanent tool in power systems and more precisely distribution networks. ICTs-based control systems are meant to give real-time and high-speed monitoring for the distribution system, it concerns state information, capacity, power status, and this for especially optimization purposes.

ICT applications in distribution systems have shown their effectiveness in protection reconfiguration and internet-based control. These applications can be seen as hardware systems i.e., radio, optical fiber technologies, and telecommunication cables. These systems are a requirement for a secure distribution system. The whole hardware part is governed by an application or software which is flexible to manage all kinds of transitions or adaption of distribution networks.

II.4 Active distribution networks

Conventional distribution networks are relatively stable and passive with a unidirectional power flow. The appellation of active distribution networks came up with the large integration of distributed generation in distribution networks influencing them to become bidirectional power flow distribution networks. As stated, the major feature of active distribution networks is their ability to support bidirectional power and data flow. This main feature is based on the latest technology of automation, information and communication technologies, as well as smart metering and power electronics equipment.

Active distribution networks according to the CIRGRE C6.11 Working group **[25]:**

Definition II.1: *Active distribution networks (ADNs) are distribution networks that have systems in place to control a combination of distributed energy resources (generators, loads, and storage). Distribution system operators (DSOs) have the possibility of managing the electricity flows using a flexible network topology. DERs take some degree of responsibility for system support, which will depend on a suitable regulatory environment and connection agreement.*

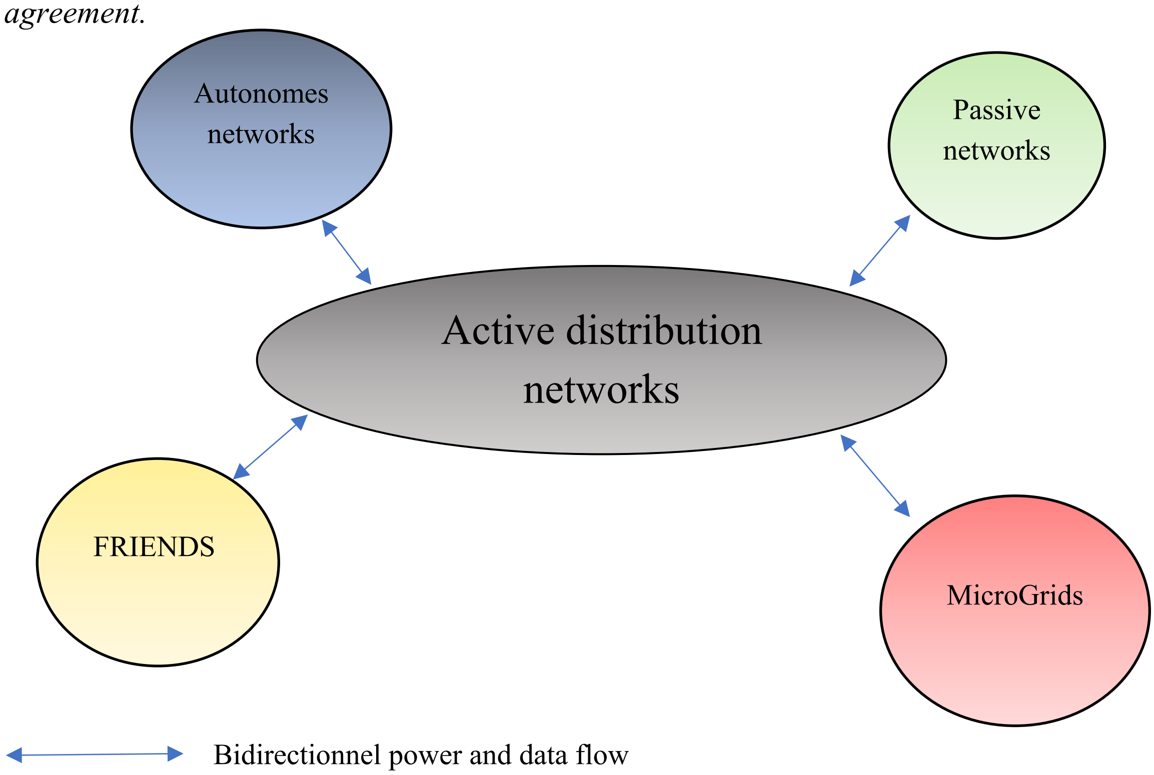

Figure II.1: Active distribution networks integration to power delivery systems

As seen in figure II.1, the future active distribution networks need to be designed in a manner that allows networks to adapt to future expectations of power systems including distributed energy resources. A microgrid is a power system that is more focused on the islanded mode operation while network instability and disturbance are happening in the grid, FRIENDS (Flexible, Reliable and Intelligent Electrical energy Delivery System) and autonomous networks are more oriented to power exchange issues using electronic devices. Despite Active distribution networks being the backbone for future networks, with the help of ICTs and their applications, it should be able to achieve integration of Microgrids, FRIENDS, autonomous systems, and passive networks.

II.4.1 Active distribution operators and control strategy

In conventional power networks, the control strategy aims to keep frequency and voltage at an acceptable level. This strategy is a three-layer control strategy [26]. The primary control, which is based on droop control, deals with the frequency deviation resulting from an imbalance between generation and consumption. This control layer acts right directly after the disturbance has occurred; it is considered as the first action when abnormality happens. Seconds after a disturbance occurs, the second layer control takes the lead from the upcoming minutes to restore the system frequency to its nominal value. The third layer of control takes charge of the dispatch of power generators. It aims to check the optimal position of generators to minimize power production's economic impact, taking into consideration the system constraints. In addition to these control layers, time is also a parameter to regulate due to the observed gap between universal and synchronous time. Because universal time may vary from one region to another when the grid is spread over a big geographical area. It is applied when the whole grid is in the interconnected operation and control and the control is generally applied once a day at a pre-set universal time [27]. In the same manner, voltage control has also a three-layered control strategy. But it focuses on the consumption load objective and not the global system goal, as the frequency system control strategy does.

Depending on the X/R ratio, transmission and distribution systems control ways differ. Since transmission systems have a high X/R, bus voltage control is affected mainly by the reactive power flows. On the contrary, distribution systems have generally a low X/R, so the control depends on both active and reactive power.

The control strategy stated above is a vertical type regulation strategy. This strategy is also subjected to a monopolistic regulation centralized in a certain region. The monopolistic strategy had a time where it operated in a relatively reliable, efficient, and stable way. Then came the logical turnover resulting from the competition of energy suppliers. This turnover deregulated the market with the increasing number of energy service suppliers, which is restructured the monopolistic market into multiple markets all over the world [28]. This split of the market gave birth to various Independent systems operators (ISOs) like transmission companies, generation companies, distribution companies, scheduling coordinators, and power exchanges [28].

When it comes to transmission systems, the transmission network operator (TNO) is treated as the owner of the transmission network. On the other hand, the independent system operator (ISO) has the mission of maintaining the balance between the generation and the consumption. It is well known that electricity production cannot be stored in big quantities, so the power balance control with the coordination of all the contributors in the system is important to keep a stable and secure system. The ancillary services constitute an important fragment of the future power systems for providing different control features like spinning reserve, economic dispatch, regulation, frequency control, automatic generation control, reactive power, and voltage control [28].

When it deals with distribution systems, the distribution system operator (DSO) is dedicated to the real-time monitoring and control of the distribution system. The distribution system operator will provide energy to cover the losses and can also be responsible for the emergency in its area, following a non-discriminatory and transparent policy. DSO may also be required to give a particular priority to power generations based on renewable energy, waste, or CHP [29]. In the same way as transmission systems, the distribution network operator (DNO) owns and operates the distribution network.

As evolving from conventional power distribution networks towards active distribution networks, with the integration of distributed generation, the rapid increase of innovation in ICTs, and the huge advancements in power electronics, DSO is expected to manage local balancing to avoid congestion, control voltage and power flows and provide more ancillary services. The most important facility, which can be achieved by future DSO, is increasing the contribution of TSO to manage the full power system. This cooperation between TSO and DSO is mainly focused on the 'load-follows-supply' approach, this approach gives more flexibility in reaction to the change of demands by the consumers, the important aspect of real-time balancing market, the role of the small and medium-size consumers and producers and even more structures [30].

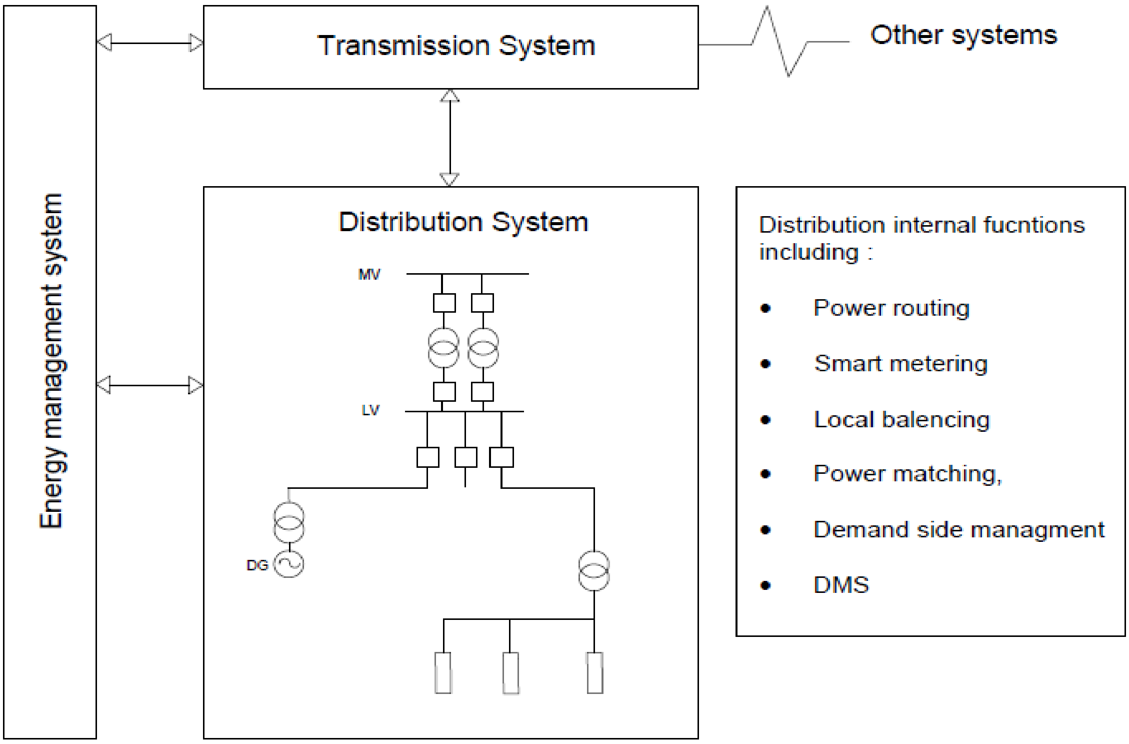

Figure II.2: Organization of the future active distribution systems ADN

As shown in figure II.2, the structure of the modern power system with an active distribution network involves both the centralized generation and the distributed generation in the energy market. As explained above, the TSO-ISO is the management level of the transmission system. similarly, the DSO is for the distribution system what the TSO-ISO is for the transmission system. Both TSO-ISO and DSO are responsible for power balancing and ancillary services through the interface set between the two management levels in the energy management system. More ancillary services are insured by the active distribution network such as local balancing, real-time power routing, and power matching might arise besides available functions of distribution management, smart metering, and Demand Side Management (DSM) [23].

II.4.2 Active distribution networks operation

Distributed generation should also be considered as an investment to sell energy to the utility grid. Aggregation of distributed generation, leading to what is called Virtual power plants (VPPs), flexible loads, and decentralized storage has an important impact on small customers. This impact is translated into facilitating access for these small end consumers to the energy market, reducing the uncertainty of availability of energy, and enhancing manageability of the scheduled energy output.

The aggregation of distributed energy can also be managed by the utility grid or the centralized energy provider, the main role of the aggregator would be to provide a suitable interface between distributed energy resources and the other system actors. Besides, distributed generations should be obliged to meet some pre-established requirements such as scheduling, nomination, and balancing obligations in the same way as other power generators do. These requirements include also some financial charges related to the energy balance.

Another important aspect is, each distributed generation should be responsible for any inquires in the system resulting in a power imbalance, in the same way, as other balancing responsible parties. It is also very beneficial for the system stability and cost reduction if variable renewable energy resources are more integrated as distributed generation in the system to reduce the forecast errors and to avoid imbalances in the market. According to the CIRGRE C6 study committee [31], the main features of the active distribution network are listed in table I.1

Table II.1. Main features of active distribution networks

Infrastructure description	Applications	Gain and benefit
• Protection devices • Communication infrastructure • Integration to classical systems • Flexibility in network topology	• Power flow management • Data acquisition and treatment • Voltage and frequency management • DG and consumption control • Fast flexibility and reconfiguration	• Improved reliability • Increased asset use • Improved use of distributed generation • Network stability • Network reinforcement alternative

the operational procedures of active distribution networks that are currently implemented are summarized below [32]:

II.4.2.1 Parallel operation of MV and LV generators

There are no general rules for the operation of MV and LV generators in active distribution networks. The rules may be set by local legislation, published in Grid codes, or can also be established by the local utility. The general rule is that distributed generation should not affect the power quality in the network. If a fault occurs in the main grid due to a distributed generation, islanding of the area where this distributed generation is located is performed. This islanding operation is automated either on a local signal or remotely from the management center of the substation.

II.4.2.2 Fault clearing

Fault clearing procedures for the feeders with distributed generation are the same as the procedures for feeders without DG and this for 60% of the operating DSOs. The remaining 40% have different dedicated procedures for fault clearing for feeders with DG. The issue is that no coordination is insured in the case when having embedded MV and LV generation.

II.4.2.3 Remote control

Only a limited number of DSOs can remotely control the DG at MV and LV levels. This number is nearly 40% of the total number of DSOs. A fewer number of DSOs has the responsibility to dispatch or regulate the power generated by DG. Most DSOs are obliged to accommodate all DG power generation. But as cited before the protection interface disconnect automatically the DG in a case of disturbance in the grid.

II.4.2.4 Voltage control

According to most DSOs, the only way to perform coordination between DG and MV feeders is to adjust the settings of the tap changer of the MV/LV transformers. When it comes to LV level the contribution of DG voltage control is not taken into consideration.

II.4.2.4 Islanding

It is very uncommon for DSOs to perform intentional islanding, in fact almost 22% of DSOs perform intentional islanding under very specific conditions. In most cases, the islanding is performed on the DG's owner load and does include the utility infrastructure. However, some DSOs can perform total islanding including also the utility system in some emergency cases.

II.4.3 Future operations for active distribution networks

Today operations implemented in Active distribution networks are applied in a limited number of cases. A survey on the operation of different DSOs indicates that the development of the following areas is primordial: protection systems, safety, fault management, communications, intentional islanding, and ancillary services. Development of the above areas is necessary to be able to explore the benefits of active distribution networks as much as possible.

The analysis of different operations indicates that some need to be done to meet the wanted requirements. It seems also that a safe operation of many distributed energy resources in a distribution network still requires further consideration. Reliable communication canals are required before some ADN applications, like ancillary services and islanding, can be taken into consideration. The fact that there are only limited remote controls of distributed energy resources needs to change to help ADN becoming more universal.

II.5 Conclusion

In this chapter, we started by introducing conventional power systems and how they cannot handle the increasing power demand and environmental world requirements. This increasing demand and environmental requirements led to the use of renewable energy resources as a distributed generation at the distribution systems level. The introduction of distributed generation gave birth to active distribution networks. We also defined, in this chapter, active distribution networks and how it operates with the common network configurations. We have also presented control, operators, and operation of active distribution networks and in the same way the future operation of active distribution networks.

In this thesis, our scope of work is related to the operation and monitoring of active distribution networks. Our work is focused on the state estimation function in active distribution networks which will be presented in the next chapter. The proposed technique for state estimation will be presented in chapter V.

The contribution of this thesis will be on state estimation and more precisely the estimation of the state variables. As stated before, the classical methods presented above have issues as non-differentiability and non-continuity due to the field equipment, also high oscillations, local minima and non-convergence raising from to the non-appropriate choice of initial conditions and linearization step. This is why we opted for a completely decentralized state estimation, inspired by DSE, with an AI optimization algorithm, which is Artificial bee colony (ABC) algorithm.

To handle the distributed aspect of the proposed technique, we will be needing one concept which became widely used in power systems. This concept is named Multi-agent systems (MAS). We will give more details about MAS in the next chapter and also explain in details the proposed approach based on MAS technology.

Chapter III: State estimation

III.1 Introduction

As discussed in the previous chapter, active distribution networks are the backbone of modern power networks (smart grids). In the operation of the distribution networks or modern active distribution networks, it is always important at the ADN management centre level, to have accurate real-time measurements. This way, we can manage, control and take the appropriate decisions on power networks, and deliver the desired power to each bus of the system. Based on these accurate real-time measurements, state estimation is one of the most important functions that must be insured at the energy management level (EMS), for the good functioning of distribution systems.

The state estimation process for a distribution network is characterized by the succession of several steps: data acquisition, topology analysis, observability analysis, estimation of the network states and bad data analysis. Our work in this thesis is mainly focused on the estimation of network states. The states in our case are voltage and angle at each bus level in the distribution system.

In this chapter, we will present the different aspects and approaches for state estimation and also a brief state of the art about the proposed techniques of state estimation. All the outlined points concern the estimation of the network states which is, as already stated, the scope of our work.

III.2 State estimation

State estimation was first introduced by Schweppes et al in 1970 [33]. State estimation is very important in the control, operation and management of power systems, including transmission and distribution networks. The state estimator uses field measurements and topology information as initial data to perform estimation of network parameters, which are, in our case, bus voltage and angle of the system.

State estimation has gained more interest with the emergence of distributed generation and hence bidirectional power flow. Since transmission systems and distribution systems differ in terms of X/R ratio, imbalances among phases and low availability of real-time measurements, transmission systems state estimation techniques are unsuitable for distribution systems state estimation (DSSE), the main aspect of this thesis.

DSSE researches have started in the ’90s [38] [39]. Since the distribution and transmission networks differ in some network characteristics, DSSE gives rise to some challenges. The main characteristics which make the difference between distribution and transmission networks are listed as follows:

Construction: Distribution networks have mostly a radial structure with a low X/R ratio. On the other hand transmission systems are more meshed.

Redundancy: the number of measurements is more important in transmission systems than in distribution systems, this is due to some technical and economic reasons. In terms of measurements, distribution systems tend to be under-determined.

Scale and complexity: Distribution systems are considered to be diverse, in other words, networks in rural areas are different from the networks in urban areas. Distribution systems have also a large number of components. Consequently, the methods which are developed for DSSE need to be scalable, applicable for the different types of networks, and should also have a low computation burden.

Phase imbalances: the conventional state estimation techniques are performed with the assumption that the networks are balanced. Distribution systems are usually subjected to phase imbalances, this is why the use of three-phase system models is preferable to handle the issue of these imbalances.

III.2.1 The process of distribution systems state estimation DSSE

State estimation is characterized by the succession of several steps. All the steps are essential in the state estimation process. The different stages are highlighted below and figure III.1 summarizes the whole process:

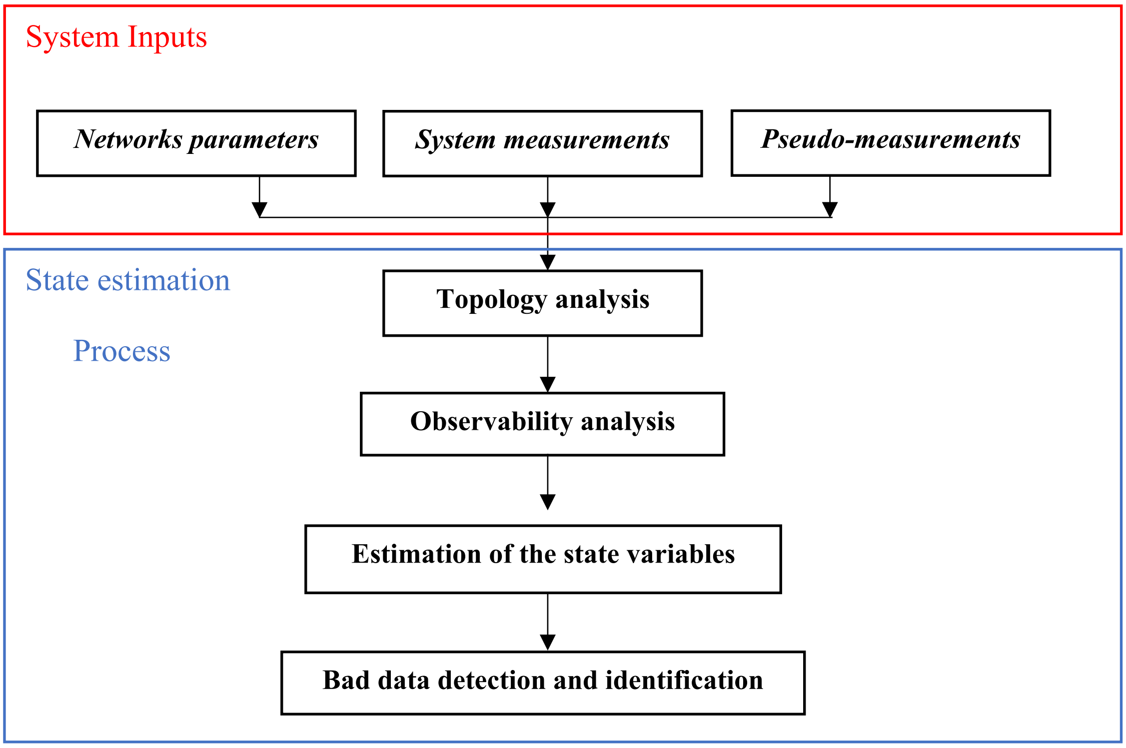

Figure III.1: State estimation process and system inputs of the process

III.2.1.1 Measurement's data acquisition

As a first step, based on the field sensors, data are sent to the EMS where it is analysed and used to carry out needed calculations for state values of the power network buses. In general, this data can be power injection measurements, power line measurements, bus voltage measurements or branch currents. This data can be the result of sensors, PMUs or also RTUs.

III.2.1.2 Topology analysis

Topology analysis deals with the physical aspect of power networks. Topology uses network equipment, like switches and circuit breakers status information to update network topology, which is necessary and very important during the process of state estimation. Network topology analysis is present to make sure that correct topology information is used in the state estimation process.

III.2.1.3 Observability analysis

During the process of state estimation, the observability analysis of the power system should be performed. Observability decides whether state estimation can be performed or not. If there exists a sufficient number and type of well-positioned measurements, the network is said to be observable. Otherwise, the network is judged to be unobservable and state estimation cannot be completed. If the network is unobservable, there will be some network islands that will be observable, and local state estimation can be performed. In this case, measurements must be introduced to make the network observable.

III.2.1.4 Estimation of the state variables

After data acquisition, topology analysis and observability analysis, we can perform the estimation of parameters. Parameters estimation is mainly an optimization problem with an objective function relating the measurements and the power flow functions of the power network. In this thesis, we are interested in this aspect of state estimation. We will deal with it in more details in the next section of this chapter.

III.2.1.5 Bad data detection and identification

Bad data detection and identification is the next step after the estimation of state variables. Based on the obtained results, we apply a test for each of the states. One popular statistical test is the Chi-squares test, formed by the square of the computed state variables [23]. When one of the Chi-square values related to one of the states is beyond the pre-set threshold, the state is suspected.

After the bad data detection is done, bad data identification is then started by calculating residuals related to the suspected state for each of the measurements which has a relation with this state. The measurement with the highest residuals is then eliminated from the measurements set. This is repeated until no other bad data is detected.

III.3 State variables estimation

As already presented in the introduction, different authors presented different methods which are based on power flow equations. The proposed methods like the Newton method [2], linear programming [3] or gradient descent [4] use iterative convergence methods to solve the state estimation optimization problem. The cited methods are based on the weighted least square (WLS) estimator [5]. To solve the state estimation problem, some other techniques were also proposed. These techniques are based on Kalman filtering [6–8].

As stated in the last section, our problem is mainly a minimization problem. In this work, the Weighted Least Square (WLS) optimization objective function is considered. The optimization comes in the form of:

$$Min\, J(x) = \sum_{i=1}^{N} w_i \left(z_i - f_i(x)\right)^2 \qquad 3.1$$

where N is the number of measurements, z_i is the i^{th} measurement, w_i is the weight related to the i^{th} measurement, x is the vector of the system states, f_i is the i^{th} power flow function relating the i^{th} measurement with the system states.

The conventional methods stated above have some issues. The issue to consider the most is the initial assumption that the power system equations are differentiable and continuous, which is not always the case. This issue is raising due to the non-differentiable and non-linear characteristics of the field equipment in power systems like circuit breakers or switches. Another issue to take into consideration is high oscillations, local minima and non-convergence issues due to the non-appropriate choice of initial conditions and linearization step.

To overcome the above issues, Artificial intelligence (AI) algorithms are considered a good alternative, since artificial intelligence is a powerful tool for non-linear optimization. In addition to this, artificial intelligence algorithms overcome also the issues of differentiability and continuity. As a first attempt, K. Selvi et al [9] proposed a genetic algorithm as an optimization tool for state estimation. After that A. A. Hossam-Eldin et al [10] proposed a modified version of the genetic algorithms for small scale distribution networks. Artificial neural networks were also an alternative solution proposed in [11], the proposed method is based on synchronized and conventional measurements. Shabani et al gave also their contribution, enhancing the WLS estimator in [12]. The enhancement was developed based on a fuzzy-logic based weight adjustment approach.

Swarm intelligence algorithms techniques are based on the behaviour of some animal’s swarm for survival goals. In this approach, the individual agents behave in a stochastic way to reach a common global goal [13]. A particle swarm optimization algorithm was proposed in [14] regarding real cases of rural and urban 3-bus power distribution systems and also a six-bus system in [15].

III.4 Distributed state estimation

Emerging, fast development, and the interesting functionalities of information and communication technologies (ICTs), has led to its integration into the area of power systems management. One of the results of this evolution is the distributed state estimation in distribution systems, and its wide exploration [16]. Distributed state estimation (DSE) depends on the way the sub-areas, subgroups of system buses, are defined. Different algorithms have been proposed in [7, 17-20,34-37] to deal with this revolutionary concept.

The most interesting fact in using distributed state estimation is to decrease computation burdens. This is resulting from the fact that the estimation is done simultaneously in a parallel way for each of the subsystems defined by the sub-areas. Distributed state estimation is becoming more interesting when dealing with huge power distribution systems with an important number of network buses. DSE also gives a certain degree of freedom for the different predefined areas of the distribution system, since each defined subsystem estimates its local state. Active distribution networks (ADN) are the most suitable for DSE applications, provided that a communication system is already embedded into them. The embedded communication system allows the different subsystems to exchange data to achieve the global goal, which is the active distribution network state estimation. The DSE problem is formulated as follows [17]:

$$Min\ \sum_{a=1}^{n} J(x_a) + \sum_{a=1}^{n} \sum_{b \epsilon B(a)} (x_a, x_b) \qquad 3.2$$

Where x_a is the state vector of the area a, x_b is the state vector of the neighbour area b, n is the number of the defined areas and $B(a)$ is the set of neighbour areas of a.

As stated above, many authors proposed different approaches for DSE. J. Zaborszky et al [19] are the first to propose a distributed approach which takes advantage of dedicated microprocessors at the local buses to circumvent interacting solution of the power flow equations. The main objective of this proposal is to reduce calculation time.

One particularly interesting work is presented in [34] and [35] by Ebrahimima and bladick. The work reported in [34] implements a decentralized state estimator considering the border buses as belonging to two areas at the same time. In [35], the same authors perform an analysis of the condition number of the Hessian matrix that determines the numerical behaviour of the algorithms to solve the estimation problem and provide hints on how to select the number and type of measurements to be considered for state estimation. Moreover, [35] also assesses the importance of this selection.

H.B. Sun and B.M. Zhang [18] proposed an approach where they take into consideration both the transmission and the distribution network as one power system. A novel master–slave-splitting (MSS) iterative method is developed in this approach, for solving the hybrid distribution and transmission problem. In this approach, state estimation problem of large scale is split into a transmission state estimation and lots of distribution state estimation sub-problems.

Some other authors are also dealing with decentralized state estimation problem recently. For example, in [36], Zhao and Abur implement a novel technique to improve the results of the state estimator for very large-scale systems in which control centres concerned with parts of the system have accurate information about the state of their corresponding subsystems. In [37], the authors analyse the state estimation problem in a distribution networks environment, based on so-called agents.

In [17] the authors presented a technique that can be distinguished from the other techniques by the need of border areas information only and which also does not need to be processed like in [34]. This technique relies also on directly solving the pertinent single-area optimization problem.

Zonouz et al [7] presented a modified coordination technique for hierarchical state estimation that is based on Kalman filtering (HKF) and they also perform an analytical and experimental comparison among the HKF, central, and distributed state estimation in terms of communication bandwidth and computation power requirements.

III.5 Conclusion

In this chapter, we first presented state estimation as a general concept in transmission or distribution power systems. Right after, we cited the main differences between transmission and distribution systems to show that the state estimation function applied to transmission systems differs from the one applied to distribution systems. We explained also in this chapter that our interest is in distribution systems state estimation DSSE.

In the second section of this chapter, we went through the whole process of state estimation and we have shown that we will be focusing on State variables estimation. After precising the main point of our work, we presented distributed state estimation (DSE) giving also the state of the art of this concept of state estimation.

In the next chapter, we will be presenting Multi-Agent systems and chapter V will be dedicated to the contribution of this thesis.

Chapter IV: Multi-Agent-based state estimation

IV.1 Introduction

In the previous chapter, we explained that the proposed method in this thesis is inspired by DSE. To implement such a method, we will need the assistance of multi-agent systems, which we are presenting in the first part of this chapter.

The second part of this chapter is dedicated to the presentation of the used optimization algorithm ABC and a full presentation of the proposed method with all the necessary details and explanations.

IV.2 Multi-Agent systems

A multi-agent system (MAS) is a collection, a group, or a community of goal-oriented, smart, and autonomous agents, which are all working for the accomplishment of a certain goal.

The MAS obeys a certain hierarchy when it comes to goal accomplishment, i.e., each agent has its own goal, named as a local goal, but global system goal comes always in priority. The agent is the fundamental part of the MAS, it is considered as a smart entity that is characterized by BDI (beliefs, desires, and intentions) and also some knowledge, each agent can have a view on the outer shell to acknowledge data of the surrounding environment.

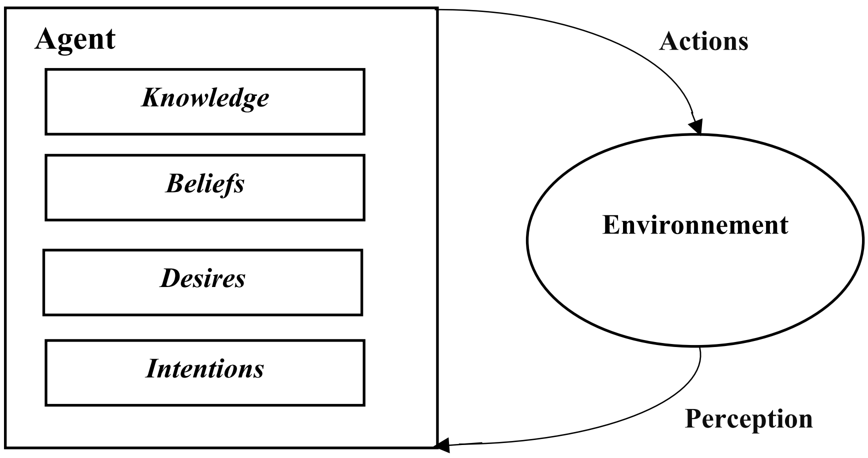

Figure IV.1: a multi-agent system agent representation

When it comes to decision making, each agent can interact with other agents and following some communication protocol. MAS agents can be implemented as software or hardware depending on the applications. In the next sections of this chapter, we will give the properties of MAS and their use in real systems in general and in power systems in particular.

IV.2.1 Multi-agent systems properties

In this section, we will present some of the fundamental properties of multi-agent systems.

IV.2.1.1 Advantages of MAS

the main advantage of the MAS over classical methods (Neural net, expert systems, artificial immune systems) is complexity and the fact that classical methods are limited when it comes to huge systems, and they require a huge amount of data transmitted and processed which is of a high cost, not like MAS which require a local view, only on the neighbor agents, which decreases the cost.

Another advantage to cite is that multi-agent systems are flexible, plug and play, and fault-tolerant. For example, adding or removing a load will be automatically acknowledged to the system, took into consideration, and will not interfere in the goal accomplishment.

From the previous properties of MAS, we can easily deduce that these systems can solve difficult problems since computations are distributed among several communicating agents. So, control is decentralized unlike today's control systems SCADA, and actions are taken locally, which gives some autonomy to the system.

MAS do not depend on a particular technology; we can merge different platforms with different languages following some standard messaging tools from FIPA (the Foundation for Intelligent Physical Agents).

IV.2.1.2 MAS design methodologies

The design of MAS, can be accomplished by several methodologies, but the same specify, analyze, and design process.

1- Specify objectives.
2- Specify the corresponding tasks.
3- Set the role of each agent.
4- Find models for the different agents.
5- Define the interactions and communication languages (communication-based on ACL or KQML).
6- Finally, the MAS is created.

IV.2.1.3 Agents implementation

Agents can be seen as a three-layered structure, defined by the following three layers stated below:

-Message handling layer: where all data are input/output from/to the agent so it communicates with the other agents or with the environment.
-Behavioral layer: for defining when tasks are to be carried out.
-Functional layer: for defining the actions which the agent will perform.

IV.2.1.4 MAS platforms

We have many tools for designing and implementing MAS. For example, JADE, ZEUS, SKELTON agent, MATLAB/Simulink, for power engineering the most used is JAVA-BASED JADE and MATLAB/Simulink.

The general architecture for MAS of power systems management is as discussed below, but due to the lack of standards in this field, several architectures exist.

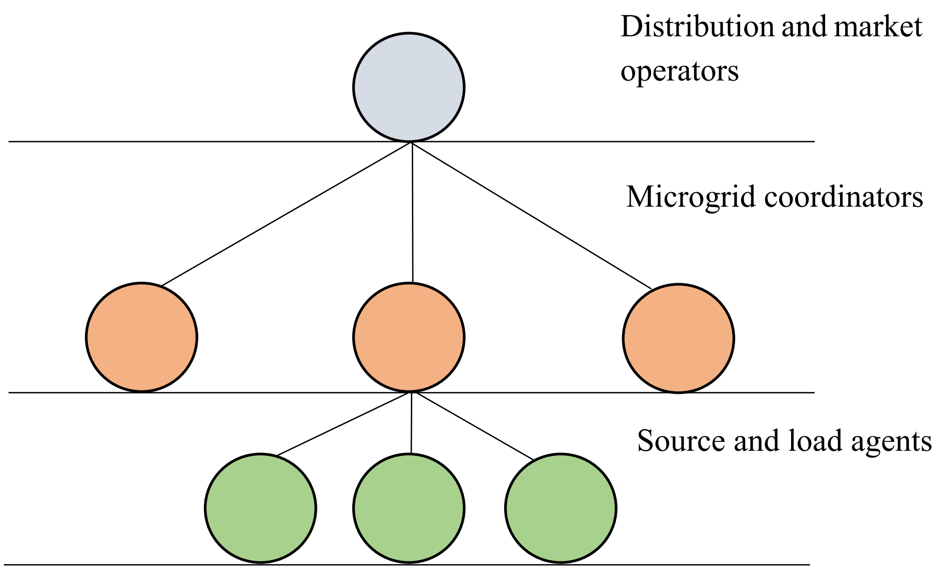

Figure IV.2: The general architecture for a multi-agent system in power systems

IV.2.2 Multi-agent systems and their applications

IV.2.2.1 Overview on the main types of agent's systems

As stated in [40], the potential applications of agent-based systems can be distinguished into three main types. The first one is assistant agent systems. In these types of systems, agent's roles are to gather information or executing transactions on behalf of their human representatives. For example, agents who book hotels and do travel arrangements for their human representatives.

The second type is multi-agent decision systems. In these types of systems, agents are smarter than the ones in the previous type. Agents involved in these systems must together make joint decisions. As an example, agents in a telecommunication network manage the operation of the network when a request is sent. Decision-making mechanisms may be generated for example from an economical restriction.

The third type, which can be distinguished from the two stated above, is multi-agent simulation systems. These types of systems are used for simulating real-world problems with different components and complex and diverse interactions. Examples to cite, human economies, society models, road traffic systems, and computer networks.

It can be deduced, that the first type is a single-agent system while the two others are multi-agent systems. Although, the agents, from the first type of systems, may interact with other agents from the two other multi-agent systems. Meanwhile, decisions in the second and third types are taken collectively and not in an individual way as in the first type.

The main difference between the second and the third type of multi-agents systems is that the second type of agent systems have the system as a goal and the third type systems have the understanding that comes from the system as a goal. In addition to this, in many simulations, the agents provide a proper representation of real components, while in the second type, agents are here for their function and they are not representative of some physical component. This is why in our work in this thesis we will be more oriented to the third type of agents system.

IV.2.2.2 Applications of multi-agent systems

IV.2.2.2.1 Industrial and commercial applications

The main areas in which agents systems are widely applied are as follows: manufacturing, process control, telecommunication systems, air traffic control, traffic, and transportation management, information filtering and gathering, electronic commerce, business process management, human capital management, skills management, (mobile) workforce management, defense, entertainment, and medical care.

For example, in manufacturing, the main areas of application are configuration design of manufacturing products, collaborative design, scheduling and controlling manufacturing operations, controlling a manufacturing robot, or determining production sequences for a factory.

In process control, where the application of agents is intuitive, we use controllers which are autonomous and reactive entities. The best-known developed platform as an application for multi-agent systems is ARCHON. It has been applied in several domains, such as transportation of electricity management and particle accelerator control. In the same manner, other systems have been developed for monitoring and diagnosis of other systems like nuclear power plants, spacecraft control, climate control, or metallurgical processing control units.

Another example of application in this area is supply chain management, Lost Wax and Cap Gemini have developed an agent-based demonstrator in which aircraft are serviced, covering routine and emergency demands for mobile service engineers. The application is modeled as a set of interacting autonomous agents executing in the Lost Wax agent framework, which provides an application programming interface (API) through which agents interact with the environment and each other.

IV.2.2.2.2 Simulation Applications

Multi-agent systems can offer efficient models for real-world problems with appropriate complexity and dynamism. Some models are a strong representation of economies, societies, biological or engineering systems.

Agent-based simulations are characterized by the intersection of three fields, agent-based computing, social sciences, and computer simulations. The social sciences study the intersection between entities in the system represented by the different agents. Computer simulations are related to the techniques of simulating the phenomena on a computer.

The intersection of three areas gave rise to new areas that are interesting and produced relevant work:

- Social sciences and agent-based computing (social aspects of agent systems)
- Computer simulation and agent-based computing (multi-agent-based simulation)
- Social sciences and computer simulation (social simulation)

Scientists find computer simulation useful when addressing changes that cannot be easily forecast, but typically the causes can be identified retrospectively. For example, flight simulators, which are used to train pilots on how to respond to many types of unexpected events. An agent-based social simulation can be more flexible and responsive. As an example, an agent-based social simulation analysis for climate, based on some worldwide environmental agreement, can take into consideration the development of social pressures as the outcome of individual choices and social interaction of agents. In this case, agents are more robust.

It turns out that three mainboards of application areas in agent-based social simulation:

- Social structures and institutions, this type of simulation is mainly based on evidence and observations to build up the model. Most of the time these simulations help to develop plausible explanations of observed phenomena, or also develop organizational structures, and can also help to take managerial decisions. For example, to help a company in the study of commercialization of a new product in the market based on the awareness, price, brand reputation, or information from other agents.

- Physical systems. This type of simulation includes agent-based models of smart buildings, traffic systems, biological systems, power flow in electrical networks. Many multi-agent systems were developed to manage power networks.

- Software systems of all types, this area includes eCommerce and information agency. Traffic on a new telecommunication system may also be forecast by the means of a multi-agent system simulation of some users' predicted interaction or behavior.

It can be deduced that simulation covers a range of phenomena from the most applied, for example manufacturing processes, traffic systems, information and control systems, to the most abstract like social dimensions to belief, trust, duty, and right.

IV.2.2.3 Multi-agent systems in power systems

The effectiveness of a power system depends mainly on its ability to economically and reliably meet consumption demands of different areas, residential, commercial, and industrial loads. Active networks represent the main backbone of future smart grids, which are both characterized by distributed generation (DG) and information and communication technologies (ICTs).

Coordination and control of these new emerging grid components are considered as a great challenge. Advanced networking and the emerging technologies of ICTs, which are more integrated into the modern grids, have motivated researchers to use Multi-agent systems. This integration offers multiple advantages like placing additional distributed generation without reengineering the whole system, eliminating the requirements of a complex central controller and the associated communication facilities.

Multi-agent systems are one of the fastest-growing domains in agent-oriented technology which deals with modern power systems when it comes to decision modeling and operation [41].

Multi-agent systems are spread to multiple modern power systems applications in the field of power system restoration, security, protection, control, monitoring energy storage and maintenance scheduling and electric power market simulation [42].

IV.2.2.3.1 Multi-agent systems approach and applications in power systems

To provide further explanations about the applications of multi-agent systems in power systems, it is worthwhile to first present the two main approaches of applications namely simulation and real [42].

IV.2.2.3.1.1 Simulation approach

Multi-agent systems, using simulation approaches, might be applied to three categories of power systems, which are planning, market, and management. In this approach, agents represent some elements of the system to predict their actions and behavior. This approach is used to test how complex the system is in the real world. In the simulation approach, the predicted data are used for the estimation in the future, while real data are used for current conditions.

IV.2.2.3.1.2 Real approach

Multi-agent systems, using real approaches, can be applied to the other four categories of power system, operation, control, monitoring and protection. In the real approach, agents present their tasks in a real way and not in a simulation environment. The decision-making process is conducted online where agents' actions are physical.

The applications of the two approaches are presented as follows:

IV.2.2.3.1.3 MAS application in planning

A great number of studies have explored MAS application in planning. For example, some studies use MAS for planning power transmission expansion in a deregulated or restructured environment. In these studies [43-45], each contributor in the power system (owner of a power station and transmission lines and groups of consumers) is modeled by MAS as an agent in the same market, where they can communicate with each other to look for appropriate partners and they can also form a long-term partnership to protect their interests.

IV.2.2.3.1.4 MAS application in the electricity market

Many researchers have put into evidence some models for multi-agent systems in the electricity market. As an example, an economical power model for simulation and its dynamic agent-based platform is proposed in [46]. The proposed research assists decision-makers in evaluating the influence of economic uncertainty such as financial crisis and the effect of regulations and restrictions on power consumption. Another example is proposed in [47], the proposed agent-based model for electrical power and CO_2 certificate markets is developed to evaluate the avoided emissions due to the renewable energy integration.

IV.2.2.3.1.5 MAS application in network management

In the literature, different models for applying MAS in network management have been proposed. For example, in [48] a comparative study on three models was proposed, a traditional optimization model, an optimization model with endogenous technological change, and an agent-based model. It has been concluded that the agent-based model will act in a better way.

A multi-agent systems-based simulator named ASPECS is proposed in [45]. This simulator is considered a tool for managing smart grids without any real device. ASPECS can simulate the behavior of electrical devices to test multi-agent systems for smart grid management.

IV.2.2.3.1.6 MAS application in network operation

For network operation, studies concerning multi-agent applications were proposed. For example, in [49] a framework for evaluating MAS-based projects in smart grids. The mechanism of evaluation is based on greenhouse gas quantity reduction, economic competitiveness, energy security, and also human integration. Another strategy based on MAS is proposed in [50]. This strategy is proposed to restore power to users in case of an outage in power systems. The restoration follows a priority order in any case of any shortage in alternative sources.

IV.2.2.3.1.7 MAS application in control

Many techniques were proposed in this area. Proposition including MAS for making control decisions and the role of intelligent systems in active network management are discussed [51]. Another study in [52] gives a solution for the load frequency control problem based on MAS. A fuzzy agent algorithm for decentralized controlling of voltage and reactive power is also discussed in [53], the algorithm aims to find the optimal tap positions of tap changing transformers for an optimal voltage profile.

IV.2.2.3.1.8 MAS application in monitoring and diagnostic

Different techniques have been developed by researchers to apply MAS to the monitoring and diagnostic. An example to cite is a condition monitoring multi-agent system commonly named COMMAS. This system is applied on transformers based on partial discharge analysis of UHF signals. This system is also considered extensible and flexible while it facilitates the integration of substations and plant components [54]. A multi-agent system named protection engineering diagnostic agent (PEDA) is usually combined with intelligent systems to automatically diagnose any fault in power systems [55]. More details about the architecture of PEDA can be found in [56].

IV.2.2.3.1.9 MAS application in protection

There are many applications for MAS in protection. For example, the research in [57] uses MAS to propose a cooperative protection system. The proposed MAS consists of distributed equipment and a communication network. The system proposes different protection functions, such as primary protection, backup protection, and adaptive protection. The researchers in [58] propose a MAS for protection. The system is called MAS-ProteC and it was applied in a smart grid. In the same manner, the authors in [59] integrate MAS-ProteC in MASGriP, which is a multi-agent smart grid platform, to perform the simulation of future power system operation and to manage smart grids in the electricity market.

IV.3 Multi-agent-based state estimation

IV.3.1 Artificial Bee Colony

ABC is an optimization algorithm based on swarm intelligence inspired by the natural behavior of honeybee swarms. ABC was first developed by D. Karaboga [22]. The algorithm is simulating the behavior of real honey-bees for solving multidimensional and multimodal optimization problems. The colony consists of three groups of bees, employed bees, onlooker bees, and scout bees. The number of food sources is equal to the number of employed or onlooker bees, which is half of the colony. The bee whose food source has been exhausted by the different bees becomes a scout bee trying to find a better food source [60].

As a first step, the algorithm initializes a population of solutions (food sources), vectors of voltage, and angle states. Second, the algorithm calculates the fitness corresponding to each solution and saves the best solution, its fitness, and its position. The next phase is "the employed bees" phase, where each 'bee' is assigned to a solution, and it tries to find a better one by combining its solution with different solutions following the equation [22]:

$$v_{ij} = x_{ij} + \varphi_{ij}(x_{ij} - x_{kj}) \tag{4.1}$$

Where v_{ij} is the new state resulting from the combination, x_{ij} is the state desired to be improved, φ_{ij} is a random variable between -1 and 1 and x_{kj} is the state chosen to do a combination with. If x_{ij} is a state then, i is the index relative to the position of the solution in the initial population. j is the index relative to the state that should be estimated. The set of estimated states represent the a solution.

In the next step, a probability is assigned to each solution. This probability describes the quality of the solution. The probability of solution i is then calculated as [22]:

$$p_i = \frac{fit_i}{\sum_{n=1}^{s_n} fit_n} \quad 4.2$$

Where fit_i corresponds to the fitness of the solution i and s_n is the dimension (number of variables) of the solution.

Next is the onlooker bee phase. Here, the onlooker bees will be dispatched to the solutions, based on the probability set in the previous phase. The higher the probability the better is the solution. Onlooker bees will also perform a combination of solutions trying to end up with a better one. If the solution cannot be improved in a certain number of cycles it will be abandoned. After abandoning a solution, the scout bees introduce a new one in the solution range. The algorithm stops if the desired requirements are met.

ABC algorithm requires fewer control parameters than other algorithms. First, the 'population', which is equal to the number of either onlooker or employed bees which is the number of initial solutions. Second, the 'limit', which is the maximum number of tries in which the solution cannot be improved and thus abandoned. Finally, the 'cycle' is defined as the number of iterations for the whole algorithm. The more interesting point in the use of ABC is its scout bees that avoid the problems of local minima in the solution set. The scout bees always aim for a better solution in the solutions set.

The flowchat below shows the ABC algorithm process.

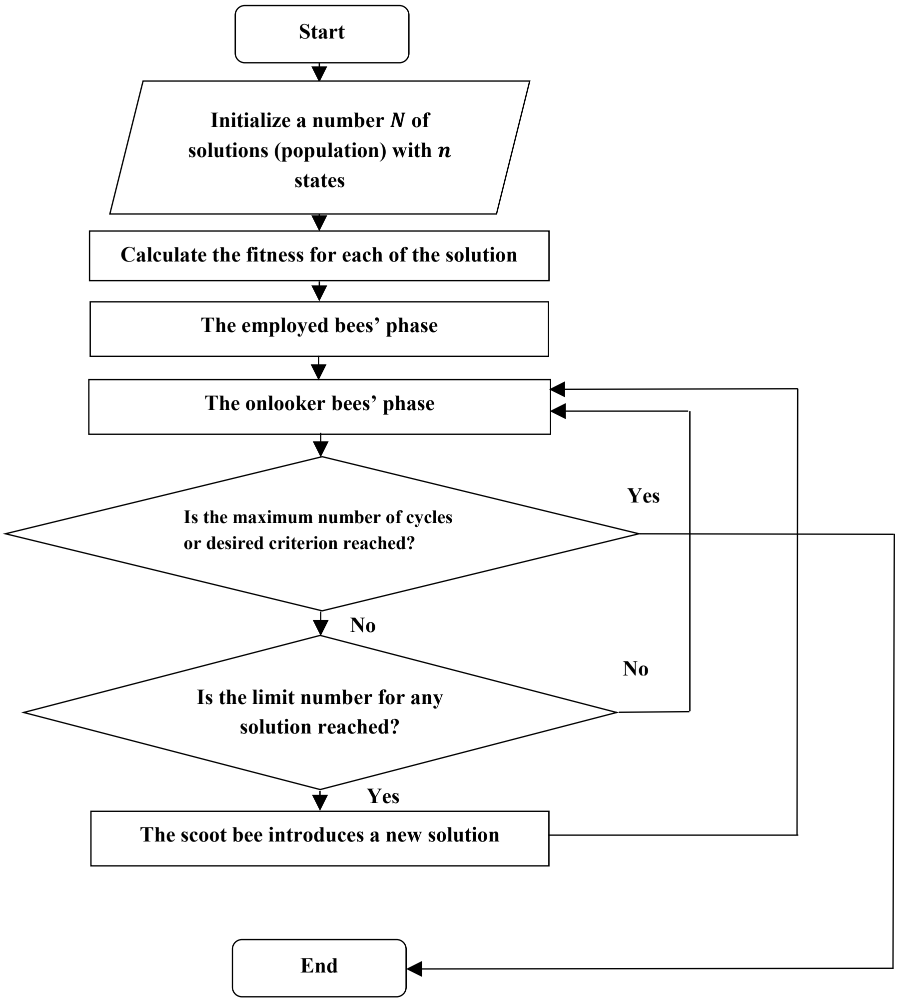

Figure IV.3: Flowchart for ABC algorithm

IV.3.2 The proposed multi-agent-based state estimation

Based on the MAS technology, this thesis proposes a new approach for state estimation in ADN. Each agent is connected to neighbor agents by a communication link, to allow data exchange.

In this approach, each agent represents and manages a network bus. The Neighborhood of a bus or the neighborhood of an agent is determined by identifying the set of all buses or agents connected to it, including all the power lines connecting these buses. Each agent will try to reach a local goal, which is the estimation of its own and neighboring bus states. State estimation of the whole ADN, which is the global goal, is achieved by combining the local goals computed previously. Since an agent is assigned to each bus, each agent will also manage a sub-distribution network related to that bus. The number of subsystems equals the number of buses in the original ADN. A subsystem N_i related to an agent bus *i* is the subsystem constructed from the same bus *i* and all the buses linked to it, i.e., its neighborhood. As an example, Figure IV.4 illustrates the subset N_1 containing bus 1 and the buses connected to it, in this case, buses 2 and 5.

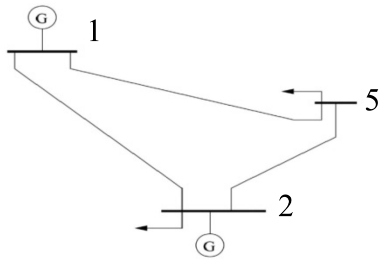

Figure IV.4: The subsystem N_1 related to Agent bus 1

Figure IV.5 illustrates three subsystems related to three agents, agents 1, 2, and 13 in the IEEE 14-bus. Where the new subsystems are much smaller and thus less time-consuming, especially when it comes to state estimation. The minimization of an objective function with 27 variables related to a 14-bus network takes more time than the minimization of an objective function with 5 variables related to a 3-bus network. Another advantage is that this split reduces tremendously the complexity of the whole ADN. Figure IV.5 gives an illustration of how ADN are split. The resulting subsystems are defined as stated before. The number of power line connections will also decrease with the number of buses, resulting in reduced complexity in the subsystems. After splitting the whole ADN, each agent performs three main functions. First, data acquisition and state estimation at the bus level is performed. After collecting all the measurements available in the local area network (within the subsystem), state estimation at the bus level is performed using this data. State estimation, in this case, is achieved by the minimization of the objective function relative to that subsystem. The objective function related to a subsystem is in the form of eq. (1) in section 2. The objective function is minimized using the ABC algorithm explained in section 3. Applying the ABC algorithm results in the vector of states (Angle and voltage) that minimizes the objective function.

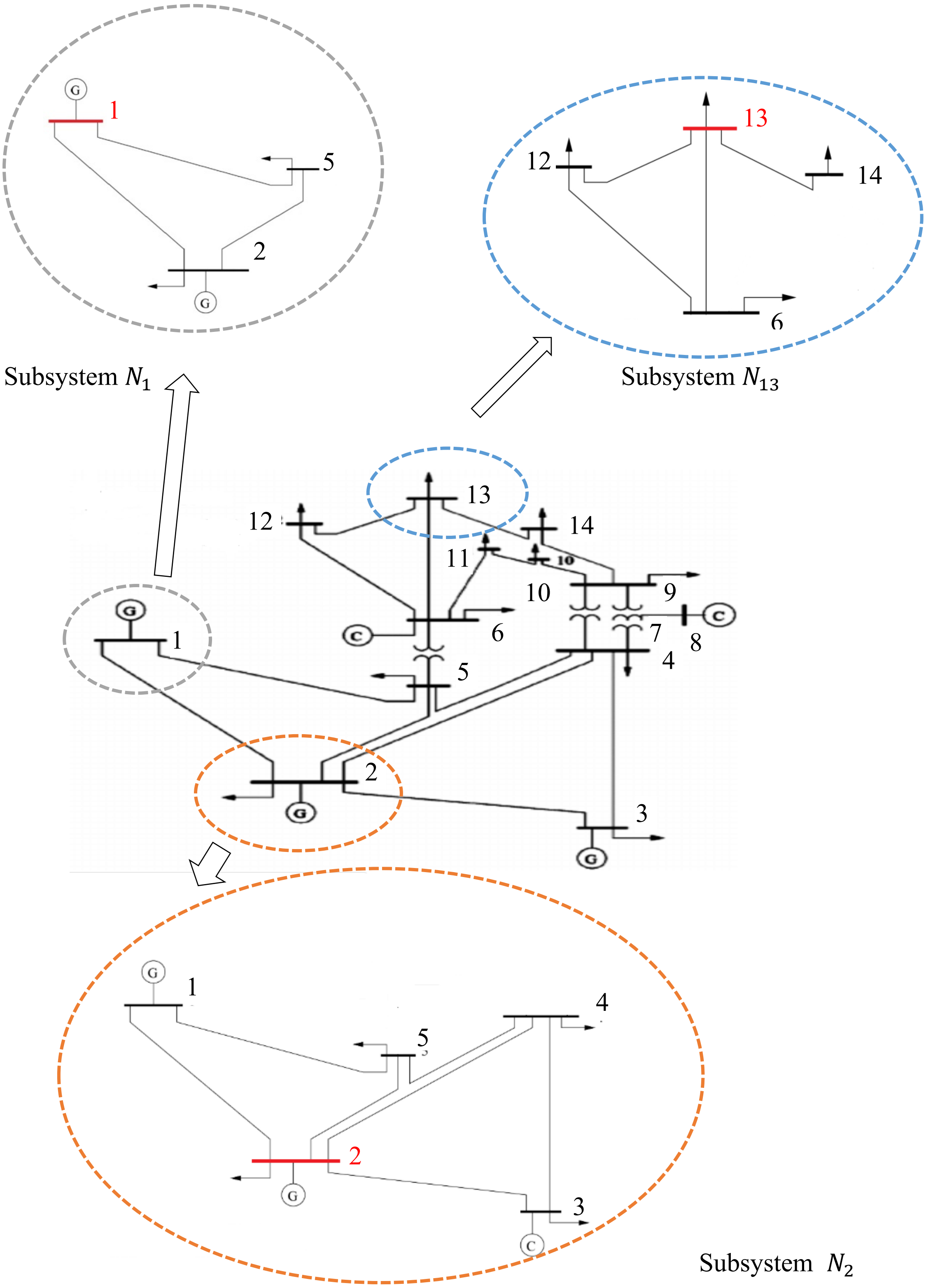

Figure IV.5: Representation of the subsystem of agent 1, 2, and 13 resulting from the split of the IEEE 14-bus

This vector includes the states of all the buses included in the subsystem seen at this agent level, for example in the IEEE 14-bus at agent 1 level, the estimation procedure ends up with the following vector $[V1_1 V2_1 V5_1 \theta1_1 \theta2_1 \theta5_1]$. In a parallel way, the same procedure is applied for the rest of the IEEE 14-bus resulting subsystems.

Next, neighbor agents will share their data. In this phase, neighbor agents will exchange data resulting from their respective estimations in the previous phase. Each bus agent will end up with all the estimated states related to its bus from the neighbor agents and its estimation. For example, agent 1 will end up with the states estimated in the previous stage and also the states from agents 2 and 5 $[V1_1 V1_2 V1_5 \theta1_1 \theta1_2 \theta1_5]$.

Finally, based on eq. (3.2), each agent deploys distributed state estimation. After the data exchange, each agent will estimate its respective bus states based on eq. (3.2). The expression of V_k and θ_k from eq. (3.2) is derived as:

$$V_k = \frac{\sum_{i=1}^{N} w_i V_{k,i}}{\sum_{i=1}^{N} w_i} \quad 4.3$$

$$\theta_k = \frac{\sum_{i=1}^{N} w_i \theta_{k,i}}{\sum_{i=1}^{N} w_i} \quad 4.4$$

Where V_k and θ_k corresponds to the voltage and the angle relative to bus k respectively, N is the number of buses in the whole ADN, $V_{k,i}$ is the voltage of bus k estimated at bus i by the agent of that bus, $\theta_{k,i}$ is the angle of bus k estimated at bus i by the agent of that bus and w_i is the weight of the estimation. w_i is defined in the range $[0, 1]$. $w_i = 0$ for the buses out of the neighborhood of bus k. $w_i = 1$ for $V_{k,i}$ estimated at the same bus k, in other words V_{kk}.This weight is inversely proportional to the distance between bus k and bus i in the neighborhood of bus k. Then global estimation solution for the ADN is reached. Figure IV.6 explains how agents perform during the state estimation.

The flowchart in figure IV.6 summarizes the proposed approach. In the first step, each agent collects the measurements in the local area network and, based on these measurements, estimates the states in its corresponding subsystem. When the estimations for all the ADN agents are done, agents in the same neighborhood share their respective estimations. Each agent ends up with the states related to its bus from the neighbor agents and its estimation. Finally, the distributed state estimation is deployed to reach the global goal which is the state estimation of the whole ADN.

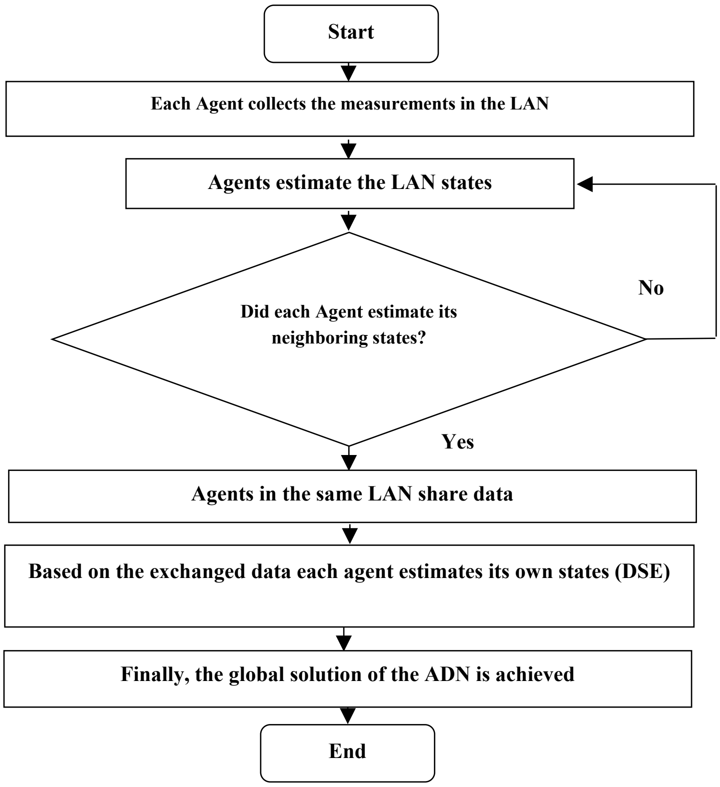

Figure IV.6: Multi-agent state estimation procedure

```
Input: N- Number of ADN buses, S-set of integer numbers from 1 to N, Ne-set of neighbor agents of Agent (i)
While (Agents do local estimation) do
        Agent (i) ⟸ Measurements in Ne.
        Agent (i) ⟹ Estimates neighboring states and agent's states.
end while
For each j ϵ Ne do
        Agent (i) ⟸ (Vi_j ,θi_j).
End for
Agent (i) ⟹ (Vi ,θi).
```

Algorithm IV.1 Multi-agent-based state estimation procedure

Our approach is a completely decentralized state estimation method, where each agent is provided with its computer or processor. This allows local estimation for each agent in a parallel way (simultaneously). Hence, the global estimation of the ADN can easily be obtained by combining the results computed earlier for each subsystem (Algorithm IV.1).

IV.4 Scope of work

As stated in chapter II, we opted for completely decentralized state estimation. and to handle such a distributed process MAS are of great help. Based on what was presented in this chapter, our proposal can be categorized into an agent-based social simulation of a physical system, which is an active distribution system. Our approach can also be seen as a real approach for MAS application in monitoring and diagnostic. In the second part of this chapter, we have explained, with all the necessary details, the proposed method which, as stated previously, is a completely decentralized state estimation method.

IV.5 Conclusion

In this chapter, we gave a brief introduction and presentation of Multi-agent systems technology including the properties of these systems, advantages, design methodologies, and implementation platforms.

We also dealt with the different agent system types and applications of these systems in different areas. In the next part, we discussed MAS approaches and their applications in power systems.

We clarified which approach of MAS use will help us to deal with our initial issue of state estimation explained in chapter II. In the second part, we presented our approach for decentralized state estimation based on MAS technology.

Chapter V: Simulations and discussions

V.1 Introduction

In this chapter, first, simulation results of a centralized approach are presented, followed by results of the proposed CDSE approach.

In the centralized approach, a meta-heuristic algorithm is applied to the whole system to estimate the ADN states. Results obtained by ABC are compared to original Particle Swarm Optimization (PSO) algorithm results and the actual values of the ADN. Actual values of the ADN, the IEEE 6-bus, and the IEEE 14-bus benchmark systems are well known [25]. The objective of this part is the validation of the ABC algorithm. If ABC algorithm performs well, compared to other algorithms, in terms of precision for the whole ADN, it will thus perform well for the resulting subsystems.

The second part is dedicated to the proposed CDSE. This part aims to show how MAS's decentralized split of the ADN reduces its complexity and state estimation time. Results for centralized estimations and CDSE on IEEE 14-bus and IEEE 30-bus are compared.

V.2 Simulation results and discussions

In the first part, let's start with the IEEE 6-bus. To ensure the observability of the distribution system, 15 measurements are considered. Among these measurements, 6 are real power and 6 are reactive power injection measurements at all the system buses, and 3 voltage measurements at bus 1, 2, and 6. All these data are presented in table V.1, the values are per unit and the power base is 100 MVA.

Table V.1. Measurements for the IEEE 6-bus

Bus	Measurements in IEEE 6-bus in P. U		
	Active power (P)	Reactive power (Q)	Voltage (V)
1	0.9597	0.4385	1.0500
2	0.5000	0.2805	1.1000
3	-0.5500	-0.1300	-
4	0.0000	0.0000	-
5	-0.3000	-0.1800	-
6	-0.5000	-0.0500	0.9185

The states that will be estimated are the voltage of the slack bus which is bus 1, and the angles and voltages of the remaining buses. In the use of metaheuristic algorithms, the range of solutions is defined. The initial population for the states is generated randomly within their allowable ranges [14]. While examining the actual values of the IEEE 6-bus benchmark system, we note that the values of the states vary as follows. The voltage V_i at bus i lay between 0.85 and 1.1, and the angle Θ_i at bus i between -20 and 20, where V_i is in P.U volts and Θ_i in degrees [15].

The initial population of both algorithms is set to 70 and the number of iterations to 1200. Parameters of PSO are the same as in [15]. The weights are considered to be 250 for voltage measurements and 100 for power measurements [15].

Simulation results on IEEE-6 bus for ABC and PSO-based estimation are presented in table V.2, table V.3, table V.4, figure V.4, and figure V.5. The estimated voltage and angle are presented in table V.2 and table V.3, respectively. Figure V.4 and figure V.5 describe the estimation error on the voltage and the angle, respectively. The mean square error obtained by the two algorithms when estimating the voltage and the angle are reported in table V.4.

Table V.2. Estimated bus voltages for the IEEE -6 bus using ABC and PSO

Bus	Estimated voltage magnitude PU		
	Actual value	ABC	PSO
1	1.0500	1.0479	1.1000
2	1.1000	1.0732	1.1000
3	0.8837	0.8755	0.9280
4	0.9424	0.9370	0.9919
5	0.9262	0.8782	0.9196
6	0.9185	0.9204	0.9707

Table V.3. Estimated bus angles for the IEEE 6-bus using ABC and PSO

Bus	Estimated angle in degrees		
	Actual value	ABC	PSO
1	0.00	0.00	0.00
2	-5.05	-4.41	-3.55
3	-13.17	-13.32	-11.94
4	-9.86	-9.89	-8.90
5	-13.03	-12.95	-11.71
6	-12.49	-12.54	-11.23

Table V.4. Mean square error on the IEEE 6-bus state estimation using ABC and PSO

States	Mean square error IEEE-6bus	
	PSO	ABC
Voltages	1.6×10^{-3}	0.52×10^{-3}
Angles	1.6029	0.0884
Both States	0.7295	0.0405

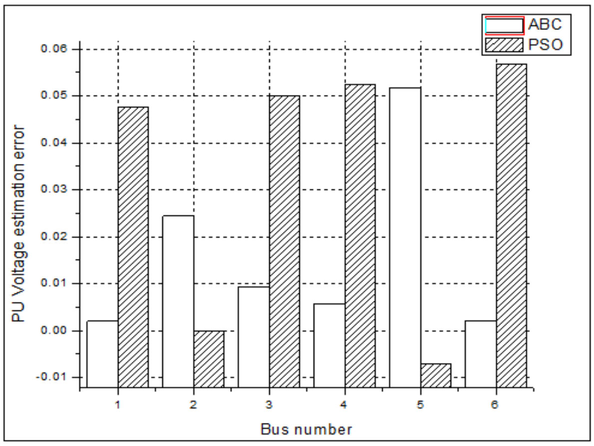

Figure V.4: Error on the estimated bus voltages of the IEEE 6-bus

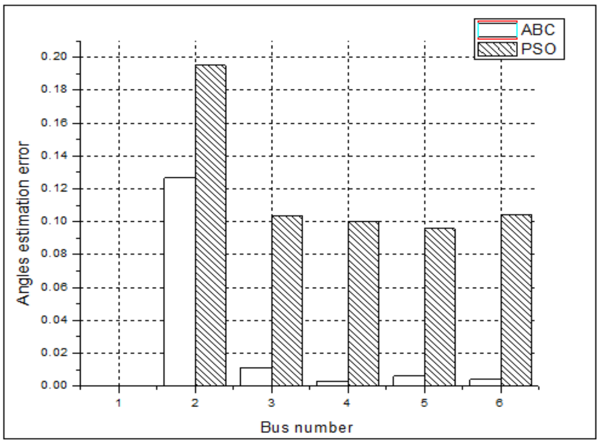

Figure V.5: Error on the estimated bus angles of the IEEE 6-bus

Table V.2 and figure V.4 show that voltage estimation for buses 1, 3, 4, and 6 is better when using ABC and better for buses 2 and 5 when using PSO. Table V.3 and figure V.5 show that ABC performs better than PSO for angle estimation for all the buses. Results of error calculations presented in Table V.4 confirm that ABC performs better than PSO. Simulation results for IEEE 6-bus show that the performances of PSO and ABC are close to each other, with a slight advantage for ABC.

Now, how do ABC and PSO perform on the larger IEEE 14-bus. The IEEE 14-bus considered is described in figure V.2. For measurement distribution, real and reactive power flow measurements are considered on all the power lines of the distribution system and 4 voltage measurements at bus 1, 8, 9, and 10 (see figure V.2). These measurements are presented below in table V.5 and table V.6.

Table V.5. Voltage measurements for the IEEE 14-Bus

Bus	Voltage Measurement in PU
1	1.060
8	1.090
9	1.051
10	1.046

Table V.6. Power flow measurements for the IEEE 14- Bus

From Bus	To Bus	Power flow measurement in PU	
		Real power flow	Reactive power flow
1	2	1.5591	-0.2018
3	2	-0.7020	0.0133
2	4	0.5602	-0.0912
1	5	0.7648	-0.0372
2	5	0.4147	-0.0832
3	4	-0.2400	-0.0404
5	4	0.6288	-0.0705
5	6	0.4374	-0.1192
4	7	0.2842	-0.1195
8	7	0.0000	0.2084
4	9	0.1610	-0.0296
7	9	0.2842	0.0638
9	10	0.0549	0.0282
6	11	0.0710	0.0498
6	12	0.0779	0.0269
6	13	0.1764	0.0795
9	14	0.0953	0.0271
11	10	0.0354	0.0305
12	13	0.0162	0.0094
14	13	-0.0548	-0.0253

The initial population for the states is generated randomly within their allowable ranges [14]. Examining the actual values of the IEEE 14-bus benchmark system, we note that the values of the states vary as follows. V_i lays between 1 and 1.1 P.U (per unit) volts and θ_{ij} between -20 and 20 degrees. These values are defined to cover all possible values for the states. Since the distribution system, in this case, is bigger than the system in the previous one, the population is set to 600. The number of iterations is set to 1500, it is not necessary to consider more than 1500 iterations, because there is no significant improvement in the minimization of the objective functions (see figure V.8). Weights are kept the same, 250 for voltage measurements and 100 for power measurements [15].

Results of simulation on the IEEE 14-bus obtained with the two algorithms are presented in tables V.7 to V.9 and figures V.6 to V.8. Estimated voltage and angle are presented in table V.7 and table V.8, respectively. Figure V.6 and figure V.7 describe the estimation error on the voltage and the angle, respectively. The mean square error is reported in table V.9. The convergence speed of the two algorithms is illustrated in figure V.8.

Table V.7. Estimated bus voltages for the IEEE 14- Bus

Bus	Estimated voltage magnitude in P. U		
	Actual value	ABC	PSO
1	1.0600	1.0552	1.1000
2	1.0450	1.0421	1.1000
3	1.0100	1.0051	1.1000
4	1.0310	1.0307	1.1000
5	1.0360	1.0357	1.1000
6	1.0700	1.0686	1.1000
7	1.0560	1.0555	1.1000
8	1.0900	1.0892	1.1000
9	1.0500	1.0491	1.1000
10	1.0460	1.0450	1.1000
11	1.0550	1.0535	1.1000
12	1.0550	1.0533	1.1000
13	1.0500	1.0485	1.1000
14	1.0320	1.0308	1.1000

Table V.8. Estimated bus angles for the IEEE 14- Bus

Bus	Estimated angle in degrees		
	Actual value	ABC	PSO
1	0.00	0.00	0.00
2	-4.93	-5.01	-4.61
3	-12.60	-12.66	-11.03
4	-10.43	-10.57	-9.59
5	-8.94	-9.07	-14.17
6	-14.66	-14.40	-18.91
7	-13.57	-13.63	-12.29
8	-13.57	-13.63	-12.29
9	-15.18	-15.17	-13.64
10	-15.36	-15.36	-13.81
11	-15.12	-14.88	-19.36
12	-15.52	-15.25	-19.70
13	-15.58	-15.31	-19.76
14	-16.39	-16.35	-14.71

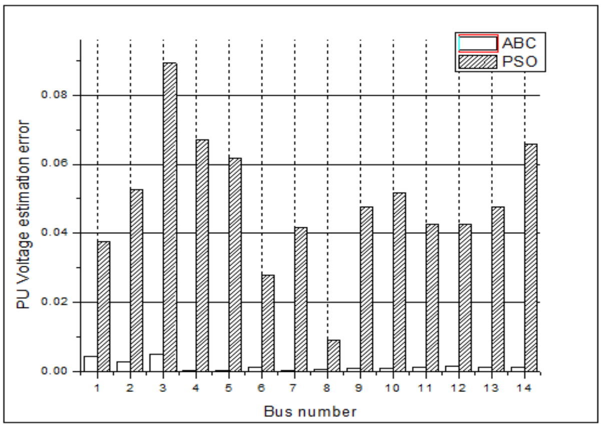

Figure V.6: Error on the estimated bus voltages of the IEEE 14-bus

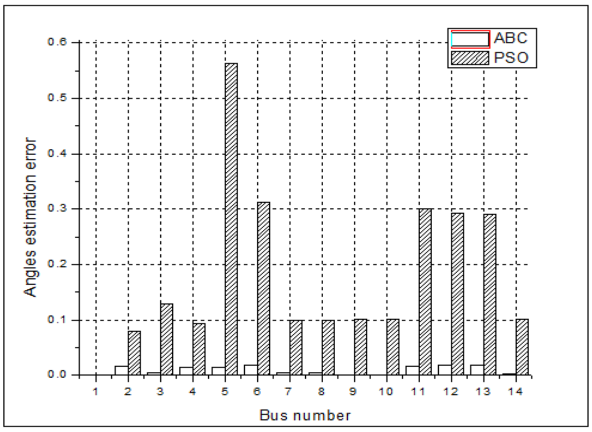

Figure V.7: Error on the estimated bus angles of the IEEE 14-bus

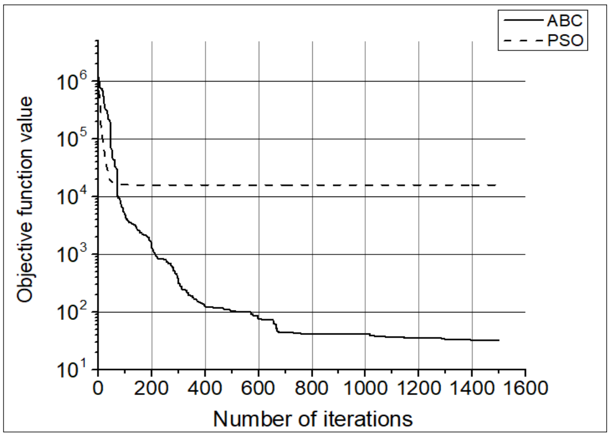

Figure V.8: Convergence speed of ABC and PSO in the IEEE 14-Bus simulation

Table V.9. Mean square error for the IEEE 14- bus state estimation using ABC and PSO

States	Mean square error IEEE 14-bus	
	PSO	ABC
Voltages	2936.29×10^{-6}	4.9×10^{-6}
Angles	8.65	0.03
Both States	416.76×10^{-2}	1.21×10^{-2}

Table V.7 and figure V.6 show that voltage estimation for all the buses is way better when using ABC. Table V.8 and figure V.7 show that ABC performs also way better than PSO for angle estimations for all the buses. Results of error calculations presented in Table V.9 confirm that ABC performance is way better than PSO. For the considered problem, figure V.8 shows that classical PSO cannot minimize the objective function lower than 1.7×10^4 even when increasing the number of iterations (convergence problem).

Simulation results show that ABC performs better than PSO for both voltages and angle estimations. Furthermore, some convergence issues with the original PSO can be noticed when it deals with higher-order systems. ABC algorithm is then adopted for the decentralized MAS-based state estimation.

Whatever is the optimization algorithm used for the minimization of the objective function, the increasing size and complexity of the ADN will result in heavy and time-consuming state estimation. To tackle this challenge, a completely decentralized MAS-based state estimation approach is used.

In this second part, investigations on the performance of the completely decentralized MAS-based state estimation method are carried out. Here the CDSE approach is applied to the IEEE 14-bus and the IEEE 30-bus and the resulting subsystems are shown. The splitting results for both the IEEE 14-bus and the IEEE 30-bus system are presented in table V.10 and V.11 respectively. The split results in subsystems with a maximum size of 6 for the IEEE 14-bus and 8 for the IEEE-30 bus.

Table V.10. Subsystems resulting from the split of the IEEE-14 Bus

Related Agent	Number of subsystems	Number of buses in the subsystem
8	1	2
1, 3, 10, 11, 12 and 14	6	3
7 and 13	2	4
2, 5, 6 and 9	4	5
4	1	6

Table V.11. Subsystems resulting from the split of the IEEE-30 Bus

Related Agent	Number of subsystems	Number of buses in the subsystem
11 13 and 26	3	2
1, 3, 5, 7, 8, 14 16, 17, 18, 19, 20, 21, 22, 29 and 30	15	3
9, 23, 24, 25 and 28	5	4
2, 4, 15 and 27	4	5
12	1	6
10	1	7
6	1	8

Tables V.10 and V.11 show that the complexity is greatly reduced for both systems. The original complexity of the IEEE 14-bus with all the power line connections is reduced to a maximum complexity of a 6-bus subsystem. This is also the case for the IEEE 30-bus where the complexity of the original system is reduced to a maximum complexity of an 8-bus subsystem.

The state estimation time for the centralized and decentralized estimation for both the IEEE 14-bus and the IEEE 30-bus are presented below.

Table V.12. State estimation time in centralized and decentralized approaches in IEEE 14-bus and IEEE 30-Bus

System	Decentralized state estimation time(seconds)	Centralized state estimation time (seconds)
IEEE 14-bus	284.59	1592.41
IEEE 30-bus	375.96	6332.42

It can be deduced from Table V.12 that the computation burden is tremendously reduced when dealing with the decentralized estimation. This is the result of the split of the system into smaller subsystems and the parallel way in which calculations are performed. As an example, it has been noticed that the computation time is 5 times smaller with the decentralized estimation than with the centralized estimation for the IEEE 14-bus system.

This difference is even greater with larger systems. For the IEEE 30-bus, the computation time for the decentralized estimation is 17 times smaller than with the centralized estimation. Overall, with the proposed CDSE approach, the computation time for the entire ADN system is almost equal to the computation time of the largest subsystem, resulting in a considerable reduction of the computation burden. This shows the effectiveness of the proposed method.

VI. General Conclusion

The work presented in this thesis is about state estimation, network parameters estimation more precisely, in active distribution networks which constitute the backbone of future distribution networks which arise from the economic and environmental pressure of societies and politics and also incessant size increase of electrical networks, and integration of different energy resources in these networks.

Our objective is to develop a technique suitable for state estimation of modern active distribution networks. Since classical methods can not handle the increasing size and technology of active distribution networks. Another motivation for this work is rapid estimation of electrical quantities in active distribution networks, which is of paramount importance and which most of the classical estimation methods fail to perform.

In chapter II, which was dedicated to state estimation, distributed state estimation which inspired our proposed technique was presented, and in chapter III, multi-agent systems, which have the technology and infrastructure to handle our proposed method, were exposed.

Chapter III allows us, after presentation of different types and applications of multi-agent systems in real systems, to classify our method as an agent-based social simulation of a physical system, and can also be seen as a real approach for MAS application in monitoring and diagnostic.

So, we proposed a completely decentralized state estimation technique based on multi-agent systems and metaheuristic algorithms. The multi-agent system is here to split and manage the active distribution network during the estimation process, and the metaheuristic algorithm is here for the optimization of the objective function. All the details of the proposed technique were presented in chapter IV.

The first part of the simulation was dedicated to the validation of our choice of state calculation metaheuristic algorithm. We compared performances of PSO and ABC algorithms, for both IEEE 6-bus and IEEE 14-bus benchmark systems, and we ended up by confirming our first supposition, which is ABC performs better than PSO. This choice of optimization algorithm does not exclude the choice of another metaheuristic algorithm.

In the second part of the simulation, our approach has been successfully tested on IEEE 14-bus and 30-bus benchmark systems. It is interesting to note that when dealing with IEEE 30-bus, the computation time for decentralized estimation was 17 times smaller, than the computation time for centralized estimation.

Another interesting point is that computation time for the entire ADN system was almost equal to the computation time of the largest subsystem. As the size and complexity of the electrical network increase, the difference compared to the obtained subsystems size and complexity is even greater, making the application of our approach even more relevant and interesting.

Finally, we believe that the proposed completely decentralized MAS-based state estimation approach is very promising and allows meeting the requirements of rapid state estimations in modern distribution networks.

As future works, it is interesting to test performances of the proposed approach in online estimation problems. The online estimation can be performed using the JAVA-BASED JADE approach.

It is also possible to consider another metaheuristic optimization algorithm, replacing ABC, to enhance the performance, and hence the results.

The minimization of the number of measurements and the optimization of their positions can also be an interesting future work to be explored. We are now working on the development of a new method of observability analysis in the proposed completely decentralized state estimation technique based on multi-agent systems and metaheuristic algorithms. This technique is based on the rank analysis of a matrix constructed of the measurements available in the network

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