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Multi-Agent Control and Operation of Electric Power Distribution Systems

by

Amer Al-Hinai

Dissertation submitted to the College of Engineering and Mineral Resources at West Virginia University in partial fulfillment of the requirements for the degree of

> Doctor of Philosophy in Electrical Engineering

Professor Muhammad Choudhry, Ph.D. Professor Asadolah Davari, Ph.D. Professor Ronald Klein, Ph.D. Professor Hong-Jian Lai, Ph.D. Professor Ali Feliachi, Ph.D., Chair

Department of Computer Science and Electrical Engineering

Morgantown, West Virginia 2005

Keywords: Distributed Generation, Dynamic modeling, Transient stability, Multi-Agent Control System, All-Electric Naval Ship

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ABSTRACT

Multi-Agent Control and Operation of Electric Power Distribution Systems

by

Amer Al-Hinai Doctor of Philosophy in Electrical Engineering West Virginia University Professor Ali Feliachi, Ph.D., Chair

This dissertation presents operation and control strategies for electric power distribution systems containing distributed generators. First, models of microturbines and fuel cells are developed. These dynamic models are incorporated in a power system analysis package. Second, operation of these generators in a distribution system is addressed and load following schemes are designed. The penetration of distributed generators (DGs) into the power distribution system stability becomes an issue and so the control of those DGs becomes necessary. A decentralized control structure based on conventional controllers is designed for distributed generators using a new developed optimization technique called Guided Particle Swarm Optimization. However, the limitations of the conventional controllers do not satisfy the stability requirement of a power distribution system that has a high DG penetration level, which imposes the necessity of developing a new control structure able to overcome the limitations imposed by the fixed structure conventional controllers and limit the penetration of DGs in the overall transient stability of the distribution system. Third, a novel multi-agent based control architecture is proposed for transient stability enhancement for distribution systems with microturbines. The proposed control architecture is hierarchical with one supervisory global control agent and a distributed number of local control agents in the lower layer. Specifically, a central control center supervises and optimizes the overall process, while each microturbine is equipped with its own local control agent.

The control of naval shipboard electric power system is another application of distributed control with multi-agent based structure. In this proposal, the focus is to introduce the concept of multi-agent based control architecture to improve the stability of the shipboard power system during faulty conditions. The effectiveness of the proposed methods is illustrated using a 37-bus IEEE benchmark system and an all-electric naval ship.

Dedication

I would like to dedicate this dissertation to my lovely mother, my sincere wife, my gorgeous kids Abdulazize and Reem, my brothers and my sister. None of my accomplishments would have been possible without their endless love, motivation and support.

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First I would like to express my sincere thanks and deep appreciation to my research advisor and committee chairman, Prof. Ali Feliachi for his insight, advice and support throughout my Ph.D. program. I would not be able to complete this research without his guidance. This dissertation came into existence during my research years supervised by Prof. Ali Feliachi, Electric Power Systems Chair Professor in the Lane Department of Computer Science and Electrical Engineering at West Virginia University.

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Chapter 1

Introduction

1.1. Objective and Significance of the problem

The main objective of this dissertation is to design novel control architecture based on a multi agent system to enhance the stability of electric power distribution systems during large disturbances and faulty conditions. Distributed control algorithms for electric power systems are the most feasible and desirable means of controlling such interconnected systems. They are performed in order to formulate the best possible local subsystem controls as part of an intelligent control structure for the whole system. Multi-Agent Systems (MAS) are distributed control structures that have been applied to several power system problems like those in operation, markets, diagnosis and protection. The technology is in the latest development stages and now on the edge of theory and practical application, where it may prove useful in solving problems in control of distribution systems that have not been investigated yet. This dissertation will explore one of the control challenges in integration of distributed generators into power distribution systems by employing MAS in the control of such complicated systems. An agent is defined as a computer system that is situated in some environment in which it is capable of autonomous action in order to meet its design objective. The multi-agent system consists of two agents or more that cooperate with each other and coordinate their knowledge and activities to accomplish a common goal. In this work, the task is to develop control architecture based in a multi-agent system to control distributed generators in power distribution systems and gas turbine generators in naval shipboard power systems.

A. Distributed Generators

Electricity is a necessary service for sustaining modern life. In spite of that, as we launch into the 21st century, electricity continues to be generated by aging power plants that have been designed in attempts to meet environmental standards and connected

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through an antiquated system of transmission lines or wires that are managed with pre-1960 control techniques. Recent deregulation of the electric grid has ignited wide interest in bringing advanced technology to the power sector. Right now, new technologies are mature enough to be implemented and could disrupt the traditional power market and transform today's one-way power network into a bidirectional energy transfer backbone connecting autonomous groups of generators. The power industry's vision for the 21st century includes distributed power. Defined simply, distributed power is modular electric generation or storage located near the point of use. Interest in the use of distributed generation (DG) and distributed resources (DR) has increased substantially over the past five years because of the potential to provide increased reliability and to lower the cost of power delivery, particularly with customer-site installation. The advent of customer choice and competition in the electric power industry has, in part, been the stimulus for this increased interest. Also contributing to this trend has been the development of small modular generation technologies, such as microturbines, photovoltaics, and fuel cells. As distributed generation becomes more reliable and economically feasible, there is a trend to interconnect DG units to the existing utilities to serve different purposes and offer more possibilities to end-users, such as:

- Peak load shaving
- Energy cost savings
- Power generation: selling power back to utilities or other users
- Reactive power compensation
- Mitigation of harmonics and voltage sag

DG can either be grid-connected or operate independently. Those connected to the grid are typically interfaced at the distribution system. In contrast to large, central-station power plants, distributed power systems typically range from less than a kilowatt (kW) to a megawatt (MW) in size. Distributed power can produce greater reliability of electric supply, better efficiency in fuel consumption with combined generation of heat and power, lower environmental pollution, improved supply redundancy, wider spread of capital costs in generation equipment, a more diversified mix of energy technologies, and the ability to compensate infrastructure investments for transmission and distribution. As the cornerstone of competition in electric power markets, distributed power will also

serve as a key ingredient in the reliability, power quality, security, and environmental friendliness of the electric power system. By supporting customer choice, distributed power may be the long-term foundation of competition in the electric power industry.

Although the application of DG and storage can bring many benefits, the technologies and operational concepts to properly integrate them into the power system must be developed. The current power distribution system was not designed to accommodate active generation and storage at the distribution level or to allow such systems to supply energy to other distribution customers. The technical issues to allow this type of operation are major concerns to the power industry and researchers.

DGs have different characteristics and, based on that, their impact on distribution systems specifically and in power systems in general will also differ. Studying the impact of DG penetrations on power distribution system stability is one of the research topics of interest to the power industry. Such an analysis requires a nonlinear simulation environment able to validate and accommodate control and operation of those new power generation technologies without compromising the overall speed of simulation or accuracy. The research group supervised by Prof. Ali Feliachi in the Advanced Power and Electricity Research Center (APERC) developed a power system simulation environment in MATLAB/Simulink called Power system Analysis Toolbox (PAT) [51]. PAT is a very flexible and modular tool for load flow, transient and small signal analysis of electric power systems. A comprehensive and accurate dynamic model of DGs suitable for transient stability analysis is another prerequisite for such analysis.

One of the analyzed DGs in this study is the microturbine. It is a small, simple-cycle gas turbine, generating electric power in the range of 25kW to 500kW [17]. The microturbine is similar to a large gas turbine with improved performance and efficiency when operated at partial kilowatts. Unlike traditional backup generators, the microturbine is designed to operate for extended periods of time and requires little maintenance. It can supply a customer's base-load requirements or can be used for standby, peak-shaving and co-generation applications. In addition, the current generation of microturbines has the following specifications [17]:

• Environmental Superiority, NOx emissions lower than 7 parts per million for natural gas machines in practical operating ranges.

- Relatively small in size, compared to other DGs.
- High Efficiency; fuel-to-electricity conversion can reach 25%-30%. However, if the waste heat recovery is used, combined heat and electric power could achieve energy efficiency levels greater than 80%.
- Durable, designed for 11,000 hours of operation between major overhauls and a service life of at least 45,000 hours.
- Economical, system costs less than \$500 per kilowatt, costs of electricity that are competitive with alternatives (including grid-connected power) for market applications.
- Fuel flexibility, capable of using alternative/optional fuels including natural gas, diesel, ethanol, landfill gas, and other biomass-derived liquids and gases.

Two configurations of microturbines are available in the market namely, single-shaft and split-shaft microturbines. Modeling of a split-shaft microturbine as a DG is considered in this study and involves two main parts: a gas turbine and an electric generator. The latter could be either a synchronous or an induction type generator. The microturbine can be controlled either mechanically through the gas turbine or electrically through the generator. Transient stability enhancement can be attained with a faster electric response controller.

The Fuel Cell is another DG considered in this study. It is defined as an electrochemical device that continuously changes the chemical energy of a fuel, hydrogen, and oxidant, oxygen, directly to electrical energy and heat, without combustion. The electrical process causes hydrogen atoms to give up their electrons. It is similar to a battery in that it has electrodes, positive and negative terminals. It does not, however, store energy as a battery does. Because there is no combustion, fuel cells give off few emissions; because there are no moving parts, fuel cells are quiet. It can be used in stationary applications like a DG or for heating buildings, and for powering vehicles, buses and trains. There are different types of fuel cells; in this study the Solid Oxide Fuel Cell (SOFC) is considered. The SOFC model used in this study has been developed by Sedghisigarchi and Feliachi [35].

Different publications verify that the stability of a distribution system depends on the type and number of DGs and instability may occur if the number of DGs increases.

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Beside the mentioned advantages of DGs, these devices can be considered as a control path and can be used effectively to enhance the transient stability of a distribution system. Several efforts by many researchers have been published in the control design of DGs but most of these controllers are linear and of a fixed structure type [4], [6] and [8]. In most cases, the controller's parameters are designed by trial and error or tuned by optimization techniques using a linearized model around selected operating conditions. Since the distribution system may become vulnerable with the installed DGs, such a design method does not guarantee smooth operation of the designed controller. A new method has been developed for tuning the parameters of fixed structure type controllers, called Guided Particle Swarm Optimization (GPSO). This method is based on a Particle Swarm Optimization (PSO) technique using nonlinear simulation. The main advantage of this design is that it gives the controller a wider range of operation compared to the linearization method and avoids the linearization computation effort. The designed controller will guarantee stable operation for the simulated disturbance and may work also with other disturbances. However, there are still some limitations with the decentralized fixed structure controllers and we need to find a novel control algorithm for DGs to overcome different tasks and restrictions in a distribution system. In this dissertation, a MAS control structure is developed for DGs to overcome the limitations imposed by the fixed structure controllers and limit the penetration of DGs in the overall transient stability of distribution system.

B. The All-Electric Naval Ship

The all-electric naval ship (AENS) is a concept of replacing all of a hydro-mechanical naval ship's parts with electrical ones in which all energy users, including propulsion, weapon and sensor systems and actuators, use electricity as their energy input. The benefits that can be drawn from such a system are summarized as follows [65]:

- Improving survivability with fast, flexible and automated operation: the system will assure that all surviving vital loads, including propulsion, are adequately and uninterruptedly powered during and after damage.
- Reducing the acoustic signature: with electric propulsion there is no need for a noisy gearbox.
- Reducing thermal emissions, by optimum loading of the power generators and prime movers.

- High power weapons and sensors: future electrically powered sensors, weapons and other pulsed loads can draw power up to the installed electric power capability, alternatively used for propulsion.
- Reducing vulnerability: the prime movers can be divided more easily over different zones and compartments and the propeller shafts can be much shorter with full-electric propulsion.
- The possibility of using podded propulsion: The use of pods gives benefits in maneuverability, space requirements and cost.
- Increasing range of operation: by keeping prime movers and power generators at the most efficient operating point, fuel consumption will be reduced.

There are similarities between the civilian power system and the electric naval power system. The electric power system of AENS can be considered as a distribution network with a main power source, gas turbine, and distributed loads. This system can be challenged by problems similar to those in a civilian power system, such as stability problems during different types of disturbances.

In this dissertation the aim is to map the concept of multi-agent system based control architecture in order to improve the overall system stability during a fault or disturbance due to battle damage or material casualty in the AENS. It is important to continuously provide power for shipboard combat systems in the presence of such major interruptions.

1.2. Dissertation Outline

This dissertation is organized as follows:

• Chapter 1: Introduction

The objective and significance of the problem followed by dissertation outlines are addressed in this chapter.

• Chapter 2: Literature Survey

This chapter presents a literature survey which is divided into four sections. The first subsection describes agent structure and the applications of multi-agent to solve different problems in a power system. In the second subsection, the problem of the impact of DGs in a power distribution system is presented. The third subsection discusses publications in control and operation of distributed generators. The last subsection presents selected publication in an all-electric naval ship power system.

• Chapter 3: Problem Formulation and Tools

Chapter three of this dissertation discusses problem formulation and presents the tools developed to solve the problem. First, the research objectives are presented. In order to study the impact of DGs and design the associated control structure, a proper modeling of these DGs is required. The second section of this chapter presents the model developed for a microturbine as a DG. The model is implemented in the power analysis toolbox which is the simulation environment of this research. The third section demonstrates the development of a new optimization technique, Guided Particle Swarm Optimization. The technique is used for controller design as well as part of the MAS based control structure. Finally, the developed MAS based control architecture is explained. Two types of agents are defined to demonstrate the MAS namely, the local control agent and the global control agent. The information structure, decision process, and architecture of each agent are presented.

• Chapter 4: Control and Operation of Electric Power Distribution Systems This chapter will discuss the issue of operation and control of distributed generators using the modeling and tools developed in Chapter 3. First, the load following problem of microturbines as DGs in parallel operation is presented. The simulation uses the microturbine model developed in the previous chapter. The load following controllers' parameters are designed using the developed optimization technique, GPSO. The transient stability problem of a distribution system with the presence of distributed generators is discussed next. The system is simulated with a solid oxide fuel cell and a microturbine as distributed generators. A control approach is designed and the microturbine controller's parameters are designed using GPSO. After that, the implementation of the developed multi-agent based control system to enhance the transient stability of a distribution system incorporating microturbines as distributed generators is presented. Then, the simulation results are presented and discussed. Finally a performance index based in nonlinear simulations is presented to evaluate the proposed multi-agent based control system.

• Chapter 5: Electric Power System of an All Electric Naval Ship

This chapter will discuss another implementation of the developed multi-agent system (MAS) based controller concept for AENS power system in order to enhance the transient stability during large disturbances in the system. First, a brief description of the AENS power system is presented and followed by problem formulation. Then, the proposed structure of the MAS based controllers is discussed. Finally, the simulation results are presented and discussed.

• Chapter 6: Conclusion

Conclusions and future work are presented in this chapter.

This research has resulted in a number of publications, given in appendix A.

Chapter 2

Literature Survey

2.1. Introduction

Distributed control and Multi-Agent Systems (MAS) have been reported in several power system applications, and some good results were obtained in several areas like operation, markets, diagnosis and protection. The focus in this research will be on the application of MAS in control of DGs in a power distribution system and self-healing strategy for service restoration in naval shipboard power systems, but we need to explore other applications of MAS in power systems.

The trend in the use of DGs has increased significantly over the past few years because of the potential to increase reliability and lower the cost of power through the use of on-site generation. Although existing literature addresses the requirements of DG operation and interconnection to the distribution system, the cumulative effect of numerous types of DGs on a given feeder is less understood [2]. The extent of the eventual integration of DGs into the electrical distribution system will depend on the limits imposed by the local grid. These, in turn, are determined by a number of utility coordination issues and standards, including the proper performance of control structure.

Another issue considered in this study is the control of an all-electric naval shipboard power system. The U.S. Navy is currently moving toward more automated and selfoperated all-electric ship by replacing the mechanical-hydraulic systems with electric solutions. This in turn creates room for several issues to be investigated like the stability of the system during a large disturbance, isolation of the faulted part and continuously providing power to the unfaulted parts by installing DGs close to the load.

In this chapter a literature survey is presented as follows: first, the concepts of agents and application of multi-agent in a power system is surveyed. Then, the impact of DGs in distribution system stability is presented followed by the control design effort to overcome the problem. Finally, selected published work in the area of a naval shipboard power system is surveyed.

2.2. Agents and Distributed Control Agent Architectures.

Weiss in his book [54] presents an up-to-date comprehensive introduction to multi agent systems and distributed artificial intelligence. Several tasks are considered starting with concepts of agents, multi-agent structure, distributed problem solving and planning, and agent algorithms. The authors present illustrative examples and study cases.

In [66] Cossentino identifies the process of designing a multi-agent system from several different perspectives such as: Architectural (a structural representation of the agents), Social (a look at the agent society involved in the solution), Knowledge (the analysis of each single agent), Resource (the study for reusing existing elements), and Physical aspects (a representation of the physical solution). The author insists that the system should reach some goals and provide specific requirements. The designer should produce an accurate model for the domain ontology, and the agents' knowledge and interactions. The structural and behavioral description of the system will descend from these elements and will also generate some constraints in the other parts of the design.

In the power system, once there is a fault the first action is the diagnosis or identification of that fault, dispatching the faulted part, and then restoring the deenergized part. In this section the application of multi-agent in post fault analysis of power systems is surveyed. First a selected publication of MAS in power system diagnosis and condition monitoring is presented. Then, publication of MAS in fault dispatching is presented followed by selected publications of MAS in power system restoration.

McArthur, Hossack and Jahn in [1] and [25] propose MAS for diagnostic and condition monitoring applications in power systems. The main task of the proposed MAS is integration of alarm interpretation, fault record classification and protection validation into flexible and scalable architecture. The MAS is classified into four layers, namely: data layer, interpretation layer, corroboration layer, and information layer. Each of the layers contains a number of agents performing different functions. The Data Layer consists of two agents; the Feature Extraction Agent and Δt Calculation Agent. The main task of this layer's agents is to extract data and send it to the upper level layer. The Interpretation Layer consists of five agents; the C5 Rule Evaluator Agent, the Back

Chapter 2: Literature Survey

Propagation Network Agent, the K-Means Clustering Agent, the Kohonen Classifier Agent, and the Knowledge Based Analysis Agent. The agents in this layer use the extracted data from the data layer and database to identify and locate the problem or defects. The Corroboration Layer agent uses the outputs from each of the diagnosis interpretation agents to find corroborative evidence of a particular defect type. The Information Layer agent sets up the results in the most appropriate way for the engineer who is using the system. The proposed algorithm is applied to diagnosis of an actual power system circuit as in [1] and to diagnosis and monitoring of a power transformer as in [25].

Ming and her group in [21] propose a Multi-Agent System Dispatching Operation Instructing System (MASDOIS) for a faulty power system network based on cooperation between Automatic Fault Section Identification System (AFSIS) and Switch Operation Instructing System (SOIS). The functional components of MASDOIS include Data Acquisition System (DAS), Database Management System (DMS), Task Decomposing System (TDS), Task Cooperation System (TCS), Fault Section Identification (FSI), Dispatching Switching Instructing System (DSIS) and MAS Learning System. The proposed scheme shows more advantages in the areas of integrated solving problems, cooperative control and information sharing, and has proven very effective for promoting the operation of power systems.

Nagata Tao, Sasaki, and Fujita in [20] implemented a multi-agent approach to decentralized power system restoration for a distribution system network. The proposed method consists of several Feeder Agents (FAGs) and Load Agents (LAGs). A LAG corresponds to the customer load, while a FAG is developed to act as a manager for the decision process. Several simple restoration strategies are imbedded in LAGs and it communicates only with its neighboring LAGs, while FAGs act to facilitate the decision process. While LAGs intend to conduct the local search, FAGs carry out the global search.

In [1] and [27] Nagata and Sasaki used a similar algorithm for power system restoration. The proposed system consists of a number of bus agents (BAGs) and a single facilitator agent (FAG). BAGs are developed to decide a suboptimal target configuration after a fault occurrence by interacting with other BAGs based on only locally available

information, while FAG acts as a manager in the decision process. The interaction of several simple agents leads to a dynamic system, allowing efficient approximation of a solution. The same principle by the authors is applied to power system restoration for a local area network in [19] and to power system normal state operations in [18].

Aoki, Esmin, and Lambert-Torres in [24], proposed a multi-agent approach to help operators during the restoration task of power substations and distribution systems. The architecture consists of two main packages of agents and support agents. Those packages are the Distribution System Package and the Power Substation Package. There are five support agents working on integration of the model with the real world and among the packages.

Masina, Lee and Ramirez in [22] proposed a multi-agent system to control a fossil fuel power unit. The architecture consists of a Central Agent (CA), a Set-point Agent (SA), a Feedforward Agent (FeFA), a Feedback Agent (FeBA), a Limiter & Scaling agent (LSA), and a Threat/Emergency Agent (TA). The CA monitors the entire situation and all other agents send signals to this agent to get acknowledged for proper operation. The SA synchronizes the slow response of the boiler with the faster response of the turbine generator to achieve a fast and stable response during load changes and disturbances. The FeFA assists finding a wide-range set-point driven operation for the plant, and to provide off-line operator-requested system adaptability to achieve optimal operation. The FeBA provides corrective control actions along the commanded set-point trajectories to overcome the effect of disturbances. The LSA sets up scaling factors in the command signals to the actuators to achieve the rated operating conditions with control valve position values within the specified physical limits. The TA stops sending signals and brings the plant to shutdown mode during emergency situations. Every agent is an intelligent agent making decisions according to the operating condition of the power plant. The FeFA control agents have learning capabilities. Combined with FeBA, both controllers perform a key role in attaining wide range operation of the plant.

Karady, Daoud and Mohamed in [26] proposed a multi-agent system for power system transient stability enhancement via turbine fast valving control. The proposed scheme mainly consists of a prediction agent that will predict power system instability and a control agent that will initiate turbine fast valving. The prediction agent uses only on-line measurements of a generators' rotor angle to predict the electrical power output of unstable units in a multimachine power system. Then, fast valving control is applied to the detected machine. The proposed MAS control is not suitable for real time application and more work is still needed to improve the speed of the control agent.

Hara, Kita, Tanaka and Hasegawa in [23] and [67] proposed Flexible Reliable and Intelligent Energy Delivery System (FRIENDS), an intelligent multi-agent concept of a future distribution system by installing a new feature called Quality Control Center (QCC) to improve the reliability, quality and emergency operation of power by controlling hybrid-type transfer switches. The author said, with proper control it is possible to generate three levels of power quality called ordinary quality, high quality and premium quality. Distribution SubStation (DSS) and QCC are modeled as agents and each agent decideds its behavior in a distributed and autonomous manner.

In this proposal, the objective is to employ the concept of MAS in control and operation of distributed generators. Distributed generators are normally dispersed in a distribution network and may have a harmful impact on the system during large disturbances. It becomes difficult to come up with coordinated controllers for each DG for every operating condition. DG is considered to be a control point or path that can be used to control and enhance the stability and reliability of the system. Each DG is equipped with at least one intelligent controller based on multi-agent technique. All agents are interconnected together via the information base and to a global agent.

2.3. Impact of Distributed Generators in Power Distribution System Stability.

In this section the literature related to impacts of DGs in power systems are presented. The following is published work discussing the effect of DGs in power distribution network stability:

Edwards, Dudgeon, McDonald and Leithead in [4] presented transient stability and small-signal analysis of the DGs in distribution systems. DGs are gas turbine driven synchronous generators of varying sizes (5-25 MW). The simulation results confirmed that three phase faults can cause all of the generators to lose synchronism. This situation can even be worsened if distributed generators of different types are used. It is concluded

that the stability of the distribution system depends on the type and number of DGs. Instability may occur if the number of DGs increases [5]. Machine time constants, size and inertia are important factors that affect system dynamics. Similar results have been achieved by Cano and Carpio in [6] while investigating effects of the number of microturbines on distribution system stability.

Kariniotakis and Stavrakak in [43], [44] have addressed the effects of DGs, mainly diesel engines and wind-turbines, on power system dynamics. The modeling of diesel engines and wind-turbines are first presented in [43] and then the effect of wind penetration level is analyzed using a small size isolated power system [44]. Kalaitzakis and Vachtesvanos in [42] investigated the impact of grid connected photovoltaic sources on system stability. They concluded that short response time of the PV arrays exhibits stable transient behavior.

Slootweg and Kling [36] investigated the impact of distributed generation, synchronous and asynchronous generators, and penetration level on the dynamics of a test system. They concluded that the impact of distributed generation on power system transient stability depends both on the penetration level and the technology of the distributed generators. Moreover, they found that distributed generation based on asynchronous generators does not have much impact on the transient stability while those based on synchronous generators decrease the overspeeding of the large scale generators, but seems to decrease the transient stability by increasing the oscillation duration. However they didn't consider the prime-mover models and they were using a transmission network. The also concluded that distributed generation based on power electronics decreases the overspeeding of generators, because it is disconnected during a fault. However, at increasing penetration levels, this results in large voltage drops at some nodes, due to the loss of large amounts of generation.

Dai and Baghzouz in [37] inspected overvoltages due to excessive active and reactive power injection by installing distributed generation units along power distribution feeders. They concluded that coordination between DG outputs and LTC tap controls is necessary in order to allow higher levels of distributed resources. Reza and his group in [38] found that both types of DG technologies and the penetration levels of DG in the power system have a strong influence on the transmission system transient stability. Canever and his group in [41] proposed a coordinated strategy for the operation of a photovoltaic array and a diesel power plant integrated into a test electrical distribution system.

2.4. Operation and Control of Distributed Generators.

DGs and storage devices can have many benefits. However, novel operational and control concepts are needed to properly integrate them into the power system. Control strategies must be further developed to achieve the targeted benefits while avoiding negative effects on system reliability and safety. The current power distribution system was not designed to accommodate active generation and storage devices at the distribution level. In the pervious section, the penetration of DGs into a power distribution system demands the need of a proper control structure for those devices. Several efforts by many researchers have been covered in controller design of DGs. The following are selected papers and published materials related to the operation and control of DGs:

This investigation of the interactions of selected DGs in a microgrid during disturbance followed by an islanding operation had been presented in [68]. The microgrid includes two diesel generators with an AVR control-loop and two microturbines with AC/DC/AC power conditioner unit with PI controllers. The DGs supply the entire load after the disturbance. The transition of the DGs to islanding mode showed unacceptable frequency deviations and the control scheme needed to be improved.

The feasibility of improving load following performance by distributed energy resources has been studied in [69]. Wind turbine, microturbine, photovoltaic and energy capacitor storage (ECS) are connected to the Kumamoto area 15 bus distribution system. Simplified dynamic models of each DG are developed in MATLAB SIMULINK. It is concluded that using fast response of ECS and slower response of a microturbine can follow the load by choosing appropriate control signals. On the other hand issues, such as coordination of controls between multiple units, phase imbalances, and feeder capacity limitations are valid problems that may limit possible control actions.

Canver in [41] proposed PI controllers for the diesel generators and impact of different control strategies have been simulated. Okuyama, Kato, Wu, Yokomizu, Okamoto and

Suzuoki in [31] and [32] proposed a method for information exchange of the output active power between DGs. The reliability of the distribution system isolated from the transmission system has been improved. In [20] with time-varying load in the distribution network, they proposed a control scheme using the information of the power flow at the distribution substation together with the information of the load in the DG bus. The overall load fluctuations are compensated for and improved by the controlled DGs. However, they used simple mathematical equations to represent DGs instead of actual models.

Sedghisigarchi and Feliachi in [34] showed the impact of gas turbines as DGs on a distribution network. A combination of fuel cells and gas turbines can help load frequency control after islanding of the distribution system. The proposed controller consists of two control loops, PI control for the power conditioner unit tuned by the genetic algorithm and proportional controller for the fuel valve. The GA tuning procedures are based on a linearized model.

Ro and Rahman in [46] designed an efficient controller for a PV-fuel cell hybrid power plant so that the combination can be used as a reliable power source. The controller consists of two loops. One loop is a neural network for power point tracking installed for PV arrays and the second loop is a PI controller which is tuned for the fuel cell. Miao in [49] concluded that SOFC with a designed controller enhances the oscillation damping of the whole system. The controller is designed using a lead-lag compensator and an optimal control algorithm based on a linearized model.

Zhu and Tomsovic in [48] studied the load following problem using a microturbine and SOFC. In this paper, the microturbine is in charge of following the load and the fuel cell is only protected from cell damages via a limiter. The microturbine designed controller is a PI tuned by trial and error. We presented in [7] a grid connected split-shaft microturbine equipped with an induction generator and SVC at the generator's terminal. The proposed controller is of a fixed-structure two stage lead-lag type and a washout stage to add supplementary control enhancement to the microturbine's SVC operation. It is based on a linearized model and a particle swarm optimization technique is used to tune the controller's parameters. The designed controller improves system performance and showed a stabilized system. The particle swarm optimization technique has been applied to power system controller design by many researchers like [28], [29] and [30].

None of the above work considers the limitations of the designed controllers where in most cases, the controller is of fixed type structure with fixed parameters (like PID, leadlag ...) and is tuned based on a linearized model around selected operating condition. However, once the system is operating far away from that operating condition that controller must be tuned again. In [8] we described the effects of DGs, namely fuel cell and microturbine, on the stability of IEEE 37 node distribution feeder due to large disturbances and a control algorithm is then proposed to enhance transient stability. The control algorithm consists of (1) disconnecting the fuel cell during the fault, and (2) implementing fixed structure decentralized Solid Oxide Fuel Cell reconnection controllers and a fixed structure decentralized Power System Stabilizer for the microturbine generator. The control parameters are designed using the particle swarm optimization technique with a proposed fitness function based on nonlinear simulation. The main advantages of this design, as it will be discussed in detail in Chapter 4, it gives the controller wider range of operation compared to the linearization method and avoids the linearization computation effort. However, there are still some limitations of the above designs and we need to find out a novel control algorithm to overcome different tasks and restrictions in distribution system.

2.5. The Power System of All-Electric Naval Ship

Navy shipboard power systems have different characteristics when compared with utility power systems. The modeling, simulation and controller designs issues have been discussed in literature. In this section, we present some examples of published research in these areas.

Zhang and Butler in [59] present a PSpice methodology for modeling shipboard power systems and transient simulation results are also presented. In [60] Adediran, Xiao, and Butler model an AC radial shipboard power system using the Alternative Transients Program (ATP). In this model the shipboard power system is designed as an ungrounded delta system to achieve system survivability in the event of a single line to ground fault. Short circuit fault scenarios were performed to study protective device coordination and system survivability.

Zivi, and McCoy in [55] present research challenges in ONR ship system with a goal to incorporate fault tolerance and system integrity as an organic component of the system architecture, control strategy, algorithms, and technology base. The investigations have centered around two laboratory scale test systems - the Naval Combat Survivability Generation and Propulsion Testbed, and the Naval Combat Survivability DC Distribution Testbed.

The investigation of replacing the AC radial shipboard distribution system to a DC zonal electric distribution system is discussed by Ciezki and Ashton in [61]. The system has starboard and port DC busses feeding electrical zones delineated by waterproof partitioned compartments. The main bus DC voltage is stepped down within the zone and then converted to three-phase AC and lower voltage DC by additional power converters. Due to the large interconnection of tightly-regulated power converters in a stiffly-connected system, negative input impedance effects create the possibility of unwanted resonances. The authors addressed the stability issues, and discuss fault detection and load shedding problems.

In [58] the authors review the methodologies for analyzing the stability of shipboard power electronics based zonal DC power distribution systems. The authors used two time-domain simulation methods namely; Generalized Immittance Analysis, and Polytopic Analysis. The simulation results of both methods agree with the observed behavior of the system. The results of each of methods as well as the respective advantages and disadvantages are compared.

The authors in [63] investigate the impact of pulsed power loads on navy shipboard power and propulsion systems. They consider two basic configurations of pulsed power charging circuits in their study; a load-commutated converter based charger and an uncontrolled rectifier - DC/DC converter based charger. They concluded that, both configurations are studied with and without the option of coordinating operation with propulsion to potentially reduce system impact.

Butler, Sarma, and Prasad in their paper [62] and [64] present methods to reconfigure the network to restore service to unfaulted sections of the system. The electric power systems of U.S. Navy ships supply energy to sophisticated systems for weapons, communications, navigation and operation. After the faults and subsequent isolation of

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the faults, there will be unfaulted sections that are left without supply. Fast restoration of supply to these unfaulted sections of the shipboard system is necessary for system survivability. The proposed methods are illustrated using various case studies on a small power system with similar topology to a shipboard power system.

Chapter 3

Problem Formulation and Tools

3.1. Introduction

The emphasis of decreasing the cost associated with electrical power transmission in energy markets, increasing the efficiency of generated electric power and reducing the environmental impact of power generation, leads to the development and the use of distributed generation (DG) technologies at consumer sites, such as the microturbine and fuel cell. However, these DGs are penetrating the distribution system and making it a dynamic system. The dynamic behavior of these DGs, following a loss of power supply from the substation or a large disturbance within the distribution system, needs to be analyzed. A proper control strategy is required to maintain stable and reliable operation of the system and to supply the customers without interruption. Disturbances, such as short circuits, loading changes, or a loss of the substation power will produce dynamic behavior that was uncommon in distribution systems. Normally, DGs are geographically dispersed and it is difficult to implement centralized controllers. A conventional decentralized controller may be used and tuned to operate around selected operating conditions. However, these controllers are limited, and once the system is operating far from these operating conditions, the controller must be tuned again. In this dissertation, a new technique in tuning decentralized fixed structure type controllers based on nonlinear simulation and using particle swarm optimization is presented. Even though this method will guarantee the operation of the controller under tuned severe disturbances, it still has some limitations. Hence, we are going to introduce the application of Multi-Agent System (MAS) in the control of DGs to overcome the limitations imposed by the fixed structure controllers and limit the penetration of DGs in the overall transient stability of a distribution system. The new control structure will provide flexible and automated operation of DGs. It will add adapted robustness with a self-learning ability, and coordinated operation of the current fixed structure controllers.

Chapter 3: Problem Formulation and Tools

This chapter presents the objectives of this research as well as the tools developed to achieve the desired goals. First, the research's objectives are presented. In order to study the impact of DGs and design the associated control structure, a proper modeling of these DGs is required. The second section of this chapter presents the model developed for microturbine as DG. The power analysis toolbox is used in this research as a simulation environment. The third section demonstrates the development of a new optimization technique, Guided Particle Swarm Optimization. This technique will be used for controller design as well as part of the MAS based control structure. Finally, the developed MAS based control architecture is explained. Two types of agents are defined to demonstrate the MAS, namely the local control agent and the global control agent. The information structure, decision process, and architecture of each agent are presented.

3.2. Objectives

The main objective of this research is to design a novel control architecture based on a multi-agent system for an electric power system to enhance the impact of distributed generators in the stability of an electric power distribution system.

This research will focus mainly on the following:

- Development of distributed generator models suitable for transient stability analysis.
- Development of an optimization technique to design the distributed generators' controllers. The technique is based on modified Particle Swarm Optimization (PSO) and called Guided Particle Swarm Optimization (GPSO).
- Design load following controller for microturbines as distributed generators for parallel operation and using GPSO as a design technique.
- Study the impact of distributed generators, mainly the microturbine and the solid oxide fuel cell on the stability of distribution network.
- Design conventional controllers for both microturbines and fuel cells using GPSO.
- Development of a Multi-Agent System (MAS) based control architecture to enhance the transient stability problem in power distribution systems.
- Implementation of the developed MAS based control architecture to two different power distribution systems, namely: a civilian distribution system and an all-

electric navel ship power system.

3.3. Dynamic Modeling of Distributed Generators

The related issues of DG integration in power distribution system are some of the hottest research topics to the power industry. Increasing the perturbation rate of DGs tends towards instability of a distribution system. On the other hand, DGs are a control path in a distribution system and with a properly designed controller, which can be used to avoid system instability and to improve the system's overall reliability. Studying the impact of DGs and controller design requires proper modeling of these DGs in a simulation package. The research group in the Advanced Power and Electricity Research Center (APERC) under the supervision of Prof. Ali Feliachi has developed a power system simulation environment in MATLAB/Simulink called Power system Analysis Toolbox (PAT) [51]. PAT is a very flexible and modular tool for load flow, transient and small signal analysis of electric power systems. Two kinds of DGs are considered in this study, namely the microturbine and the Solid Oxide Fuel Cell (SOFC). The model of split-shaft microturbine as a DG is developed in this study and involves two main parts: a gas turbine and an electric generator. The latter could be either a synchronous or induction type generator. The SOFC model used in this study has been developed by Sedghisigarchi and Feliachi [35].

3.3.1 Microturbine

Microturbines are small and simple-cycle gas turbines, generating electric power in the range of 25kW to 500kW [17]. While it is widely accepted that microturbines play an important role in power generation, there is little work done on the modeling and control of these devices. Once connected to the power distribution system, these generators will affect the dynamics of the system whose transient behavior can be assessed only if a detailed nonlinear dynamic model is used. There are two different configurations of microturbines. The first one is the single-shaft microturbine, where the electric generator is directly connected to the turbine in the same shaft. In this configuration, the electric power is generated in the range of 1500 to 4000 Hz. Then, a power-conditioning unit is used to connect the microturbine to the power system. The model for this type of

microturbine has been presented in [9], [12]and [13]. The second configuration is called the split-shaft microturbine, where a synchronous or induction generator is connected to the turbine via a gearbox. A model of this configuration has been presented in [48] and [16].

In this research we are going to consider the second configuration of a microturbine. A schematic diagram of the split-shaft microturbine model is presented in Figure 3.1. It consists primarily of the split shaft turbine, prime mover, and electric power generator.

A. Prime Mover

Similar to combustion gas turbine, the split shaft turbine mainly involves an air compression section, a recuperator, a burner or combustor, and a power turbine driving a load as shown in Figure 3.1. The exhaust gas from the combustion chamber forces the high-pressure compressor turbine that drives the compressor. The power turbine drives the generator. A special heat exchanger unit and a recuperator that captures the exhausted thermal energy from the power turbine preheat compressed air. This improves overall electrical efficiency. The waste heat recovery or heat exchanger captures the exhaust energy, which significantly improves power generation output and efficiency.



Figure 3.1: Schematic Diagram of the Split-Shaft Microturbine Model

The electric-mechanical behavior is of main interest in this research. Therefore, the recuperator and the heat exchanger unit are not included in the model. The turbine model

is presented in Figure 3.2 and has been implemented in PAT. The model parameters are presented in Appendix B.



Figure 3.2: Microturbine Prime-Mover Model

B. Electric Power Generator.

Two types of generators are used in the modeling of the split-shaft microturbine; a synchronous and an induction generator. The induction generator microturbine based model is presented in [7] and [16]. A SVC is connected at the generator's terminal to assist as a reactive power source. Both the induction generator and SVC models are implemented in PAT and have been described in [14] and [15]. The induction generator's parameters are similar to those used in [48]. The synchronous generator microturbine based model is presented in [8] and [52]. Both models can be used effectively in transient stability analysis.

3.3.2 Microturbine Controllers

The proposed microturbine model can be controlled via two paths, mainly the mechanical power from the turbine to the generator and the microturbine's terminal voltage via attached Static VAR Compensator (SVC) in case of using an induction generator or via an excitation system, Power System Stabilizer (PSS), in case of using a synchronous generator. The mechanical power controller is used to match the generated electric power with the load and to regulate the system's frequency at 60 Hz. This controller is considered to be the primary control loop which is used primarily to compensate for the output generated electric power with load changes.

If a fast disturbance occurs such as a short circuit fault, the mechanical power control

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will be slow and will not be effective. On the other hand, fast action can be taken with a proper SVC or excitation controller design. The proposed controllers in both configurations are of fixed-structure type and consist mainly of a stabilizing gain, washout stage and lead-lag filters as shown in Figure 3.3



Figure 3.3: Microturbine Damping Controller.

A. SVC Damping Controller

The schematic diagram of control loops of a microturbine induction generator based model are shown in Figure 3.4. The input signal for the SVC controller is the real power deviation from nominal value ΔP , while the output signal is the firing angle of the Thyristor Controlled Reactor (TSC), α .



Figure 3.4: Microturbine Control loops of the Induction Generator Based Model.

B. Power System Stabilizer

The schematic diagram of control loops of the microturbine synchronous generator based model is shown in Figure 3.5. The basic function of a power system stabilizer (PSS) is to add damping to a microturbine's rotor oscillations by controlling its excitation using an auxiliary stabilizing signal. This device acts as an add-on device to the Automatic Voltage Regulator (AVR). In this work, PSS uses shaft speed deviation as input. The output signal is used to compensate for the phase lag introduced by the AVR and the field circuit of the simulation environment generator, and are tuned so that speed oscillations give a damping torque on the rotor. The PSS output is added to the difference



between reference and actual value of the terminal voltage.

Figure 3.5: Microturbine Control loops of the Synchronous Generator Based Model.

3.3.3 Solid Oxide Fuel Cell (SOFC)

The fuel cell is a simple static device that converts chemical energy in a fuel directly and continuously into electrical energy. Isothermal operation of fuel cells makes them high efficiency energy resources in comparison to the other power generators. In this work, we are going to consider one specific type of fuel cell, namely Solid Oxide Fuel Cell (SOFC). This DG produces DC electric power from fuel and oxidant via an electrochemical process. Then, a Power Conditioner Unit (PCU) is attached to DC terminal output voltage for connection to AC power system. The SOFC model used in this study has been presented in [35]. Figure 3.6 shows a schematic diagram of a SOFC model, which the reader may refer to [35] for the model's details.

3.3.4 Solid Oxide Fuel Cell's Controllers

Similar to microturbines, fuel cells have two control paths: a slow one via the fuel valve and a fast one via the PCU as shown in Figure 3.7. A proportional controller can be used to mach the change in the output DC current, output power, to the change of fuel flow by adjusting the fuel valve. For transient stability enhancement, control actions are taken through PCU.


Figure 3.6: Schematic Diagram of the Fuel Cell Model

The fuel cell power and voltage controllers presented here are Proportional-Integral (PI) type controllers, which adjust the firing angle and modulation index of the converter according to the power and voltage deviations respectively. The reader may refer to [34] for more detail.



Figure 3.7: Schematic Diagram of the Fuel Cell Control Loops.

3.4. Controller Design (Optimization Technique)

In several engineering fields, the scale of optimization problems has grown in size and complexity. The solution of such complex multidimensional problems can't be attained using classical optimization techniques. This brings attention to a special class of searching algorithms, namely, heuristic algorithms. These techniques and their foundations are based on the evolutionary patterns and activities observed in living organisms.

A number of heuristic tools have been developed in recent decades that have assisted in solving optimization problems that were previously very difficult or impossible to solve. Some of these tools include, but are not limited to: genetic algorithms, evolutionary strategies, evolutionary programming, simulated annealing, taboo search and particle swarm optimization. Several applications of each of these tools have been widely published in different areas.

The field of exploration that concerns all evolutionary algorithms is known as evolutionary computation. An evolutionary algorithm searches for the solution to an optimization problem based in a population of individuals that evolves over a number of generations motivated by the Darwinian principle of survival of the fittest. The searching algorithm is based on cooperation and competition among the population members. Several applications conclude that population-based optimization approaches find very good solutions efficiently and effectively.

Most of the population-based search approaches are motivated by evolution as seen in nature. Particle swarm optimization, in contrast, takes its motivation from the simulation of the social behavior of birds' flocking. All of these algorithms are based on updating the population of individuals by applying some kinds of operations which evaluate at fitness function, so that the individuals of the population can be expected to move in the direction of more suitable areas of the problem's search space. Moreover, the computation techniques maintain a population of configurations that change according to rules of selection, recombination and mutation. Each individual in the population obtains a measure of its fitness in the environment. Then, reproduction considers specifically the high fitness individuals. Recombination and mutation excite these individuals, providing general heuristics for exploration.

Particle Swarm Optimization (PSO) is considered as an evolutionary computation technique. The system is initialized with a random population as feasible solutions in the search space. Each individual in the population is a candidate solution which is evaluated based on a user-defined fitness function. PSO searches for the optimal solution by updating generations using a stochastic operation. Each individual is associated with an updated velocity vector. The velocity update may be comparable with the mutation operation of general evolutionary computation techniques. The population of candidate solutions in the PSO technique progress through the search space by updating the positions according to velocity factors updates. The Particle Swarm Optimization technique is detailed in the next section.

3.4.1 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a new evolutionary algorithm that may be used to find optimal or near optimal solutions to numerical and qualitative problems. James Kennedy, a social psychologist, and Russell Eberhart, an electrical engineer, first developed PSO in 1995 [53] and [70]. The idea emerged from earlier experiments with algorithms that modeled the flocking behavior seen in many species of birds. Even though there were several such algorithms available at the time, Kennedy and Eberhart became mainly interested in the models developed by Frank Heppner, biologist [71]. Heppner considered in his study the behaviors of flocking birds when attracted to a roosting area. The simulations show that birds would begin by flying around with no particular destination and instinctively forming flocks until one of the birds flew over the roosting area. The birds control their speed and destination such that a bird pulling away from the flock in order to land at the roost would result in nearby birds moving towards the roost. Once the birds found the roost, they would land there and attract other birds toward it until the entire flock had landed. Finding a roost is similar to finding a solution in a field of possible solutions in a solution space. The way in which a bird who has found the roost guides its neighbors to move toward it increases the chances that other birds will also find it. The particle learns primarily from the success of its neighbors. Eberhart and Kennedy improved and applied Heppner's methodology [71] to solve the optimization problem. The particles could fly over a solution space and land on the best

solution imitating the birds' behavior. Particles compare themselves to others and imitate the behavior of others who have achieved a particular objective successfully. The PSO model, developed by Eberhart and Kennedy, balances the collaboration between the particles in the swarm. It considers the balance between individuals' explorations looking for a good solution (local solutions) and taking advantage of the success of other individuals' explorations (global solution). In summary, the Eberhart and Kennedy model attempts to find the best compromise between its two main components, individuality and sociality.

3.4.2 Particle Swarm Optimization Algorithm

In Particle Swarm Optimization, the particles fly through the problem space by following the current optimum particles. Each particle keeps track of its coordinates in the problem space, which are associated with the best solution that it has achieved so far.



Figure 3.8: Concept of Updating Individual Position in PSO

This implies that each particle has a memory, which allows it to remember the best position on the feasible search space that it has ever visited; this location is called *pbest*. Another best value that is tracked by the particle swarm optimizer is the best value obtained so far by any particle in the neighborhood of the particle; this location is called *gbest*. The basic concept behind the Particle Swarm Optimization technique consists of changing the position of each particle toward its *pbest* and the *gbest* positions at each

time step as presented in Figure 3.8. This means that each particle tries to modify its current position and velocity according to the distance between its current position and *pbest*, and the distance between its current position and *gbest*.

A. Problem Formulation

The problem is to find "m" parameters $\{x_j, j = 1, ..., m\}$ that optimize an objective function J(x). The solution is assumed to lie in a range of an m-dimensional space described by $[x_j^{min}, x_j^{max}], j = 1, ..., m$. In this search space, there are "n" members called particles that are potential solutions. These n particles form a population. Each particle has a position denoted by "X_i" and a velocity "V_i", $\{i = 1, ..., n\}$. Figure 3.9 shows the PSO algorithm. The steps of the algorithm are given below:

<u>Step 1 — Initialization</u>: An initial population of n particles is generated randomly within the specified range. Both position and velocity of each particle are generated randomly within the pre-specified range defined by equation 3.1.

Set: iter = 0, count = 0 (iter is the iteration counter and count is a performance evaluation counter)

Select: n, iter_{max}, count_{max}

$$X_{i}(0) = \begin{bmatrix} x_{i,1}(0) & \dots & x_{i,m}(0) \end{bmatrix} \quad \text{within the range} \begin{bmatrix} x_{j}^{\min}, & x_{j}^{\max} \end{bmatrix}$$
$$V_{i}(0) = \begin{bmatrix} v_{i,1}(0) & \dots & v_{i,m}(0) \end{bmatrix} \quad \text{within the range} \begin{bmatrix} -v_{j}^{\max}, & v_{j}^{\max} \end{bmatrix} \quad (3.1)$$
$$v_{j}^{\max} = \frac{x_{j}^{\max} - x_{j}^{\min}}{NI} \qquad i = 1, ..., n \qquad j = 1, ..., m$$

Where:n: size of population.

m: number of variables.

iter_{max}: maximum allowable number of iterations.

count_{max}: maximum number of iterations since last change of global best solution.

NI: a chosen number of intervals in the jth dimension.

The initial searching point is set to *pbest* for each particle. Then, each particle is evaluated via objective function. The best-evaluated value of *pbest* is set to *gbest*.

• Population is evaluated using the given objective function, $J_i = J(X_i)$

- Set $J_{i}^{*} = J_{i}$ and $X_{i}^{*}(0) = Xi(0)$
- Find the best value of the objective function and set it to J_{best}
- Set the particle associated with J_{best} as the global best $X^{**}(0)$

<u>Step 2 — Velocity update</u>: the velocity of each particle is modified by the following equation:

$$v_{i,j}(iter) = K \Big[v_{i,j}(iter-1) + c_1 r_1 \Big(x_{i,j}^*(iter-1) - x_{i,j}(iter-1) \Big) + c_2 r_2 \Big(x_j^{**}(iter-1) - x_{i,j}(iter-1) \Big) \Big]$$
(3.2)

$$K = \frac{2}{2 - \varphi - \sqrt{\varphi^2 - 4\varphi}} \qquad where : \varphi = c_1 + c_2, \varphi > 4 \tag{3.3}$$

Where:

c1 and c2 are specified weighting factors.

r1 and r2 are generated random numbers.

<u>Step 3 — Position update</u>: based on the updated velocities each particle changes its position according to the following equation:

$$x_{i,j}(\text{iter}) = v_{i,j}(\text{iter}) + x_{i,j}(\text{iter} - 1)$$
 (3.4)

<u>Step 4 — Evaluation</u>: each particle is evaluated to the updated position via the given objective function, $J_i = J(X_i)$.

<u>Step 5 — Individual best update</u>:

• If $J_i < J_i^*$ then $J_i^* = J_i$ and updated individual best is $X_i^*(\text{iter}) = X_i(\text{iter})$

Step 6 — Global best update:

- Search for the minimum value J_{min} among J_{i}^{*} .
- If $J_{min} < J^{**}$ then the updated individual best is $X^{**} = X_{min}(t)$ and $J^{**} = J_{min}$.

<u>Step7 — Stopping criteria</u>: the condition under which the search will terminate. In this algorithm, the search will stop if one of the following criteria is satisfied:

- 1. The number of iterations since the last change of the best solution is greater than or equal to the prespecified number, solution is satisfactory.
- The number of iterations reaches the maximum allowable number; either there is no feasible solution or the pre-set maximum number of iteration is not large enough.

Step 8 —: Go back to Step 2.



Figure 3.9: The Particle Swarm Optimization Algorithm

The PSO technique appears to adhere to five basic principles of swarm intelligence, as defined by Eberhart [70]:

- *Proximity*, the swarm must be able to perform simple space and time computations.
- *Quality*, the swarm should be able to respond to quality factors in the environment.
- Diverse response, the swarm should not commit its activities along excessively narrow channels.
- *Stability*, the swarm should not change its behavior every time the environment alters.
- Adaptability, the swarm must be able to change its behavior, when the computational cost is not prohibitive.

Certainly, the swarm in PSO performs space calculations for several time steps. It responds to the quality factors implied by each particle's best position, *pbest*, and the best particle in the swarm, *gbest*, allocating the responses in a way that ensures diversity. In addition, the swarm alters its behavior (state) only when the best particle in the swarm (or in the neighborhood, in the local variant of PSO) changes, therefore, it is both adaptive and stable [70].

3.4.3 Global Optimization Examples: Particle Swarm Optimization and Genetic Algorithm

PSO can easily be implemented and is computationally inexpensive, since its memory and CPU speed requirements are low [53]. Moreover, it does not require gradient information of the objective function under consideration, but only its values, and it uses only primitive mathematical operators. PSO has been proven to be an efficient method for many global optimization problems and in some cases it does not suffer the difficulties encountered by other evolutionary computation techniques. This section presents a comparison of results obtained from four optimization tests of a 2-D system using PSO and Genetic Algorithm (GA). The test systems are:

- 1. Levy function # 3.
- 2. Levy function # 5.

- 3. Freudenstein-Roth function.
- 4. Goldstein-Price function.

All of these test functions have only one Global Minimum (GM) and lots of Local Minimums (LM). Each function is plotted in 3-D with x_1 , x_2 and $f(x_1,x_2)$ axes. Both PSO and GA searched for the GM and the final search results are indicated in the 3-D plot and following tables.

The performance index in all of the four test functions is given as:

$$\min_{x_1, x_2} J = f(x_1, x_2)$$
(3.5)

The global minimum was found in all four cases by the PSO algorithm, but the GA algorithm found it only in two cases, namely case three and case four. This is shown in Figure 3.10, Figure 3.11, Figure 3.12, and Figure 3.13. Also, the PSO algorithm is about two times faster than the GA. Specific details are shown in Table 3.1, Table 3.2, Table 3.3, and Table 3.4.

The GA solution is obtained using the MATLAB GA Toolbox which is available from the web site [89].

1. Levy Function # 3

$$f(x_1, x_2) = \sum_{i=1}^{5} [i\cos((i-1)x_1 + i)] \sum_{j=1}^{5} [j\cos((j+1)x_2 + j)]$$
(3.6)



Figure 3.10: Levy Function # 3

PSO AND GA RESULT FOR LEVY FUNCTION # 3				
	PSO			
x ₁	-1.3072372	-0.3508452		
x ₂	-1.4249612	-0.8003212		
$f(x_1, x_2)$	-176.5415032	-145.4777372		
Computation Time* [sec.]	2.30	5.08		

TABLE 3.1 PSO and GA result for Levy function # 3

* In Pentium 4 with 1.8 GHz PC.

2. Levy Function # 5

$$f(x_1, x_2) = \sum_{i=1}^{5} [i\cos((i-1)x_1 + i)] \sum_{j=1}^{5} [j\cos((j+1)x_2 + j)] + (x_1 + 1.42513)^2 + (x_2 + 0.80032)^2$$
(3.7)



Figure 3.11: Levy Function # 5

TABLE 3.2	
SO AND GA RESULT FOR LEVY FUNCTION # 5	

PSO AND GA RESULT FOR LEVY FUNCTION # 5				
	PSO GA			
X1	-1.3068562	-0.3521262		
X2	-1.4248402	-0.8003222		
$f(x_1, x_2)$	-176.1375782	-144.3250262		
Computation Time* [sec.]	1.98	3.55		

* In Pentium 4 with 1.8 GHz PC.

3. Freudenstein-Roth Function

$$f(x_1, x_2) = [-13 + x_1 + ((5 - x_2)x_2 - 2)x_2]^2 + [-29 + x_1 + ((x_2 + 1)x_2 - 14)x_2]^2 \quad (3.8)$$



^x₁ Figure 3.12: Freudenstein-Roth Function

PSO AND GA RESULT FOR FREUDENSTEIN-ROTH FUNCTION				
	PSO	GA		
X1	4.9986282	5.000002		
X2	4.0000582	4.000002		
$f(x_1,x_2)$	0.0000052	0.0000002		

3.44

8.18

TABLE 3.3 PSO and GA result for Freudenstein-Roth function

* In Pentium 4 with 1.8 GHz PC.

Computation Time* [sec.]

4. Goldstein-Price Function

$$f(x_1, x_2) = \left[1 + (x_1 + x_2 + 1)^2 (19 - 14x_1 + 3x_1^2 - 14x_2 + 6x_1x_2 + 3x_2^2) \right] \\ * \left[30 + (2x_1 - 3x_2)^2 (18 - 32x_1 + 12x_1^2 + 48x_2 - 36x_1x_2 + 27x_2^2) \right]$$
(3.9)



Figure 3.13: Goldstein-Price Function

I ABLE 3.4				
PSO AND GA RESULT FOR GOLDSTEIN-PRICE FUNCTION				

2 4

	PSO	GA		
x ₁	-0.0000122	-0.0000042		
X2	-1.0000132	-1.0000002		
$f(x_1, x_2)$	3.0000002	3.000002		
Computation Time* [sec.]	2.88	3.60		

* In Pentium 4 with 1.8 GHz PC.

3.4.4 Guided Particle Swarm Optimization

In [29] and [7], PSO is employed to design controller parameters in a power system. The controller parameters are tuned based on linearized models around selected operating points. Moreover, the linearized models are obtained during small disturbances in the system like load(s) changes or loss of line(s). Such procedures required a computation effort in terms of obtaining the linearized models and it may not be valid when the operating point changes due to large disturbances. A new procedure is proposed for power system controller parameters tuning using the Guided Particle Swarm Optimization (GPSO) technique. The GPSO is a nonlinear simulation based optimization technique with guided constraints. Consider Figure 3.14; these are output signals from nonlinear simulations for four different PSO provided solutions. The guided constraints will reject solution 1, 2 and 3 while it will approve only the solutions that fall within the maximum and minimum specified boundaries, namely solution 4. Once the monitored signal hits either boundary, the simulation is interrupted and that solution will be ignored.



Figure 3.14: The Output Terminal Voltage Signals From the Nonlinear Simulation of 4 Different PSO Solutions

The GPSO represents the "Evaluation" block in the PSO algorithm as in Figure 3.9. It will follow the algorithm presented in Figure 3.15, which has the following steps:

<u>Step 1</u>: Compute particle swarm optimization solution $[X]_n$, the constraints of parameters' minimum and maximum limits are considered during the PSO search, basically when the X_i s fall between $x_{j min}$, and $x_{j max}$. Start at step *i*.

<u>Step 2</u>: Perform a nonlinear simulation considering the PSO provided controller(s), X_i , at the preferred disturbance.



Figure 3.16: Guided Particle Swarm Optimization Algorithm

<u>Step 3</u>: Check the GPSO constraints; for instance the terminal voltage of a generator, the rotor angle, and the speed of the shaft, at each time step. If any of those constraints are violated then set J_i = large number (for minimization problem) and go to step # 5; this solution is not considered as a candidate solution, otherwise continue.

<u>Step 4</u>: Compute the objective function " J_i ".

<u>Step 5</u>: Check if i > n, exit else continue.

<u>Step 6</u>: i = i + 1 and go back to Step 2.

The dynamics of the system can be expressed by a set of nonlinear differential equations of the following form:

$$\dot{\mathbf{x}}(\mathbf{t}) = \mathbf{f}(\mathbf{x}(\mathbf{t}), \mathbf{u}_{i}(\mathbf{K}_{j}))$$
$$\dot{\mathbf{i}} = 1, \dots \mathbf{N}$$
$$\dot{\mathbf{j}} = 1, \dots \mathbf{m}_{i}$$

Where:

x: system state variables.

 u_i : i-th controller, i = 1, ... N

N: number of controllers.

m_i: number of control parameters for controller # i.



Figure 3.15: System with Two Control Stations

Consider the system given in Figure 3.16, the objective is to minimize the performance index, J given by Equation (3.10):

$$J = \sum_{i=1}^{2} J_{i}$$
$$J_{i} = \int_{0}^{t} (\alpha y_{i1} + \beta y_{i2}) dt$$

subject to:

control constraints:

$$K_{ij_{min}} \le K_{ij} \le K_{ij_{max}}$$
 (3.10)
variables constraints:
 $z_{min} \le z \le z_{max}$

where:

 α and β : weighting factors

 $z = C_z \cdot x$; z: constrained output variables

Cz: output matrix

 K_{ij} : control parameters to be designed, i = 1, ...N and j=1,...m

GPSO design is less sensitive since it considers a preferred disturbance based on nonlinear simulations rather than linearization around selected operating conditions. Nonlinear simulation based design allows consideration of large disturbances, such as short circuit faults, and will guarantee the controller performance for these kinds of disturbances. The guided constraints provide faster PSO searching by ignoring the undesired solutions and allow the selection of the desired performance. Once a solution hits the boundaries, the next search will start and that solution is not considered as a desired answer.

3.4.5 Case Study: Comparison using GPSO and PSO

A three machine nine bus test system is considered as a case study to compare controller design results using PSO with a linearized system and using GPSO with a nonlinear system to compute the optimization objective function. The details of the system data are provided in [88]. The single line diagram of this system is shown in Figure 3.17. Generator # 2 and # 3 are equipped with a Power System Stabilizer (PSS). The PSS uses speed deviation as an input signal and has two stages of lead-lag plus a wash-out stage that provides a supplementary signal to the excitation system, Figure 3.18.



Figure 3.17: The Three Machine Nine Bus Test System

$$\min \sum_{i=1}^{n_{c}} J_{i}$$

$$J_{i} = \int_{0}^{t} (\alpha | \Delta \omega_{i} | + \beta | \Delta \delta_{i} |) dt$$
subject to control constraints:
$$K_{j_{min}} \leq K_{j} \leq K_{j_{max}}$$
variable constraints:
$$\Delta \omega_{i_{min}} \leq |\Delta \omega_{i}| \leq \Delta \omega_{i_{max}}$$

$$\delta_{i_{min}} \leq \delta_{i} \leq \delta_{i_{max}}$$

$$V_{ti \min} \leq V_{ti} \leq V_{ti max}$$
(3.11)

Where:

 α and β : Weighting factors on generator speed and power angle deviations. ω , δ , and V_t: Generator's speed, power angle and terminal voltage respectively. K_i: control parameters to be designed, j=1,...m. The variables constraints (generator: speed deviations, power angle, and terminal voltage) are the guided constraints. These constraints vary in type and limit according to design preference.

The PSS parameters design of this system using PSO with a linearized system are presented in [29]. The time constant Tw, T2, and T4 are set as 5, 0.05 and 0.05 sec respectively. Hence the optimized parameters are Ks, T1 and T3 for each generator. Similar PSS parameters are designed with GPSO using the objective function presented in Equation 3.11 and the GPSO generators' speed deviations and the generators' terminal voltage constraints as shown in Figure 3.19 and Figure 3.20. The power angle constraint is bounded between 150° and -50°. Table 3.5 presents the PSO parameters. The generators' speed response for both PSS designed by PSO with a linearized system and GPSO during a 3-phase to ground fault between bus # 6 and bus # 9 and cleared in 100 msec is shown in Figure 3.21. It is obvious that the GPSO PSS design stabilizes the system faster compared to the PSS designed by PSO with a linearized system.



Figure 3.18: The Generator Excitation System with PSS

PARTICLE SWARM OPTIMIZATION TECHNIQUE PARAMETERS								
Bounds	K _{s min}	$K_{s max}$	$T_{1\min}$	T_{1max}	T _{3min}		T _{3max}	
	0	20	0.06	1	0.06		1	
Weighting factors			C ₁		C ₂			
			2 2.0		2.01			
Number of population "n"				5	50			
Maximum # of unchanged solution "count _{max} "			10					
Maximum # of iterations "iter _{max} "			50					

 TABLE 3.5

 PARTICLE SWARM OPTIMIZATION TECHNIQUE PARAMETERS



Figure 3.19: The GPSO Generators' Speed Deviations Constraint



Generators Terminal Voltage GPSO Constraint

Figure 3.20: The GPSO Generators' Terminal Voltage Constraint





Figure 3.21: The Generators' Speed Response during a 3-Phase-to-Ground Fault

3.5. Distributed Control Agents

While the penetration of DGs in the power distribution system stability is reported, these devices can be considered as a control path and can be used effectively to enhance the transient stability of distribution systems. Several efforts by many researchers have been published in control design of DGs but most of these controllers are conventional, decentralized and of fixed structure type. In most cases the controllers' parameters are designed by trial and error or tuned by optimization techniques using linearized models. Since the distribution system may become vulnerable with the installed DGs, such conventional fixed structure controllers do not guarantee stable operation of the DGs during large and severe disturbances. In most cases DGs get disconnected during disturbances [79] as required by IEEE 1547 Standard for interconnection of DGs with electric power systems. Based on these issues, it is clear that there is a need to find a novel control algorithm to overcome different tasks and restrictions. Such control architecture must have the following features:

- 1. Coordinated control among the DGs, to avoid contradictive control actions.
- 2. Adapted controllers, the control actions must adapt to different operating conditions.
- 3. Self-learning ability to end up with a robust and reliable system.
- 4. Fast control and protection actions to avoid any damage to the DGs while keeping them in service.

In this section a new control algorithm based on multi-agent system is proposed for control of DGs to enhance the transient stability of power distribution system. The proposed control architecture provides a flexible and automated control system with the above mentioned features.

3.5.1 Multi-Agent System

An agent is defined as a computer system that is situated in some environment, perceiving that environment via sensors and acting autonomously in order to meet its design goals [54]. The agent structure is not unique as various attributes associated with agents are of different importance for different domains. For example, in some

applications the ability of agents to learn from their experience is of dominant importance; for other applications learning is not only unimportant, it is undesirable [1]. Multi-Agents System (MAS) is a team of problem solving agents which can react intelligently and flexibly to changing operating conditions and demands from the surrounding processes. The multi-agents system processes an inquiry and generates an output in form of an activity or information. The inquiry is processed autonomously, depending on the process status and the boundary conditions. In this research we will be dealing with multi-agents control system since both the target definition and the resulting action of the system serve to control a process. The main advantage that can be drawn from such architecture is that it is expected to act over longer intervals and especially within broader boundaries, without necessitating a manual intervention into the system. Multi-agents systems make sense in complex processes, which underlie high and flexible demands such as those in power systems. This is closely related to the fact that actions must be taken regardless of little or prior knowledge. Intelligent talents, such as learning from experience, planning of actions or detection and identification of errors, used to be part of the process operator duties, are integrated into the multi-agents system. The advantages are reflected in the avoidance of human operating errors, the enhancement of the reaction rate and performance, and the reduction of the operator's effort [1].

Several applications have been reported of MAS in power system problem solving, and some good results were obtained in different fields and studies. The electric power system is complex and distributed in nature where the power source and the load are dispersed geographically. While the plant operator's interactions are constrained by speed and complexity limits, the emergence of distributed generators (DG) to electric power system adds more complexity and the volatility of the operational tasks will increase. This brings about an increase of the degree of automation and distributed control among power system equipment. On the other hand, the limitation imposed by the conventional fixed-structure DG's controllers necessitates finding a novel control architecture that provides a controller with coordinated operation, adaptive action, self-learning ability, and fast control and protection action. In this study, we have developed a MAS based control architecture that holds to the mentioned features to enhance the control and

operation of distributed generators.

3.5.2 Multi-Agent Approach in Control of Distributed Generators

Operation and control of DGs becomes of a major concern as the number of DGs increases in electric power distribution systems. The main objective of having DGs in distribution systems is to supply on-site power to the load and reduce the dependency on the main substation during steady state operation. However these DGs may have harmful impact on the system during large disturbances. It becomes difficult to come up with coordinated controllers for each DG at every operating condition. A DG is considered to be a control point or path that can be used to control and enhance the stability and reliability of electric power distribution systems.



Figure 3.22: The Multi-Agents Structure in Control of Distributed Generator

This section explains how the multi-agent structure can be translated and applied to the control and operation of DGs. The agents are trained in such a way that their behavior follows a global process goal. On the other hand, each agent acts locally based as much as possible on local data to satisfy its local goal, but in spite of this, the global target is

reached in the sense of an optimal local performance. The communication between the agents can be used to avoid conflicting actions. In the area of distributed generators, the control process is organized in a multiple parallel but also hierarchical way. Each DG is equipped with one intelligent controller. All agents are interconnected together via the information base to a global agent. The whole system presented in Figure 3.22 can be classified into three different layers as shown in Figure 3.23.



Figure 3.23: The Multi-Agents Layer in the Control of a Distributed Generator

The bottom layer represents the physical distribution network with distributed generators. The middle layer presents the control system layer which is basically one controller or more attached to each DG. The top layer is the multi-agent system layer. In this layer there is a local control agent associated to each DG and a global control agent that supervises and optimizes the overall process. The details of each agent structure and operation algorithm are presented in the next sections.

3.5.3 Local Control Agent

A Local Control Agent (LCA) is an agent connected directly to a controller mounted on the distributed generator. It has direct access to local measurements like information on the distributed generator's bus or the distributed generator's operating status. Figure 3.24 illustrates the function of this agent.



Figure 3.24: The Local Control Agent

The state assessment section continuously evaluates the operating conditions of the distributed generator and compares them with predefined set points. Once a disturbance has occurred, the distributed generator operating condition changes and based on that, the disturbance detection section with a trained Neural Network (NN) classifies that disturbance. The execution and adaptation section represents the heart of the agent. It uses the disturbance detection results to execute the control actions. Each LCA is equipped with local data storage. Such a feature is extremely useful, especially when the agent loses communication with the rest of the system. The agent will try to map the event with the best suitable controller setting available in the local database. In addition, a local data base provides faster data access during controller adaptation processes.

A. LCA Information structure

LCA has two types of input. The first type is online measurements from the physical layer through sensors as shown in Figure 3.24. Some of these measurements are used for system monitoring and assessment to detect any changes or violations in the system, such as terminal voltage of the distributed generator. On the other hand, some of these measurements are used by the disturbance detection section as input to the Neural Network (NN) to classify the disturbance and based on that, the execution control action and adaptation section generates the proper control action. The second type of input is information from the Global Control Agent (GCA), such as an update for the database of a new controller setting or the NN update for a new disturbance. This agent generates two types of output. The first type is a control action of adapting the setting of the controller in the control layer or disconnecting of the DG from the grid in case of unsuccessful controller settings. The second output is information exchanged with the GCA like passing the Local Emergency Signal (LES) and requesting an update for the local database.

B. The LCA Decision Process

The LCA will follow the algorithm presented in Figure 3.25, which has the following steps:

1. The state assessment section continuously evaluates the operating conditions of the distributed generator, such as terminal voltage, shaft speed and generated power. Then it compares them with predefined set points.

 Once a violation is detected, the disturbance detection section which is equipped with up-to-date trained neural network will identify and classify the detected disturbance and pass the result to the execution control action and adaptation section.



Figure 3.25: The Local Control Agent Algorithm

- 3. If the disturbance detection fails, the collected data is sent to the GCA to update the neural network with the new disturbance.
- 4. The execution control action and adaptation section will use the disturbance detection section result to assign the proper setting of controller parameters from the local data base.
- 5. If the problem is solved, the system is stabilized after the disturbance; continue monitoring the system i.e. go to step # 1.

- 6. If the problem still exists and the violation is driving the system to a state of instability, the execution control action section will disconnect the DG from the grid and continues to supply the local load. The LCA will generate a LES and pass it to the GCA.
- 7. Go back to step # 1.

C. The LCA Architecture

The LCA processes the information measured from the physical layer and responds accordingly with the proper control action. The intelligence of this agent appears in control decisions, the identification of the disturbance according to the local database by using up-to-date the NN, adaptive control actions, and self-learning. This agent adapts the controller parameters settings to the classified disturbance from the local database. If the controller setting is unsuccessful, a fast control action is passed to the control layer to disconnect the distributed generator from the grid. This action will protect the distributed generator while preventing the propagation of a stability problem to the rest of the system. After sending the LES to GCA, the latter will provide the proper controller parameters to that disturbance as well as updating the NN. The LCA can use this particular controller and the NN in the future for all similar situations and therefore has learned and extended the capability of the control layer.

3.5.4 Global Control Agent

Figure 3.26 illustrates the structure of the Global Control Agent (GCA). It represents the brain of a multi-agent control system. This agent contains three main parts: overall system evaluation and supervision, coordination and learning, and emergency signal section. The main target of the GCA is to keep the system running within the predefined operating conditions, such as known stability margins (voltage stability, synchronization, etc.) during any possible large disturbances. The overall system evaluation and supervision section provides continuous assessment of the system based on LCAs' performance. The emergency section processes the generated LES from LCAs. In addition it is responsible for initiating the Global Emergency Signal (GES). Both cases are reported to the coordination and learning section. The coordination and learning section is equipped with the Guided Particle Optimization (GPSO) technique for the

controller design and the Neural Network (NN) training section to update the LCAs networks with the new reported disturbances. A brief description about the NN is presented later.



Figure 3.26: The Global Control Agent

The coordination and learning section processes the reported LES or GES and conducts off-line study to design and coordinate new controller settings to the associated faulted LCAs. In addition, it runs the NN training to include the new disturbance in the local NN. The designed settings and trained networks will be passed to LCAs via the information base and stored in a local database so that the LCAs can use those designs for future similar situations. It has therefore learned and extended the capability of the LCAs. Then, it will initiate a request to restore the disconnected DGs and bring them back to the grid.

A. The GCA Information structure

Unlike the LCA, the GCA exchanges information with local control agents only and does not interfere with the other layers. The input to this agent is the local emergency signals from local control agents and requests to update the local control agents' data base with controller settings or neural networks updates. The GCA generates output

which is either a GES or updates to local control agents data base.

B. The GCA Decision Process

The GCA will follow the algorithm presented in the flowchart in Figure 3.27, which can be summarized as follows:

- 1. The GCA will continuously process the signals and requests from the LCAs in order to update their databases.
- Once the GCA receives an LES from any LCA, it conducts a GPSO search to find a new setting for the new disturbance. Then, it will send the new design back to the LCA database.



Figure 3.27: The Global Control Agent Algorithm

- 3. The GCA will also run the NN training to update the network with the new disturbance either while receiving the LES or an individual request. The result will be sent back to the LCA.
- 4. If all LCAs send LESs, then the GCA sends a GES to the LCA to disconnect all DGs from the grid and supply the remaining loads from the main substation. The GCA will conduct both a GPSO search and a NN training for the new disturbance, then, send the results back to LCAs.
- 5. GCA will initiate a request to restore the disconnected DGs and bring them back to service.
- 6. Go back to step # 1.
- C. The GCA Architecture

The GCA is responsible for the evaluation and supervision of the performance of local control agents by processing the incoming local emergency signals. The most important job of this agent is to perform coordination between the designed controllers at each LCA. This coordination appears in the optimization process (GPSO) either while processing a single LES or during generation of a GES. GPSO designs the controller in the first case, while considering the setting of the remaining controllers. In the second case, all the controllers are tuned simultaneously and in a coordinated manner. The process of finding the proper controller setup and updating the neural networks is a main participation of this agent to the self-learning feature of the MAS based controller.

D. The Neural Network

The use of pattern recognition for power system security analysis was first investigated in 1968 [75]. Since the NN has a superior ability of pattern recognitions, other applications to power system have been investigated, such as transient classification including short circuit analysis [76] and [77]. In this work, the NN is employed as an embedded tool in the proposed MAS to classify the disturbance in the distribution network. Once a disturbance is detected, a local measurement is recorded for a short period of time, less than 50 msec, and passed to the trained NN. The classified result from the NN is mapped to a proper setting of the controller from the database, which can be used to elevate the transient instability problem. The back propagation algorithm is

used to train the NN for all possible disturbance types. This algorithm is an iterative gradient algorithm designed to minimize the mean square error between the actual output of a multilayer feed-forward perceptron and the desired output. It requires continuous differentiable non-linearities. Figure 3.28 assumes a sigmoid logistic non-linearity [78].

The back propagation algorithm is classified as a supervised learning mechanism for multilayered, generalized feed forward network. It has been discovered by different researchers independently [Werbos(1974), Parker(1982), and Rumelhart(1986)]. It played a major role in the repetition of neural networks as a tool for solving a wide variety of problems.

Back propagation algorithm has been selected as a part of MAS disturbance classifier for the following reasons:

- It is the most well known and widely used among the current types of NN systems.
- Use of differentiable activation functions.
- Robust and stable (based on gradient descent technique, i.e. approximate steepest descent)
- It recognizes patterns similar to those they have learned.



Figure 3.28: NN Back Propagation

The details of the training data and parameters of the NN used in this work are presented in the MAS implementation section.

Chapter 4

Control and Operation of Electric Power Distribution Systems

4.1. Introduction

Although placing distributed generators at the lower voltage level network, distribution system, will reduce the reliance on the high voltage transmission grid, it brings problems of control and operation of each unit. Several researchers indicate the requirements to trip the distributed generators during abnormal conditions [79] and [81] IEEE 1547 Standard requires that distributed generators disconnect from the grid when there is a disturbance. A similar disturbance is overload; disconnection of the distributed generator in such a case is considered to be a wrong action since the load, not the distributed generator, needs to be disconnected. The current power distribution system was not designed to accommodate active generation and storage at the distribution level or to allow such systems to supply energy to other distribution customers. The net result necessitates designing and implementing a central real time monitoring and control system in the distribution level.

This chapter will discuss the issue of operation and control of distributed generators using the modeling and tools developed in Chapter 3. First, the load following problem of a microturbine as DG in parallel operation is presented. The simulation uses the microturbine model developed in the previous chapter. Then, the load following controller parameters are designed using the developed optimization technique. The transient stability problem of a distribution system with the presence of distributed generators is discussed after that. The system is simulated with a solid oxide fuel cell and a microturbine as distributed generators. A control approach is designed and microturbine controller parameters are designed using GPSO. After that, the implementation of the developed multi-agent based control system to enhance the transient stability of distribution system incorporating microturbines as distributed generators is presented. Finally, simulation results are presented and discussed.

4.2. Distributed Generators and Load Following

Load following control is a mechanism in power systems, which balances generated power and demand in order to maintain system frequency at 60 Hz and to ensure that power is exchanged at an acceptable range. Usually, small changes in load have significant changes in frequency from its nominal value, which is not desirable. So there is a need for controlling the real power output of generating units, in response to changes in system frequency. The system originally running in its normal state with complete power balance between generation and demand is the case where the frequency is at normal value. Consider adding or removing load from the system, so that there will be a power imbalance, which will change the speed or the frequency. This change is undesirable and can be reduced to an acceptable range with proper load following controller design for the controllable power generating units.

Integration of distributed generators into a power system covers only part of the total load. The rest of the load is still covered by the large power plants. In most cases, the DG does not participate in voltage or frequency control; this part is normally taken by central generation. This section will describe the parallel operation of a microturbine as distributed generators and the load following control design using GPSO.

4.2.1. Problem Description

Distributed generators are operated either in islanded mode, not connected to the grid, or parallel mode, connected to the grid. Islanding operation of distributed generators has been addressed in several publications such as [79], [68] and [82]. In this section, the parallel operation of a microturbine as distributed generator is considered. The parallel operation is when external voltage and frequency exist since the distributed generator is tied to electrical grid or another generating unit. The main target here is to consider the load changes in the network and to adapt the microturbine electric power output to those changes. Once a change is detected, the set or the reference point of the controller is changed to compensate as the load changes. In the next section, the microturbine's load following controller is presented and followed by a case study.

4.2.2. Microturbine Load Following Controller

The purpose of this controller is to control the motive force of the microturbine prime mover as the load changes. This can be accomplished by increasing or decreasing the fuel flow or the fuel valve positioning. Figure 4.1 presents the microturbine load following controller. The controller consists of proportional and integral controls with anti-reset windup loop. While the proportional control is employed to give a constant response to the error, the integral control calculates the error over time and responds accordingly. The input to the controller is the deviation of the generator real power output from the set or reference point and produces an output control signal to the prime mover. The controller parameters will be tuned using GPSO. The next section will present an implementation to control three microturbines connected to IEEE 37 Node Feeder. The design process and simulation results are presented and discussed after that.



Figure 4.1: The Microturbine Load Following Controller

4.2.3. Case Study I: IEEE 37 Feeder with 3 Microturbines

Consider the one-line diagram of the IEEE 37 Node Feeder, Figure 4.2, with three microturbines at nodes 6, 12 and 15, each rated 160 kW. The power supplied from these units is 20% of the total power demand, with the remaining 80% of the power comes from the substation. The objective is to design a load following controller using GPSO if the power from the substation drops from 80% to (a) 70%, then (b) to 50% and (c) back to 75%. The load following controller structured as a PI controller including anti-reset windup loop is shown in Figure 4.1. The controller output is limited to 0.001 - 1 p.u. and kw = 1000*ki. The controller parameters are designed using GPSO as presented in Chapter 3.
Table 4.1 presents the PSO parameters. The design process involves two GPSO constraints. Figure 4.3 shows the GPSO speed deviation constraint while the generated real power constraint is bounded between zero and 150kW. The minimization of the microturbines' speed deviations is used as a performance index as shown in Equation (4.1).



Figure 4.2: The IEEE 37 Node Feeder With Three Microturbines As DGs

min
$$J = \sum_{i} \left(\int_{0}^{t} |\Delta \omega_{i}^{2}| dt \right)$$

subject to control constraints:
$$K_{j_{min}} \leq K_{j} \leq K_{j_{max}}$$
(4.1)
variables constraints:
$$\Delta \omega_{i_{min}} \leq |\Delta \omega_{i}| \leq \Delta \omega_{i_{max}}$$
$$P_{ei_{min}} \leq P_{ei} \leq P_{ei_{max}}$$



Figure 4.3: The GPSO Speed Deviation Constrain For Load Following Controller Design

TABLE 4.1 Particle Swarm Optimization Technique Parameters							
Bounds	KPi min KPi max KIi min KIi ma						
	-1	1	-1	1			
W	eighting factors	C_1	C ₂				
			2	2.01			
Nun	nber of population	50					
Maximum # of unchanged solution			10				
Maxi	mum # of iteratio	ons		50			





Figure 4.4: The Microturbines' Speed [Open-Loop Response]



Figure 4.5: The Microturbines' Generated Real Power [Open-Loop Response]





Figure 4.6:The Microturbines' Speed [Close-Loop Response]



Figure 4.7: The Microturbines' Generated Real Power [Close-Loop Response]

LOAD FOLLOWING CONTROLLER PARAMETERS							
$MT_1 \text{ at bus } \# 6 \qquad MT_2 \text{ at bus } \# 12 \qquad MT_3 \text{ at bus } \# 15$							
kp	0.0096	0.3552	0.8115				
ki	0.2241	0.2656	0.8577				

TABLE 4.2

Table 4.2 presents the designed controller parameters.

The total loading of the test system is 819 kW and each microturbine is 160 kW rated power. Table 4.3 presented the generated real power changes between the substation and microturbines, where the microturbines' load is divided equally.

GENERATED REALTOWER CHANGES DETWEEN THE SUBSTATION AND WICKOTORDINES							
Substation [P _g]		Microtur	Each MT				
80 %	655.2 kW	20 %	163.8 kW	54.6 kW			
70 %	573.3 kW	30 %	245.7 kW	81.9 kW			
50 %	409.5 kW	50 %	409.5 kW	136.5 kW			
75 %	614.25 kW	25 %	204.75 kW	68.25 kW			

TABLE 4.3 GENERATED REAL POWER CHANGES BETWEEN THE SUBSTATION AND MICROTURBINES

The simulation is carried out in PAT, the data file and PAT's Blocks are attached in Appendices A and B. Figure 4.4 and Figure 4.5 present the open-loop response while Figure 4.6 and Figure 4.7 present the close-loop response for the desired operation. It can be seen that the output P_e of each microturbine doesn't match the scheduled one for the open-loop case. The close-loop response of P_e matches the scheduled P_e as specified in the problem and Table 4.3. In addition, the oscillations at point of power changes are eliminated or reduced with the designed controllers; smooth transitions have been achieved.

4.2.4. Case Study II: Load Following

Consider the IEEE 37 Node Feeder shown in Figure 4.2, with three microturbines at nodes 6, 12 and 15, each rated 160 kW. Initially, the power supplied from these units is 124.6 kW which represents about 46% of the total power demand, while the remaining is supplied by the substation. The system is simulated while losing the main load bus at t = 10 sec, bus # 2, which represents about 26% of the total load. Then the system will recover that load at t = 200 sec. The three microturbines are responsible for following the

load changes equally using the controllers designed in the previous section.

Table 4.4 presents the generated real power changes between the substation and microturbines, where the load sharing is divided equally.

0							
Time	Total Load	Bus # 2	Substation [P _g]		Microturbines [P _g]		Each MT
0-10	814 kW	210 kW	452 kW	55.5%	373.8 kW	46%	124.6 kW
10-200	604 kW	0 kW	452 kW	74.8%	163.8 kW	27.1 %	54.6 kW
200-400	814 kW	210 kW	452 kW	55.5%	373.8 kW	46%	124.6 kW

 TABLE 4.4

 GENERATED REAL POWER DURING LOAD CHANGES AT BUS # 2

The simulation is carried out in PAT. Figure 4.8, Figure 4.9 present the response of each microturbine during the load changes at bus # 2. The substation power supply is kept constant and the microturbines will follow the load changes equally. It can be seen that the output P_e of each microturbine is following the load changes and smooth transitions have been achieved. Figure 4.10 present the response of the supplied P_e from the substation.



Figure 4.8: The Microturbines' Speed during Load Changes at Bus # 2





Figure 4.9: The Microturbines' Generated Real Power during Load Changes at Bus # 2



Figure 4.10: The Substation's Real Power during Load Changes at Bus # 2

4.3. Conventional Distributed Generators' Control for Transient Stability Enhancement of Distribution System

While the advantages of having DGs in the power system are well-known, the technical impacts of those small dispersed power generating units are still not yet well addressed. Connection of the DGs to a distribution level, which is not designed to include such power sources, can raise technical issues such as power distribution stability during severe disturbances. The severity of this problem would vary depending on the type of the DGs, and the type, location and duration of the disturbance.

This section describes the negative impact of distributed generators, namely a fuel cell and a microturbine, on the stability of electric power distribution systems. It deals with a fuel cell, namely a solid oxide fuel cell (SOFC), and a split-shaft microturbine (MT) as distributed generators supplying power to the distribution system in addition to the main substation. The objectives are, first, to analyze the effects of these DGs on distribution system stability during a large disturbance, mainly a three-phase to ground fault, and, second, to design appropriate controllers to stabilize the system using only the specified DGs. Both a microturbine and a SOFC are chosen for this study because they are efficient small generators in the range of 5kW-3MW that are expected to become a part of future distribution systems. A control algorithm is then developed to enhance transient stability following a large disturbance.

4.3.1 Problem Description

Stability investigation of a distribution system for large disturbances, consisting of a SOFC and a microturbine as distributed generators is considered in this section. A fuel cell (FC) and a microturbine as distributed generators could experience severe damages following a large disturbance. Specifically, the fuel cell current could reach a level that will damage it, and hence it must be disconnected. Neither the fuel cell stack nor its interfacing equipment can tolerate these variations. It is obvious that the closer the fault to the fuel cell, the higher the fuel cell current. In addition, after the fuel cell is reconnected, the microturbine experiences stability problems. Therefore, appropriate control actions need to be taken for both the FC and the microturbine. These behaviors have been experienced on the IEEE 37 Node Feeder test system which is shown in

Figure 4.11 and reported in this section. A 240kW microturbine and a 100 kW SOFC are connected to buses #11 and #13, respectively. The total loading of this feeder is 819 kW where almost 42% of the power is provided by the DGs. Figure 4.12 demonstrates the fuel cell current when a three-phase fault to ground occurs at t = 0.1 sec at bus #30. Based on the relative angle of buses #1 and #11 plotted on Figure 4.13, The microturbine's generator rotor starts accelerating and consequently losing synchronization; however, the fuel cell is restored after clearing the fault. Similar results have been noticed at different nodes of the network. Appropriate power/voltage controllers need to be designed for the FC in addition to a Power System Stabilizer (PSS) for the microturbine to enhance system stability. The appropriate design of the controllers will be presented in the next section.



Figure 4.11: The IEEE 37 Node Feeder with a MT and SOFC as DGs



Figure 4.12: The Fuel Cell Current During 3-Phase To Ground Fault Between Bus # 21 And Bus # 20



Figure 4.13: The Relative Angle Of MT During 3-Phase to Ground Fault Between Buses #10 and #11

4.3.2 Control Approach

The results presented in the previous section demonstrate the need for control actions to avoid damaging the FC and instability of the system. The actions involve a design of control mechanisms for both the FC and the microturbine.

A. FC Controller

Due to the large current and to avoid FC damage, the FC is first disconnected during the fault. To reconnect FC to the grid, after the fault is cleared, the following control actions have to be taken through the power conditioning unit (PCU) [34]:

- 1. Power control: Due to grid connection issues [83], when the fuel cell is reconnected, output FC voltage angle should be synchronized with the grid network. Adjusting the firing angle of the inverter accomplishes this task.
- 2. Voltage control: Output FC voltage will be higher than its nominal condition when it is disconnected; therefore, a voltage controller is needed to match the output fuel cell voltage and grid voltage levels at reconnection time. Adjusting the modulation index of the converter, which affects the magnitude of the converter output voltage, achieves this.



Figure 4.14: The Fuel Cell Control Scheme

The fuel cell power and voltage controllers presented here are Proportional-Integral (PI) type controllers, which adjust the firing angle and modulation index of the converter according to the power and voltage deviations, respectively, as illustrated in Figure 4.14. These controllers match the output voltage level and angle of the fuel cell with the grid voltage level and angle at reconnection time (similar to synchronization).

The next step is to implement the 2nd control strategy, which is the design of a Power System Stabilizer (PSS) for the synchronous generator of the microturbine, explained in the second part of this section.

B. MICROTURBINE Controller

The microturbine can be controlled via two paths, namely the mechanical power from the turbine to generator and synchronous generator excitation voltage via the Power System Stabilizer (PSS). If a fast disturbance occurs such as a short circuit fault, the mechanical power control will be slow and of no interest. On the other hand, fast action can be taken with a proper PSS design. In this section, a PSS of fixed-structure type is used as a damping controller for the microturbine. The basic function of the PSS is to add damping to the generator rotor oscillations by controlling its excitation using an auxiliary stabilizing signal. The device acts as an add-on device to the Automatic Voltage Regulator (AVR). In this section, the PSS uses the microturbine's shaft speed deviation as input. The stabilizer itself mainly consists of a stabilizing gain, washout stage and two lead-lag filters as shown in Figure 4.15. These are used to compensate for the phase lag introduced by the AVR and the field circuit of the generator, and are tuned so that speed oscillations give a positive damping torque on the rotor. The PSS output is added to the difference between reference (Vref) and actual value (Vact) of the terminal voltage.



Figure 4.15: The Microturbine Controller (PSS)

The PSS is usually designed to operate in a decentralized structure, where input signals from remote sites are not considered reliable enough and avoided. The damping controller used in this section is of a fixed structure type:

$$U = K_s \frac{sT_w}{1 + sT_w} \frac{1 + sT_1}{1 + sT_2} \frac{1 + sT_3}{1 + sT_4}$$
(4.2)

where,

Ks: stabilizer gain

 T_w : parameter of washout filter

 T_1, T_2, T_3 , and T_4 : parameters of lead-lag filters

For simplicity the second lead-lag stage will be taken to be similar to the first one. The overall controller transfer function can then be represented by:

$$U = K_{s} \frac{sT_{w}}{1 + sT_{w}} \frac{\left(1 + \frac{\sqrt{\gamma}}{\sigma}s\right)^{2}}{\left(1 + \frac{1}{\sigma\sqrt{\gamma}}s\right)^{2}}$$
(4.3)

From the viewpoint of a washout function, the precise value of the associated time constant T_w is not critical. The main consideration is that it should be small enough so that stabilizing signals at the frequencies of interest will be relatively unaffected [10]. For this reason, it is considered to be a known parameter. As a result we are left with Ks, σ , and γ to be the parameters that should be determined by the tuning procedure. In this work those parameters are tuned using a Guided Particle Swarm Optimization technique [7]. The optimization Fitness Function (FF) used for the PSS design is given by (3). In [7], [30] the parameters are tuned based on damping of linearized models at selected operating conditions to achieve better robustness. The linearized models are obtained for small disturbance in systems with different load(s) changes and/or loss of line(s). Such procedures require a computation of effort in terms of obtaining the linearized models and cannot consider large disturbances during the linearization process. The latter will not assure the robustness of the designed controller. The controller parameters are tuned using GPSO technique as described in Chapter 3.

4.3.3 Case Study: IEEE 37 Node Feeder with a Microturbine and a SOFC.

The IEEE 37 Node distribution test Feeder is selected for this study and the average balanced single-phase system is obtained from an unbalanced three-phase system. Table 4.5 presents the PSO parameters. During the search procedures as explained before, GPSO constraints in this case are the microturbine's speed deviations and relative rotor angle. The controller's parameters are tuned with speed deviations to be bounded as

shown in Figure 4.16 while the rotor angle is limited between the upper and the lower bounds of 200 degrees. Equation (4.4) presents the optimization performance index used in this study.

I AKTICLE SWARM OF HIMIZATION TECHNIQUE I ARAMETERS								
Bounds	$K_{s \min}$	K _{s max}	γ_{min}	γ_{max}	C	5 _{min}	σ_{max}	
	0	400	0.1	10		1	12	
W	C_1 (C ₂					
	2 2.01		2.01					
Nun		:	50					
Maximum # of unchanged solution				10				
Maximum # of iterations						50		

 TABLE 4.5

 PARTICLE SWARM OPTIMIZATION TECHNIQUE PARAMETERS



Figure 4.16: The GPSO Speed Deviation Constraint

min
$$J = \sum_{i} \left(\int_{0}^{t} (|\Delta \omega_{i}| + |\Delta \delta_{i}|) dt \right)$$

subject to control constraints:
 $K_{sj_{min}} \leq K_{sj} \leq K_{sj_{max}}$
 $\gamma_{jmin} \leq \gamma_{j} \leq \gamma_{jmax}$ (4.4)
 $\sigma_{jmin} \leq \sigma_{j} \leq \sigma_{jmax}$
state variables constraints:
 $\Delta \omega_{imin} \leq |\Delta \omega_{i}| \leq \Delta \omega_{imax}$
 $\delta_{imin} \leq \delta_{i} \leq \delta_{imax}$

where,

 K_s , γ . and σ : are controller parameters.

 $\Delta \omega$: microturbine speed deviation [GPSO constraint]

δ: microturbine power angle [GPSO constrain]

Two scenarios are given below to demonstrate the effectiveness of the proposed control using the IEEE 37 Nodes Feeder as shown in Figure 4.11, where a 240 kW microturbine and a 100 kW SOFC are connected to buses #11 and #13, respectively. The total loading of this feeder is 819 kW. At steady state, DGs provide 42% of the total load. In the first scenario, a three-phase to ground fault occurs near bus #4 at t = 0.1 sec and is cleared at t = 0.12 sec and the second one occurs near bus #30 at t = 0.1 sec and is cleared at t = 0.15 sec. The proposed control algorithm is implemented and nonlinear simulations are performed for the following cases:

- 1. Open-loop, when there is no controller for both the FC and the microturbine. (Solid lines)
- Closed-loop, when power and voltage controllers are added to the FC as well as PSS to the microturbine. (Dashed lines) Figures 4.17, 4.18 and 4.19 show the microturbine relative angle, output voltage and active power output of the microturbine. Figure 4.20 shows the Active power outputs of the Fuel cell and the Substation.
- Case 1, Fault near bus #30:

When there is no controller, simulations stop because of active and reactive power mismatch resulting in an unstable system. Dashed lines demonstrate the effectiveness of the proposed control scheme.





Figure 417: The MT Generator Rotor Angle (deg)









Figure 4.19: The Active Power Outputs of The MT



Figure 4.20: The Active Power Outputs Of The Fuel Cell and The Substation

• Case 2 Fault near bus #4:

Another scenario is presented for the case where the fault location is closer to the DGs. Both open loop and closed loop results are compared. Proposed controllers are

tuned and stability of the system is achieved; however, these oscillations are more severe than the previous scenario for both with and without DG controllers.



Figure 4.21: The MT Generator Rotor Angle (Deg)









Figure 4.23: The Active Power Outputs of the MT

This can be summarized as follows:

- Condition # 1: an unstable system and the simulation crashes, related to fact that during reconnection of the FC, the FC's inverter needs a proper controller in order to be synchronized with the grid.
- 2. Condition # 2: an unstable microturbine power angle but the power supply can be restored because proper controllers have been designed for the FC.
- 3. Condition # 3: a stable system, both the FC reconnection controllers and the microturbine's PSS are designed and implemented.

4.4. Multi-Agent Based Controller Design

The transient stability problem of dispersed DGs is one of the main distributed generators' integration barriers. On the other hand, these DGs can be used as control paths to overcome this, and many other problems. It has been found that conventional fixed structure controllers are not suitable to control DGs in such a complex environment. This section will explain the implementation of the developed MAS control architecture, presented in Chapter 3, to solve the stability problem of DGs during large disturbances in the system. The presented case studies show a distribution feeder with two and three microturbines as DGs. Each microturbine is equipped with a LCA attached to a PSS and a GCA as a supervisory agent at the substation of the PSS at each microturbine. These features will help to control the DGs in a flexible and automated manner. The simulation results of selected cases are presented to demonstrate the robustness of the proposed control system.

4.4.1. IEEE 37 Feeder with two Microturbines.

The IEEE 37 Node distribution test Feeder with two microturbines as distributed generators is selected to implement the proposed MAS control algorithm. The average balanced single-phase IEEE 37 Node Feeder is obtained from an unbalanced three-phase system [8]. As shown in Figure 4.24, the microturbines rated 160 kW and a 240 kW are connected to buses # 13 and # 36, respectively. The total loading of this feeder is 819 kW. The microturbines provide about 49% of the total load. They are equipped with a Power System Stabilizer (PSS). The PSS parameters are tuned using GPSO, as presented in Chapter 3. If a large disturbance takes the system far from the operating condition used to tune the controllers, this could have a negative impact and would be no longer effective, or even harmful. However, with the proposed MAS based controller, such an issue is no longer a problem. The objective here is to use the MAS based control algorithm to enhance the transient stability of the distribution network.

A. GPSO Setting.

The coordination and learning section in the GCA is equipped with Guided Particle Swarm Optimization [84] to tune microturbine's controller. Table 4.6 presents the PSO

parameters. During the search procedures, as explained before, GPSO constraints in this case are the microturbine's speed deviations and rotor angle. The controllers are tuned with speed deviations to be bound as shown in Figure 4.25 while the rotor angle is limited between upper and lower bounds of 200 degrees. Equation (4.5) presents the optimization performance index used in this study.



Figure 4.24: The IEEE 37 Node Feeder with Two Microturbines

PARTICLE SWARM OPTIMIZATION TECHNIQUE PARAMETERS								
Bounds	$K_{s min}$	$K_{s max}$	$\gamma_{ m min}$	γ_{max}	σ_{min}	σ_{max}		
		40.0	0.4	10		10		
	0	400	0.1	10	1	12		
Weighting factors				C1		C_2		
		2		2.01				
Nun			50					
Maximum # of unchanged solution				10				
Maximum # of iterations					50			

 TABLE 4.6

 PARTICLE SWARM OPTIMIZATION TECHNIQUE PARAMETERS

min J =
$$\sum_{i} \left(\int_{0}^{t} (|\Delta \omega_{i}| + |\Delta \delta_{i}|) dt \right)$$

subject to control constraints:
 $K_{i\min} \leq K_{i} \leq K_{i\max}$ (4.5)
state variables constraints:
 $\Delta \omega_{i\min} \leq |\Delta \omega_{i}| \leq \Delta \omega_{i\max}$
 $\delta_{i\min} \leq \delta_{i} \leq \delta_{i\max}$

where,

Ki represents the controller parameters Ks, γ , and σ .



Figure 4.25: The GPSO Speed Deviation Constraint [2MT]

B. NN Setting.

The MATLAB Neural Network toolbox is used in this analysis as a part of the GCA coordination and learning NN training section to update the LCAs networks with any new reported disturbance. The following MATLAB functions are used for this purpose:

 \Rightarrow newff: to create a feed-forward backpropagation network.

\Rightarrow train: to train a neural network.

Table 4.7 presents the NN training section parameters. A MATLAB m-file is written to collect training data from PAT simulations for all possible three-phase-to-ground fault locations in the test system. The voltage magnitude at microturbine's terminal is selected to be the collected training data. The trained network has been tested and has proven the ability to classify all possible faults and map them with the proper setting of the microturbine's controller.

Backpropagation network description	Parameters
Training performance function	sse (Sum-Squared Error)
Training parameter goal	0.1
# of hidden layers	3
# of neurons in hidden layers	[200 300 200]
# of neurons in output layer	22
Transfer function	logsig (in all layers)
training function	traingd
Maximum number of epochs to train	100000
Momentum constant	0.95
Minimum performance gradient	1e-10

 TABLE 4.7

 The NN Backpropagation Training Parameters

C. Case Study: IEEE 37 Node Feeder with two Microturbines

Three scenarios are given below to demonstrate the effectiveness of the proposed MAS control algorithm using the IEEE 37 Node Feeder as shown in Figure 4.24. In the first scenario, Figure 4.26: a three phase-to-ground fault occurs near bus # 30, far from DGs, at t = 0.1 sec and is cleared at t = 0.2 sec. The second scenario, Figure 4.27: a three phase-to-ground fault occurs near bus # 1, close to the main substation, at t = 0.1 sec and is cleared at t = 0.15 sec. The third scenario, Figure 4.28: a three phase-to-ground fault occurs near bus # 10, close to DGs, at t = 0.1 sec and is cleared at t = 0.15 sec.

• Scenario 1, *The Fault near bus #30:*



Figure 4.26: A Three-Phase to Ground Fault between Line 30-31.





Figure 4.27: A Three-Phase to Ground Fault between Line 1-2

Scenario 3, The Fault near bus # 10:



Figure 4.28: A Three-Phase to Ground Fault between Line 10-11

The proposed control algorithm is implemented and nonlinear simulations are performed for the following cases:

- A disturbance occurred and there is no suitable controller available in the database for both microturbines. LCAs disconnect the microturbines and send a LES to the GCA, which generates or designs controllers for this specific disturbance and updates the LCAs NN. [No suitable controller is found].
- A disturbance occurred, was classified by NN and LCAs adapted the controller to cope with the disturbance, both local and global goals are satisfied [the LCA found suitable controller].

The simulation software, PAT, prevents multiple simulations of the disturbances at a time. In all the three simulated scenarios, system stability is achieved using the proposed algorithm.

4.4.2. IEEE 37 Node Feeder with three Microturbines.

Another implementation of the developed control algorithm is described in this section for the IEEE 37 Node distribution test Feeder with three microturbines. As shown in Figure 4.29, the microturbines rated 160 kW are connected to buses # 6, # 12 and # 15, respectively. The microturbines are scheduled to provide about 45% of the total load. Similar to the previous case, microturbines are equipped with a Power System Stabilizer (PSS). Each microturbine is equipped with a LCA and interconnected to a GCA, which is located at the substation. The control algorithm will follow the procedures presented in Chapter 3.

A. GPSO Setting.

The coordination and learning section in the GCA is equipped with GPSO to tune the microturbine's controller. The PSO parameters are similar to those present in Table 4.6. GPSO constraints in this case are the microturbine's speed deviations, rotor angle and microturbine's terminal voltage. The controllers are tuned with speed deviations and terminal voltage to be bound as shown in Figure 4.30 and Figure 4.31, respectively. The rotor angle is limited between upper and lower boundaries of 200 degrees. Equation (4.6) presents the optimization performance index used in this case.



IEEE 37 node Feeder

Figure 4.29: The IEEE 37 Node Feeder with Three Microturbines

min
$$J = \sum_{i} \left(\int_{0}^{t} \left(|\Delta \omega_{i}| + |\Delta \delta_{i}| \right) dt \right)$$

subject to control constraints:
 $K_{i\min} \leq K_{i} \leq K_{i\max}$ (4.6)
variables constraints:
 $\Delta \omega_{i\min} \leq |\Delta \omega_{i}| \leq \Delta \omega_{i\max}$
 $\delta_{i\min} \leq \delta_{i} \leq \delta_{i\max}$
 $V_{ti\min} \leq V_{ti} \leq V_{ti\max}$

where,

 K_i represents the controller parameters K_{si} , T_{wi} , T_{1i} , T_{2i} , T_{3i} , and T_{4i} . $\Delta \omega$, δ and V_t are the microturbine: shaft's speed deviations, power angle and terminal voltage, respectively.



Figure 4.30: The GPSO Speed Deviation Constraint [3 MT]

B. NN Setting.

The microturbine's terminal voltage magnitude is selected to be the collected training data. The trained network has been tested and has proven the ability to classify all possible faults and map them with proper settings of microturbine controller. The NN training section parameters are similar to those presented in Table 4.7.



GPSO Terminal Voltage Constraint

Figure 4.31: The GPSO Terminal Voltage Constrain [3 MT]

C. Case Study: IEEE 37 Node Feeder with three Microturbines

Three scenarios are presented below to demonstrate the effectiveness of the proposed MAS control algorithm using the IEEE 37 Node Feeder as shown in Figure 4.29. In the first scenario, Figure 4.32: a three phase-to-ground fault occurs near bus # 1, close to main substation, at t = 0.1 sec and is cleared at t= 0.2 sec. The second scenario, Figure 4.33: a three phase-to-ground fault occurs near bus # 4, isolates microturbines #1 and #2, at t = 0.1 sec and is cleared at t= 0.2 sec. The third scenario, Figure 4.34: a three phase-to-ground fault occurs near bus # 8, isolates microturbine # 2, at t = 0.1 sec and is cleared at t= 0.2 sec.

• Scenario 1, *The Fault near bus #1*:







Figure 4.32: A Three-Phase to Ground Fault between Line 1-2[3MT]

• Scenario 2, *The Fault near bus # 4:*



3-Phase to Ground Fault between Line4-5 cleared in 100 msec [Measured at MT # 2]



Figure 4.33: A Three-Phase to Ground Fault between Line 4-5 [3MT]

Scenario 3, The Fault near bus # 8:

-0.5 L 0

0.5

1.5

1

2



Time [sec.] Figure 4.34: A Three-Phase to Ground Fault between Line 8-9 [3MT]

2.5

3

3.5

4.5

5

4

In all scenarios, system stability is achieved using the proposed algorithm. The simulations show the microturbines' performance for the following cases:

- Disturbance occurred and there is no suitable controller available in the database for the microturbines.
- Disturbance occurred, was classified by NN and LCAs adapted the controllers to accommodate the disturbance.

The simulation software, PAT, prevents multiple simulations of the disturbances at a time. However, it is clear that the proposed control algorithm extends the operating range of the conventional microturbines' controllers, PSS. It was impossible to tolerate such disturbances without adapting the setting of the controllers.

4.5. Evaluation of the Multi-Agent Based Controller

The developed control algorithm is evaluated in this section by running multiple simulations with different loading conditions and different clearing time. Equation (4.7) is used as measure to compute the local control agent's performance index.

$$J_{LCA} = \sum_{i} \left(\int_{0}^{t} \left(\Delta \omega_{i}^{2} \right) dt \right)$$
(4.7)

Fault	Load	Fault	Clearing	LC	LCAs Found		
Type	Change		Time	(Controlle	er	
51	C C			LCA ₁	LCA ₂	LCA ₃	
Fault A	+10 %	-	-	Yes	Yes	Yes	
Fault B	-	3-Phase-Ground L12	100 msec	Yes	Yes	Yes	
Fault C	+10 %	3-Phase-Ground L12	100 msec	Yes	Yes	Yes	
Fault D	+10 %	3-Phase-Ground L12	100 msec	NO	Yes	Yes	
Fault E	+10 %	3-Phase-Ground L12	100 msec	Yes	NO	Yes	
Fault F	+10 %	3-Phase-Ground L12	100 msec	Yes	Yes	NO	
Fault G	+10 %	3-Phase-Ground L45	120 msec	Yes	Yes	Yes	
Fault H	+10 %	3-Phase-Ground L45	120 msec	NO	Yes	Yes	
Fault I	+10 %	3-Phase-Ground L45	120 msec	Yes	NO	Yes	
Fault J	+10 %	3-Phase-Ground L45	120 msec	Yes	Yes	NO	
Fault K	+10 %	3-Phase-Ground L89	150 msec	Yes	Yes	Yes	
Fault L	+10 %	3-Phase-Ground L89	150 msec	NO	Yes	Yes	
Fault M	+10 %	3-Phase-Ground L89	150 msec	Yes	NO	Yes	
Fault N	+10 %	3-Phase-Ground L89	150 msec	Yes	Yes	NO	

TABLE 4.8 Agents' Evaluation Fault Type

Fault Type	LCA ₁		LCA_2		LCA ₃		
	J _{LCA}	LES	J _{LCA}	LES	J _{LCA}	LES	
Fault A	0.0000076	OFF	0.0002692	OFF	0.0000587	OFF	
Fault B	0.0132	OFF	0.0041	OFF	0.0029	OFF	
Fault C	0.0244	OFF	0.0114	OFF	0.0099	OFF	
Fault D	0.2124	OFF	0.0199	OFF	0.0255	OFF	
Fault E	0.0253	OFF	0.4549	ON	0.0912	OFF	
Fault F	0.0085	OFF	0.0128	OFF	0.3215	ON	
Fault G	0.0191	OFF	0.0100	OFF	0.0100	OFF	
Fault H	0.1872	OFF	0.0199	OFF	0.0165	OFF	
Fault I	0.0301	OFF	0.1230	OFF	0.0150	OFF	
Fault J	0.0129	OFF	0.0264	OFF	1.3723	ON	
Fault K	0.0197	OFF	0.0107	OFF	0.0077	OFF	
Fault L	0.1793	OFF	0.0203	OFF	0.0125	OFF	
Fault M	0.0287	OFF	0.1144	OFF	0.0151	OFF	
Fault N	0.0139	OFF	0.0299	OFF	1.8337	ON	

TABLE 4.9 LOCAL CONTROL AGENTS' EVALUATION

The system presented in Figure 4.29, IEEE 37 Node distribution test Feeder with three microturbines, is selected to run this evaluation. The three microturbine's prime-movers controllers are designed as presented in section 4.2.3 and the microturbine's generators are designed as presented in section 4.4.2. Several types of disturbances are selected to test the system and compute the performance index including different loading conditions, different fault locations with different clearing times as presented in Table 4.8. The results are presented in Table 4.9 as well as in Figure 4.35. The objective is to keep J_{LCA} to as minimal as possible. The results can be summarized as follow:

- During load changes only, +10%, Fault A: the LCA did not take any action since there is no detection of a large disturbance and the system is running stable.
- During large disturbances, J_{LCA} value depends on the fault location, fault's clearing time, ability of the LCA to detect and apply the proper setting of the controller.
- The highest J_{LCA} is recorded to the LCA with the LES, again the J_{LCA} value increased as the fault clearing time increased and as the fault closer to microturbine.
- In some cases like Faults E, F, J, and N; one of the LCA is generating a LES to the GCA. The associated DG is disconnected from the grid while the other DGs are still in service.



Figure 4.35: The Local Control Agents Evaluation during Selected Faults
Chapter 5

Electric Power System of an All Electric Naval Ship

5.1. Introduction

An All-Electric Naval Ship (AENS) is a modern warship where everything aboard, from fire pumps to the sophisticated weapons systems and computer networks, is operated by electric power [55]. Besides the warship and sophisticated electric operated weapons, the all-electric ship operated system adds other benefits that can be summarized as follows:

- The assembly of the ship will be easier, because of a greater modularity of electrical operated equipment.
- The cost of substituting new technology (new modules) into existing systems will be reduced with electrical interface.
- Electrical power sources and loads are easy to interface to a common power distribution system. This enables commonality of equipment across platform types and with the industrial world.
- The number of prime movers can be less than in the case of separate propulsion and generation, still maintaining the same level of redundancy. The number of prime movers running can be minimized, operating them at their most efficient point. This will result in maintenance cost reduction, fuel savings and emission reductions.
- Improved survivability, automation and reduced maintenance (less mechanical components) will result in reduced manning cost.

However, besides all of the benefits mentioned above for AENS, many open questions are still under investigation from the electrical power engineering point of view; examples are:

 The study of different AENS configurations: the number of prime movers, an AC or DC network.

- Power management strategies; integrated monitoring and control systems; new power generation methods.
- The stability of the AENS power system during faulty condition or large disturbances.
- The application of decentralized power generation and energy storage.
- The survivability of the AENS through improvement of power system network.
- The electromagnetic interference inside an AENS and electromagnetic compatibility measures.

Similar to a civilian power system, the naval ship power system may experience stability problems during large disturbances due to battle damage or material casualty. The survivability of the AENS is related somehow to the stable operation of the AENS power system during and after such disturbances. Considerable system survivability improvements may be achieved with modest control of the AENS power system.

This chapter will discuss another implementation of the developed multi-agent system (MAS) based control concept for AENS power system in order to enhance the transient stability during large disturbances in the system. First, a brief description of the AENS power system is presented and followed by a problem formulation. Then, the proposed structure of the MAS based controllers is discussed later.

5.2. All-Electric Naval Ship

The new warship system is changing to be fully electric system in order to reduce manning and cost operation by replacing mechanical-hydraulic systems with electric solutions. Moreover, such change is expected also to improve the reliability and survivability of the system. The circuit diagram of shipboard power system is shown in Figure 5.1. The system has two main three-phase synchronous generators driven by gas turbines and providing the power to the two kinds of AC loads and a DC distribution system. The AC loads are two propulsion induction motors serving as prime-movers to the ship and two pulsed loads. The DC distribution testbed is fed by two AC sources. The AC is converted to DC for distribution by two DC buses, the port-bus and starboard-bus, to the load centers. To improve the survivability of the system, different zones are formed and fed from each of the buses by additional DC/DC converters. This allows a certain redundancy as well as graceful performance degradation as the converters are used to

actively limit currents and can be used to isolate faulty loads or entire parts of the system. The converters can be operated to supply loads from either or both buses and to switch continuously between them. The three zone loads are a mix of constant impedance and constant power load [56].

The main function of a shipboard's electrical power system is to maintain the availability of energy to all the connected loads in order to keep all systems and equipment operational. When there is a fault in a shipboard power supply (PS) due to battle damage or material casualty, only the smallest portion of the system should be interrupted. It is important to quickly isolate the faulted portion and continuously supply power to as many loads as possible.



Figure 5.1: The Electric Power System Diagram Of All-Electric Naval Ship.

5.3. Problem Formulation

The concept of all-electric war ship is a transition of the current hydro-mechanical systems in which all energy consumers in the ship (including, but not limited to, propulsion load, weapons and sensor system, and actuators) use electricity as their energy source. Such a concept will lead to a more flexible and automated operation of the

system. This automated system requires dependable, integrated control to dynamically and efficiently stabilize the system during disturbances. This requirement is critical during the major disruptions associated with battle and damage control operations.

The AENS power system are integrated AC and DC circuits, as described in the pervious section. The DC distribution testbed is fed by two power converters or as noted in the figure as power sources. The loads within the DC distribution system are interfaced via Ship Service Converter Module (SSCM). In the same way, the other two loads, the propulsion induction motor and pulsed load, are interfaced via power converters and a DC-link. Faults between the converter module and diode are mitigated by imposing current limits on the converter modules; and again the bus opposite the fault can supply the component. Finally, faults within the components are mitigated through the converter module controls. The result is a highly robust system [58]. Since both circuits, AC and DC, are completely decoupled, our attention will be limited to investigating the stability of the AC circuit alone. The AENS loads can be represented as constant power loads. Figure 5.2 represents the online circuit diagram of the AENS AC circuit power system.



Figure 5.2: The Online Diagram of the AENS AC/DC Circuit Power System

The AC circuit of the AENS power system consists of two gas turbine generators rated 59 kW each, two 37 kW propulsion induction motors that work as AENS prime-movers, and a DC distribution system is represented by a 13 kW constant power load. The DC-link or DC-distribution network decouples both sides of the AENS AC circuits; Figure 5.3 describes one side of the separated AC network.



Figure 5.3: One Side of the AENS AC Circuit Power System

Similar to a civilian power system, the AC network of the naval ship power system may experience stability problems during faulty conditions or large disturbances. The next section will discuss an implementation of the developed multi-agent system (MAS) based control concept for AENS power system in order to enhance the transient stability during large disturbances in the system.

5.4. MAS Based Controllers for AENS

This section will describe briefly an implementation of the developed MAS based control concept to enhance the transient stability problem of the AENS power system during large disturbances. As illustrated in the previous section, the AENS power system has two synchronous generators driven by gas turbines. During fast disturbances such as a short circuit fault, the gas turbine mechanical power controllers will be slow and of no interest. On the other hand, fast action can be taken through the generator excitation control system. In this section, a Power System Stabilizer (PSS) of fixed-structure type is used as a damping controller in the excitation control loop. The basic function of the PSS

is to add damping to the generator rotor oscillations by controlling its excitation using an auxiliary stabilizing signal. Similar to a microturbine, this PSS uses a generator's shaft speed deviation as input. The stabilizer itself consists mainly of a stabilizing gain, washout stage and two lead-lag filters similar to Figure 4.12. These are used to compensate for the phase lag introduced by the Automatic Voltage Regulator (AVR) and the field circuit of the generator, and are tuned so that speed oscillations give a positive damping torque on the rotor.



Figure 5.4: The Schematic Diagram Of AENS MAS Based Controller

Again the problem of conventional fixed-structure controller emerges; if a large disturbance occurs, the PSS could have a negative impact to the AENS power system and would no longer be effective. However, with the developed MAS based controller, such an issue is no longer a problem. The main target here is to apply the MSA based control algorithm to eliminate the PSS limitations and enhance the transient stability of the AENS power system. Each gas turbine generator is equipped with a local control agent (LCA) and the global control agent (GCA) is connected to both LCAs, Figure 5.4. The agents will follow the structure and decision process as presented in Chapter 3.

Upon the implementation of the new control structure, it will: adapt the PSS setting to any possible disturbance, add the self-learning ability to control system and end up with a more robust system, and fast control action will be taken in a decentralized manner by local control agents. Such a control algorithm is expected to guarantee stable operation of the AENS power system.

5.4.1. Case Study: AENS Power System

The one side AC circuit of the AENS system, Figure 5.3, is implemented in the Power Analysis Toolbox. Figure 5.5 presents the gas turbine model developed by Rowen [86]and [87]. The model is implemented in PAT and used in this simulation as the generator's prime mover. The subtransient generator model, excitation system and electric loads are imported from the PAT library and the models' parameters are presented in Appendix F. The MAS based controller algorithm is applied to the AENS system as described in Chapter 3.



Figure 5.5: The AENS Gas Turbine Mode in PAT

A. GPSO Setting.

The coordination and learning section in the GCA is equipped with GPSO to tune the AENS generator controller. The PSO parameters are similar to those presented in Table 4.6. GPSO constraints in this case are the generator speed deviations, rotor angle and generator terminal voltage. The controller is tuned with speed deviations and terminal voltage to be bound similar to those shown in Figure 4.30 and Figure 4.31,

respectively. The rotor angle is limited between upper and lower boundaries of 200 degrees. Equation (5.1) presents the optimization performance index used in this case.

min
$$J = \int_{0}^{t} (|\Delta \omega| + |\Delta \delta|) dt$$

subject to control constraints:
 $K_{i\min} \le K_i \le K_{i\max}$ (5.1)
variables constraints:
 $\Delta \omega_{\min} \le |\Delta \omega| \le \Delta \omega_{\max}$
 $\delta_{\min} \le \delta \le \delta_{\max}$
 $V_{t\min} \le V_{ti} \le V_{t\max}$

where,

 K_i represents the controller parameters K_s , T_w , T_1 , T_2 , T_3 , and T_4 .

 $\Delta \omega$, δ and V_t are the generator: shaft speed deviations, power angle and terminal voltage, respectively.

B. NN Setting.

The AENS generator terminal voltage magnitude is selected to be the collected training data. The trained network has been tested and has proven the ability to classify all possible faults and map them with proper settings of generator controller. The NN training section parameters are similar to those presented in Table 4.7.

C. Case Study: AENS

Two scenarios are given below to demonstrate the effectiveness of the proposed MAS control algorithm to enhance the stability of the AENS power system. In the first scenario: a three phase-to-ground fault occurs near bus #1, close to the gas turbine generator, at t = 0.1 sec and is cleared at t = 0.2 sec. The system response of this fault is shown in Figure 5.6. The second scenario: a three phase-to-ground fault occurs near bus # 3, close to the propulsion load, at t = 0.1 sec and is cleared at t = 0.2 sec. The system response of this fault is shown in Figure 5.7.





Figure 5.6: The AENS Response During 3-Phase-To-Ground Fault At Bus #1

• Scenario 2, The Fault near bus #3:



Figure 5.7: The AENS Response During 3-Phase-To-Ground Fault At Bus #3

Chapter 5: Electric Power System of an All Electric Naval Ship

The proposed control algorithm is implemented and nonlinear simulations are performed for the following cases:

- A disturbance occurred and there is no suitable controller available in the database for the generator controller, the PSS. LCAs disconnect the generator and send a LES to the GCA, which generates or designs a controller for this specific disturbance and updates the LCAs NN. The AENS is powered by the second generator.
- A disturbance occurred, was classified by NN and LCAs adapted the controller to cope with the disturbance, both local and global goals are satisfied [LCA found suitable controller].

In both scenarios, system stability is achieved using the proposed algorithm.

Chapter 6

Conclusion

This research presents a novel control architecture based on a multi-agent system (MAS) to enhance the transient stability of power distribution systems. The study investigates the impact of distributed generators (DGs) integration in a power distribution system. Such analysis requires proper modeling of the system and a suitable simulation package. The Power Analysis Toolbox (PAT) [51] is used in this study as a simulation environment. Two types of DGs are investigated, namely; Microturbines (MT) and Solid Oxide Fuel Cells (SOFC) [8]. The dynamic model of the microturbine is developed and presented in [12] and [16]. The Particle Swarm Optimization (PSO) technique is implemented and used to design microturbines' conventional controllers [7]. A new technique based on PSO called Guided Particle Swarm Optimization (GPSO) is developed to improve the DGs controllers' design; this technique is presented in [8] and [84]. However, the limitation of the conventional controllers does not satisfy the stability requirement of a power distribution system that has a high DG penetration level, which imposes the necessity of developing a new control structure able to overcome the fixed structure conventional controller's limitations and enhance the overall transient stability of the distribution system. The developed MAS based control architecture is implemented to control distributed generators in a power distribution system [52] and [85]. Finally, the concept of MAS based control architecture is described for an all-electric naval ship (AENS) power system to enhance its transient stability during faulty conditions.

In order to achieve this research's objectives, this dissertation contributes to the development of the following:

- Modeling of a microturbine as a Distributed Generator.
- An optimization technique for controller design, called here Guided Particle Swarm Optimization (GPSO).
- A Multi Agent System based control architecture.

Specifically, first, the parallel operation of microturbines as DGs is investigated. A

Chapter 6: Conclusion

load following controller is proposed to control the motive force of the microturbine prime mover according to the load changes. This can be accomplished by increasing or decreasing the fuel flow or the fuel valve positioning. The controller consists of proportional and integral controls with anti-reset windup loop. The input to the controller is the deviation of the generator real output power from the set or reference point and produces an output control signal to the prime mover. The controller parameters are tuned using GPSO. The simulation of three microturbines with the proposed controller installed in an IEEE 37 node distribution feeder showed satisfactory results. Both microturbines are controlled to match the scheduled generating power during different tested load changes. In addition, the system oscillations during load changes are eliminated or reduced and smooth transitions have been achieved.

Second, the effects of DGs, mainly a SOFC and a microturbine, on the stability of a test distribution system due to large disturbances have been presented. The effects shown are damage to the fuel cell and instability in the system. To mitigate these behaviors, control actions and designs are presented using the average balanced single-phase IEEE 37 node distribution feeder and including a FC and a microturbine. A primarily nonlinear simulation of a three-phase to ground fault at any node in the system resulted in loss of synchronism for the microturbine generator and damaged fuel cell stacks. As a result, proper control action(s) are required. The following control design has been proposed to alleviate:

- 1. Disconnection of the FC during the disturbance.
- 2. Reconnection of the FC after clearing the disturbance with proper synchronization controller(s).
- 3. The PSS design of the microturbine generator to stabilize the overall system.

The control parameters are designed using the developed Guided Particle Swarm Optimization (GPSO) technique with a proposed fitness function. The control algorithm has been implemented and simulation results show promising results for the control of the DGs. Based on the nonlinear simulation results, the amount of load and distance between the disturbance and DGs are the main factors to be considered during the design stage. For example, the disturbance clearing time should be shorter when the disturbance is closer to the DG.

Chapter 6: Conclusion

Finally, the intelligent agent approach as a novel control algorithm to DGs is developed and implemented. The control approach has distributed local control agents and a global control agent. The functions and integration of both types of agents have been described. Each Local Control Agent (LCA) will try to keep the associated DG in service (local goal) according to local operation restrictions. It will also try to regulate the overall system (global goal) according to given set-points, which are stored locally in the data base. If a particular agent fails to satisfy the local goal, the associated DG gets disconnected from the grid and the local load is now supplied from that DG. The Local Emergency Signal (LES) will be initiated and sent to the Global Control Agent (GCA). The remaining agents will try to adapt themselves to the new situation. The GCA will conduct an off-line GPSO search to design new controller settings as well as Neural Network (NN) training considering the failure situation and will pass them to LCAs via the information base. Then, a restoration of the disconnected DG will be processed (selfhealing). If the global goal is violated, a Global Emergency Signal (GES) will be initiated. All DGs get disconnected from the grid while loads will have the main substation as the sole source of power. Again the GCA will conduct an off-line learning optimization and training. The system is ready either for manual or automated DG restoration. The IEEE 37 node distribution feeder with two and three microturbines as a distributed generator has been used to illustrate the proposed method. The simulation results demonstrate the effectiveness of the proposed algorithm; system stability is achieved autonomously for all tested cases.

The above summary describes the implementation of multi-agent approach to the control of distributed generators. The algorithm can be applied regardless of the number or type of DGs. It has the ability to self-learn, so after adequate training, the system should reach a high level of robustness. The MAS based control architecture, while extending the controllers' range of operation; keeps the basic conventional control structure. Another advantage of this approach is that it is not unique and accepts add-on tasks and depending on system complexity, other features may be added.

The local control agents of the developed MAS control architecture are evaluated with a proposed performance index. The evaluation results can be used to improve the performance of these agents by introducing a penalty and reward mechanism. Similarly, the concept of MAS based control architecture is described to enhance the transient stability of the AENS power system. The AENS power system has two synchronous generators driven by a gas turbine. Each gas turbine generator is equipped with a LCA and interconnected to a GCA. The agents followed the structure and decision process as described in Chapter 3. The simulation results showed stable operations of the AENS power system.

While the proposed MAS architecture has been successfully applied to the test systems given in this dissertation, more work is needed to take full advantage of this method and to demonstrate that it can handle a wide range of control problems. The following extensions of this work are suggested:

- Use the MAS architecture to include agents that will have as an objective a load following task.
- Use agents for both Automatic Voltage Regulator (AVR) loop and Power System
 Stabilizer (PSS) for microturbine and other DG controllers.
- Coordinate a number of various types of agents, i.e. agents with different objectives.
- Demonstrate that MAS is an effective control structure for a system with a large number of DGs and/or different types of DGs with various control tasks such as load following, stability enhancement, voltage profile, etc.
- Develop a mechanism to evaluate the performance of each control agent thru rewards and penalties.

Appendix A

Publications

This research so far has been presented at several conferences and published in the corresponding proceedings. Each publication is given with its abstract and reference:

• Power System Stability Enhancement Using Backstepping Controller Tuned by Particle Swarm Optimization Technique.

Abstract: A method for designing controls through the excitation system and Particle Swarm Optimization technique to search for the optimal setting of the controller gains to improve transient stability and damping is presented. Simulation of multimachine power systems are performed to show the effectiveness of the proposed controller. Comparisons with two other control schemes namely (i) a voltage regulator combined with a power system stabilizer and (ii) excitation controls designed by using the Direct Feedback Linearization (DFL) technique are given to further benchmark the control scheme.

Reference: A. Karimi, A. Al-Hinai, , K. Schoder and A. Feliachi, "Power System Stability Enhancement Using Backstepping Controller Tuned by Particle Swarm Optimization Technique," *Proc. of IEEE Power Engineering General Meeting*, San Francisco, CA, June 12-16, 2005. [Submitted and accepted]

• Energy Management System with Automatic Reconfiguration for Electric Shipboard Power Systems.

Abstract: The automatic reconfiguration of electric shipboard power systems is an important step toward improved fight-through and self-healing capabilities of naval warships. The improvements are envisioned by redesigning the electric power system and its controls. This research focuses on a new scheme for an energy management system in form of distributed control agents. The control agents' task is to ensure supply of the various load demands while taking into consideration system constraints and load and supply path priorities. A self-stabilizing maximum flow algorithm is investigated to allow implementation of the agents' strategies and find a global

solution by only considering local information and a minimum amount of communication. A case study using the distributed agents within a multi-layer system architecture to function as energy management system is presented.

Reference: Ganesh, S. B., Schoder, K., Lai, H.-J., Al-Hinai, A., Feliachi, A., "Energy Management System with Automatic Reconfiguration for Electric Shipboard Power Systems," *EMPH Reconfiguration and Survivability Symposium*, Tallahassee, FL, February 2005

• Application of Intelligent Control Agents in Power Systems with Distributed Generators.

Abstract: This paper introduces the application of intelligent agents to the control and operation of distribution systems that contain distributed generators (DGs). The proposed control architecture is hierarchical with one supervisor that optimizes the overall process and a distributed number of local control agents associated with each DG. Control and protection actions need a fast reaction time and are taken by the control agents. They consist of fixed sets of parameters. Coordination, modifications of the criteria and parameters for the control and protection equipment, are performed at the control center. The proposed intelligent control agent based architecture is illustrated using a test system with two microturbines as DGs.

Reference: A. Al-Hinai and A. Feliachi, "Application of Intelligent Control Agents in Power Systems with Distributed Generators," *Proc. of IEEE Power Engineering Society's 2004 Power Systems Conference and Exposition (PSCE)*, NY, Oct. 2004.

• Stability Enhancement of a Distribution Network Comprising a Fuel cell and a Microturbine.

Abstract: The paper demonstrates that distributed generators, namely a fuel cell and a microturbine, could cause instability of electric power distribution systems following fault conditions. A control algorithm is then proposed to enhance transient stability in case of large disturbances. The control algorithm consists of (1) disconnecting the fuel cell during the fault, and (2) implementing fixed structure decentralized Solid Oxide Fuel Cell reconnection controllers and fixed structure decentralized Power System Stabilizer for the microturbine generator. The stabilizer parameters are tuned using a Swarm Optimization technique.

Reference: A. Al-Hinai, K. Sedghisigarchi, and A. Feliachi, "Stability Enhancement of a Distribution Network Comprising a Fuel cell and a Microturbine," *Proc. of IEEE Power Engineering General Meeting*, Denver, CO, June 6-10, 2004.

• Intelligent Agent Control Concept of Distributed Generators.

Abstract: Distributed Generators (DGs) can provide solutions to recent energy challenges as they provide either an alternative source of power or a complementary power to an existing electric power system. Hence, additional loads and peak demands could be supplied from DGs instead of expanding traditional power systems by building large generation stations and/or new transmission lines. However, as the number of DGs increase, i.e. the DG penetration level becomes significant, the power distribution system becomes more and more complex to operate and control because of the dynamic nature, size, number and location of the DGs. In this case, the distribution system instead of being a traditional system with one sub-station and loads, it becomes a complex dynamic system with distributed dynamic components whose interactions and controls will affect the reliability, availability and sustainability of the power delivered to the consumers. This paper introduces a new approach in addressing the control and operation of such a distribution system that has a number of DGs. The approach is to apply the theory of intelligent agents to a power distribution system that has a high DG penetration level. The proposed control architecture is hierarchical with one supervisor and a distributed number of control agents in the lower layer. Specifically, a central control center supervises and optimizes the overall process, while each DG is equipped with its own control agent. Operations, like switching and slow control tasks, are triggered by a human operator and executed in the control center. On the other hand, control and protection actions, which need a faster reaction time, are taken by the control agent. These actions are taken mostly with fixed sets of parameters. Coordination, modifications of the criteria and parameters for the control and protection equipment, are performed at the control center. Actions for the optimization of the system are mostly initiated manually through the centralized control system on the basis of predefined network control schedules and performance indices. The proposed intelligent control agent based architecture for operation of a power distribution system that has a high DG

penetration level is describes in this paper.

Reference: A. Al-Hinai and A. Feliachi, "Intelligent Agent Control Concept of Distributed Generators," *Proc. of First Baha Technical Meeting (BTM)*, Baha, Saudi Arabia, May 2004.

• Control of Microturbines in A Power Distribution System Using Particle Swarm Optimization.

Abstract: Microturbines connected to electric power distribution systems as distributed generators could be exposed to severe conditions following a disturbance or a change in operating conditions. Split-Shaft microturbine equipped with induction generator requires a source of reactive power such as a Static Var Compensator (SVC). In this case, the SVC could provide additional damping control. In this paper, this supplementary control enhancement is designed using a Particle Swarm Optimization (PSO) approach. A test system is given to illustrate the proposed methodologies.

Reference: A. Al-Hinai and A. Feliachi, "Control of Microturbines in A Power Distribution System Using Particle Swarm Optimization," *Proc. of 35th North American Power Symposium (NAPS)*, Rolla, Missouri, 2003.

• Control of Grid-Connected Split-Shaft Microturbine Distributed Generator.

Abstract: In this paper, a split-shaft microturbine model using induction generators is used to assist transient stability of microturbines when connected to the grid as distributed generator. Microturbines can be controlled via two paths, control of the turbine's mechanical power and control of terminal voltage from induction generator using connected SVC at the generator's terminal. PI controllers, for SVC and output turbine mechanical power are designed based on linearized model using genetic algorithms as optimization technique. Model development and simulation are presented within the MATLAB/ Simulink (Power System Analysis Toolbox (PAT)) environment using various toolboxes.

Reference: A. Al-Hinai K. Schoder and A. Feliachi, "Control of Grid-Connected Split-Shaft Microturbine Distributed Generator," *35th Southeastern Symposium on System Theory (SSST)*, March, 2003.

• Dynamic Model of a Microturbine used as a Distributed Generator.

Abstract: In this paper, a dynamic model of a microturbine, used as distributed generator, is developed. The model is suitable for transient analysis and simulation of an unbalanced three-phase power system. A microturbine unit consists of four parts: a gas turbine engine, a permanent magnet generator, a three-phase bridge AC to DC rectifier and a power DC to AC inverter. The proposed model is built from the dynamics of each part and their interconnections. To illustrate the proposed model, an unbalanced 3-phase system that consists of a microturbine generator connected to a load is simulated using Matlab Simulink Toolbox and Power System Blockset. **Reference:** A. Al-Hinai and A. Feliachi, "Dynamic Model of a Microturbine used as a Distributed Generator," *34th Southeastern Symposium on System Theory (SSST)*, March, 2002.

Appendix B IEEE-37 Distribution Feeder Data

IEEE TEST DISTRIBUTION SYSTEM DATA						
From	То	Resistance	Reactance	Bus	Active	Reactive
Bus	Bus	(Ohm)	(Ohm)	#	Power	power
					(kW)	(kVAr)
1	2	0.2978	0.2049	2	210	105
2	3	0.1545	0.1063	3	0	0
3	4	0.2125	0.1462	4	0	0
4	5	0.4420	0.2245	5	28	14
5	6	0.1473	0.0748	6	0	0
6	7	0.2357	0.1197	7	0	0
7	8	0.2357	0.1197	8	28	14
8	9	0.4125	0.2095	9	14	7
9	10	0.4715	0.2394	10	46	23
10	11	0.2947	0.1496	11	42	21
11	12	0.2947	0.1496	12	0	0
12	13	0.2947	0.1496	13	14	7
3	14	0.2591	0.1347	14	28	14
14	15	0.3831	0.1945	15	0	0
15	28	0.0589	0.0299	16	28	14
28	29	0.3831	0.1945	17	0	0
15	16	0.5893	0.2993	18	31	15
16	33	0.4420	0.2245	19	14	7
33	34	0.2063	0.1047	20	14	7
16	30	0.6777	0.3442	21	14	70
30	31	0.5599	0.2843	22	28	14
30	32	0.0884	0.0449	23	0	0
3	17	0.2947	0.1496	24	14	7
17	18	0.2357	0.1197	25	0	0
17	27	0.1768	0.0898	26	28	14
4	19	0.1768	0.0898	27	28	14
19	20	0.2063	0.1047	28	12	6
20	21	0.2063	0.1047	29	28	14
20	37	0.1473	0.0748	30	0	0
6	22	0.4420	0.2245	31	14	7
6	23	0.0001	0.0001	32	53	26
7	24	0.2357	0.1197	33	0	0
9	25	0.3831	0.1945	34	14	7
25	36	0.9429	0.4788	35	28	14
25	35	0.1473	0.0748	36	14	7
12	26	0.1473	0.0748	37	42	21

TABLE B.1

Appendix C

Microturbine Model in PAT



Figure C.1 Microturbine Model in PAT



Figure C.2 Microturbine's Controller [PSS]





Figure C.3 Microturbine's Prime-Mover Model



Microturbine Prime-Mover's Controller

Figure C.4 Microturbine's Prime-Mover Controller

WICKOTURBINE STRIME WOVER WODEL FARAMETERS			
N	Per unit turbine rotor speed.	p.u	
P _{in}	Controller output signal to		
	turbine.		
$W_{\rm F}$	Per unit fuel flow.	p.u	
P _{mech}	Turbine output mechanical power.	p.u	
Wmin	Minimum fuel flow.	0.23	
а	Valve positioner.	1	
b	Valve positioner.	0.05	
с	Valve positioner.	1	
$ au_{ m F}$	Fuel control time constant.	0.4 sec	
K _F	Fuel system feedback.	0	
E _{CR}	Combustion reaction time delay	0.01 sec	
$ au_{\mathrm{CD}}$	Compressor discharge volume	0.2 sec	
	time cons.		

 TABLE C.1

 MICROTURBINE'S PRIME MOVER MODEL PARAMETERS

TABLE C.2

MICROTURBINE	'S INDUCTION	GENERATOR	PARAMETERS
MICKUIUKDINE	SINDUCTION	UENEKATUK	IANAMETERS

	Rated Power.	250 kW		
Н	Inertia.	8.22 sec		
X _{ls}	Leakage reactance of the stator.	$0.07620 \ \Omega$		
X _{lr}	Leakage reactance of the rotor referred to	0.23289 Ω		
	stator windings.			
X _m	$X_{\rm m} = \frac{3}{2} X_{\rm ms}$, $X_{\rm ms}$ is magnetizing reactance	3.44979 Ω		
	of stationary circuit.			
rs	Stator resistance.	0.00708 Ω		
r _r	Rotor resistance referred to stator windings.	0.00759 Ω		

Appendix C: Microturbine Model in PAT

Description	Parameter	Machine # 1	Machine # 2
Machine rating	Р	200 kW	300 kW
Voltage	V	380 V	380 V
Armature resistance	r _a	0.095 pu	0.067 pu
d-axis reactance	X _d	345 pu	260 pu
q-axis reactance	Xq	207 pu	156 pu
d-axis transient reactance	X' _d	24 pu	22 pu
q-axis transient reactance	X'q	22 pu	-
d-axis sub-transient reactance	X" _d	16.5 pu	15.0 pu
q-axis sub-transient reactance	X"q	24.75 pu	22.5 pu
d-axis transient time constant	T' _{do}	1.725 sec	1.182 sec
d-axis sub-transient time constant	T" _{do}	0.015 sec	0.015 sec
q-axis sub-transient time constant	T" _{qo}	1.700 sec	1.180 sec
Inertia constant	Н	1.5 sec	1.8 sec

 TABLE C.3

 MICROTURBINE'S SYNCHRONOUS GENERATORS PARAMETERS

Appendix D

GPSO: Codes and MDL Files

In order to implement the Guided Particle Swarm Optimization technique, the following m-files are written in MATLAB and incorporated with PAT. Figures D.1 to D.3 present the GPSO design of microturbines' controllers in distribution feeder using PAT as simulation environment.

% This file describes the setup parameters for PSO.

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%

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% any later version.

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% but WITHOUT ANY WARRANTY; without even the implied warranty of

% MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the

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% This configuration depends in the problem, the given example is to design % Ppower System Stabilizer parameters: K1 T11 T12 K2 T21 T22

```
global K1 T11 T12 K2 T21 T22
%%
c1=2.0;c2=2.01;
n=50;M=5;tmax=50;
bounds =[ 0 60;
0.1 0.5;
0 0.1;
0 60;
0.1 0.5;
0 0.1]; % Parameters max and min intervels
evalFN = 'objectives';
[Jss,xss,Jsss,t] = psomax(bounds,evalFN,tmax,c1,c2,n,M);
```

[%] Partical Swarm Optimization for Matlab

[%] This program is free software; you can redistribute it and/or modify

function [Jss,xss,Jsss,t] = psomax(bounds,evalFN,tmax,c1,c2,n,M)

% PSOmax run a Partical Swarm Optimization to maximize the objective function. % function [x,endPop,bPop,traceInfo]=ga(bounds,evalFN,tmax,c1,c2,n,M) % % Output Arguments: % Jss - the best solution found during the course of the run. % xss - the final population. % Jsss - a trace of the best population. % t - number of iteration. % % Input Arguments: % bounds - a matrix of upper and lower bounds on the variables. % evalFN - the name of the evaluation .m function. % tmax - maximum number of iteration. % c1 - weighting factor. - weighting factor. % c2 - number of population. % n - maximum number of iteration of unchanged soltion. % M % Partical Swarm Optimization for Matlab % Copyright (C) 2003 Amer Alhinai % % This program is free software; you can redistribute it and/or modify % it under the terms of the GNU General Public License as published by % the Free Software Foundation; either version 1, or (at your option) % any later version. % % This program is distributed in the hope that it will be useful, % but WITHOUT ANY WARRANTY; without even the implied warranty of

% MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the

% GNU General Public License for more details. A copy of the GNU

% General Public License can be obtained from the

x_int= bounds;

```
t=1; % 1st iteration.
```

```
K=2/(abs(2-phi-sqrt(phi^2-4*phi)));
```

for i=1:length(x int) % initial population position

 $x(i,:)=x_int(i,1)+(x_int(i,2)-x_int(i,1))*rand(1,n);$ end

for i=1:length(x_int) % initial velocities
Vmax(i)=max(x(i,:));Vmin(i)=min(x(i,:));
vk(i)=(Vmax(i)-Vmin(i))/n;

```
V(i,:)=-vk(i)+(vk(i)+vk(i))*rand(1,n);
end
vmax=vk;vmin=-vk;
size V=size(V);
xs=x; %vs=V;
for i=1:size V(2)
                   % evaluate the initial population
  xc=x(:,i);
  e1str=['jc=' evalFN '(xc);'];
  eval(e1str);
  J(i)=jc;
end
Js=J;
                   % initial best individual
Jss=max(Js);xss=x(:,find(Jss==Js));
Jsss(t)=Jss;
                    % initial best global
m=0;
while t<tmax % check maximum # of iteration
             % check the number of iterations since the last change
  if m>M
     break % of the best solution "m" is greater than "M"
  end
  t=t+1
  m
  r1=rand(1);r2=rand(1);
                        % update the velocity
  for i=1:size V(1)
     for k=1:size V(2)
       v cal=K^{(i,k)+c1*r1*(xs(i,k)-x(i,k))+c2*r2*(xss(i)-x(i,k)));
       if (v cal>=vmin(i) & v cal<=vmax(i))
          V(i,k)=v cal;
       else
       end
     end
  end
  for i=1:size V(1)
                         % update position
     for k=1:size V(2)
       x cal=V(i,k)+x(i,k);
       if (x \text{ cal} \ge x \text{ int}(i,1) \& x \text{ cal} \le x \text{ int}(i,2))
         x(i,k)=x cal;
       else
       end
     end
  end
  for i=1:size V(2) % evaluation
    xc=x(:,i);
```

```
e1str=['jc=' evalFN '(xc);'];eval(e1str);
     J(i)=jc;
  end
  for i=1:size V(2)
                        % update best individual
     if J(i)>Js(i)
       Js(i)=J(i);
       xs(:,i)=x(:,i);
     else
     end
  end
  Jmax=max(Js);
  if Jmax>Jss
                      % update best global
    m=0;
     Jss=Jmax
     xss=xs(:,find(Jss==Js));xss=xss(:,1);
  else
     m=m+1;
     fprintf('%2.0f',m)
  end
  Jsss(t)=Jss;
end
return
```

```
function [val] = objectives(sol)
```

```
% This function compute the Partical Swarm Optimization objective function.
% function [val] = objectives(sol)
%
% Output Arguments:
            - PSO performance index value
% val
%
% Input Arguments:
            - PSO candidate solution
% sol
% Partical Swarm Optimization for Matlab
% Copyright (C) 2003 Amer Alhinai
%
% This program is free software; you can redistribute it and/or modify
% it under the terms of the GNU General Public License as published by
% the Free Software Foundation; either version 1, or (at your option)
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%
% This program is distributed in the hope that it will be useful,
% but WITHOUT ANY WARRANTY; without even the implied warranty of
% MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
% GNU General Public License for more details. A copy of the GNU
```

K1=sol(1); Tw1=sol(2); T11=sol(3);T12=sol(4); T13=sol(5); T14=sol(6);

K2=sol(7); Tw2=sol(8); T21=sol(9);T22=sol(10); T23=sol(11);T24=sol(12);

K3=sol(13);Tw3=sol(14); T31=sol(15);T32=sol(16); T33=sol(17);T34=sol(18);

 $0\!\!/_00\!\!/$

sim('m IEEE37 2MT') % Nonlinear Simulations

if tout <7 % If the guided constrains interepted the simulation ignor this solution val=0

else % Good candidate solution j=min(sum(J)); % J is the simulation performance index computed within PAT val=1e6/j

end



Figure D.1 PSO Performance Index

$$J = \int_{0}^{1} (10|\Delta\omega| + \delta) dt$$



Figure D.2 GPSO Constraints



Figure D.3 PAT Simulation of Microturbines in Distribution Feeder

Appendix E

MAS: Codes and MDL Files

```
clc
  clear all
  ps=setps;
  line=ps.envS.line;
  nline=length(line)
  for k=1:nline
    ps.envS.sw con(2,2)=ps.envS.line(k,1);
    ps.envS.sw con(2,3)=ps.envS.line(k,2);
    ps = Init MDL st(ps);
[K1,Tw1,T11,T12,T13,T14,K2,Tw2,T21,T22,T23,T24,K3,Tw3,T31,T32,T33,T34]=get
controller(ps);
    tsim=input('\n Input Simulation time:\n');
    tsim=6;
    sim('m IEEE37 3MT')
    if tout(length(tout))<tsim
      fprintf('\n
        *****
      fprintf('\n * There is aproblem and controllers need to be designed *')
      fprintf('\n *
                        LOCAL EMERGENCY SIGNAL
                                                             *')
      fprintf('\n
answer=input('Do you want to go ahead and design the controllers? y/n/n','s');
      if answer=='y'
        fprintf('\n OK let us start')
        con pso;
        if Jss~=0
          load con;
        else
          fprintf('\n It seems there is a difficulty to')
          fprintf('design a controller for this case between Line %2.0f-%2.0f \n',
ps.envS.sw con(2,2), ps.envS.sw con(2,3))
          fprintf('\n Please check the system configuration and try again\n')
          %break
        end
      else
        *')
        fprintf('\n
                       Perfect
                                 Your
                                        System
                                                 is
                                                      runing
                                                               Great
```

```
plot r3
       end
    end
  end
  function
[K1,Tw1,T11,T12,T13,T14,K2,Tw2,T21,T22,T23,T24,K3,Tw3,T31,T32,T33,T34]=get
controller(ps)
  % This function extracts the controllers paramters from controllers matrix
  % data base.
  a=ps.envS.sw con(2,2);
  b=ps.envS.sw con(2,3);
  c=ps.envS.sw con(2,6);
  load controller;
  switch c
    case 0
       % type of fault - 0 three phase
       m=1;
    case 1
       %
                  - 1 line to ground
      m=2;
    case 2
                 - 2 line-to-line to ground
       %
      m=3;
    case 3
       %
                  - 3 line-to-line
       m=4;
    case 4
       %
                 - 4 loss of line with no fault
      m=5;
    case 5
       %
                  - 5 loss of load at bus
       m=6:
  end
  n=find((ps.envS.line(:,1)==a \& ps.envS.line(:,2)==b) ...
     | (ps.envS.line(:,1)==b & ps.envS.line(:,2)==a));
  j=0;idx=1:6;
  while isempty(controller(n,:,m))
    i=i+1;
    m=idx(j);
    if j == 6
       break
    end
  end
  K1=controller(n,1,m);Tw1=controller(n,2,m);
```

Appendix E: MAS: Codes and MDL Files

T11=controller(n,3,m);T12=controller(n,4,m); T13=controller(n,5,m);T14=controller(n,6,m);

K2=controller(n,7,m);Tw2=controller(n,8,m); T21=controller(n,9,m);T22=controller(n,10,m); T23=controller(n,11,m);T24=controller(n,12,m);

K3=controller(n,13,m);Tw3=controller(n,14,m); T31=controller(n,15,m);T32=controller(n,16,m); T33=controller(n,17,m);T34=controller(n,18,m);

```
% This file is written to upload new designed controllers to controller
% matrix [Local Data Base]
a=ps.envS.sw con(2,2);
b=ps.envS.sw con(2,3);
c=ps.envS.sw con(2,6);
load controller;
switch c
  case 0
     % type of fault - 0 three phase
    m=1;
  case 1
                 - 1 line to ground
     %
    m=2;
  case 2
    %
                 - 2 line-to-line to ground
    m=3;
  case 3
                 - 3 line-to-line
    %
    m=4;
  case 4
    %
                 - 4 loss of line with no fault
    m=5;
  case 5
    %
                 - 5 loss of load at bus
     m=6;
end
n=find((ps.envS.line(:,1))==a \& ps.envS.line(:,2)==b) \dots
   | (ps.envS.line(:,1)==b & ps.envS.line(:,2)==a));
for j=1:length(xss)
  controller(n,j,m)=xss(j);
end
controller(n,j+1,m)=Jss;
save controller controller
```

```
clc
   clear all
   % This file will generate 3-phase to graound fulat data for IEEE-37 Feeder with
   % Microturbine installed at buses # 13 and 36. The fault is cleared in 50 msec.
   % Then the generated Data will be used to train a selected Neural Network
   % and at the designed network is tested using simulation data.
   ps=setps:
   line=ps.envS.line;
   nline=length(line)
   for k=1:nline
     ps.envS.sw con(2,2)=ps.envS.line(k,1);
     ps.envS.sw con(2,3)=ps.envS.line(k,2);
     ps = Init MDL st(ps);
     sim('m IEEE37 2MT NNData')
     [s row,s col]=size(speed);
     tn=find(fix(speed(:,1)*100)==10);tf(k)=tn(1);
     speedg1(1:s row,k)=speed(:,2);speedg2(1:s row,k)=speed(:,3);
     Peg1(1:s row,k)=Pe(:,2);Peg2(1:s row,k)=Pe(:,3);
     Vbus13(1:s row,k)=Vbus(:,14);Vbus36(1:s row,k)=Vbus(:,37);Vbus1(1:s row,k)=Vbus(:,2);
   end
   data length=500;
   data acc=80;
   for idx=1:nline
     SG1(:,idx)=speedg1(tf(idx):tf(idx)+data length,idx);
     SG2(:,idx)=speedg2(tf(idx):tf(idx)+data length,idx);
     PeG1(:,idx)=Peg1(tf(idx):tf(idx)+150,idx);
     PeG2(:,idx)=Peg2(tf(idx):tf(idx)+150,idx);
     V13(:,idx)=Vbus13(tf(idx):tf(idx)+data acc,idx);
     V36(:,idx)=Vbus36(tf(idx):tf(idx)+data acc,idx);
     V1(:,idx)=Vbus1(tf(idx):tf(idx)+data acc,idx);
   end
   %%%%%%
   targets=eve(22);
   del line=[13 17 20 22 23 25 26 29 30 31 32 33 35 36];
   idxn=0;
   parameter=V36;
   for idx=1:36
     if ~isempty(find(idx==del line))
       else
       idxn=idxn+1;
       selec par(:,idxn)=parameter(:,idx);
     end
   end
   alphabet=selec par;
   [R,Q] = size(alphabet);
   [S2,Q] = size(targets);
   net = newff(minmax(alphabet), [200 300 200 S2],...
     {'logsig' 'logsig' 'logsig' 'logsig'},'traingd');
   net.LW{2,1} = net.LW{2,1}*0.01;
   net.b{2} = net.b{2}*0.01;
   %
      TRAINING THE NETWORK WITHOUT NOISE
   %
   net.performFcn = 'sse';
                            % Sum-Squared Error performance function
```

```
net.trainParam.goal = 0.1; % Sum-squared error goal.
```

```
net.trainParam.show = 20;
                            % Frequency of progress displays (in epochs).
net.trainParam.epochs = 100000; % Maximum number of epochs to train.
net.trainParam.mc = 0.95;
                            % Momentum constant.
net.trainParam.min grad = 1e-10 % Minimum performance gradient
% Training begins...please wait...
P = alphabet;
T = targets;
[net,tr] = train(net,P,T);
% Test the NN
for tt=1:Q
  comp_out=selec_par(:,tt);
  [row comp out,col comp out]=size(comp out);
  if row comp out < 151
    length_comp_out=length(comp_out);
    final value=comp out(length comp out);
    comp out(length comp out+1:151)=final value;
  elseif row_comp_out > 151
    comp out=comp out(1:151);
  end
  out = sim(net,comp_out);
  idx=find(out>0.8);
  if \sim is empty(idx) == 1
    fprintf('\nThe disturbance in line %d', idx);
  else
    fprintf('\nThe disturbance is unrecognized');
  end
end
```

Appendix F

AENS: Data and MDL Files



Figure F.1 AENS PSO Performance Index



Figure F.2 AENS GPSO Constraints


Figure F.3 AENS One-Side AC Network Model in PAT

TABLE F.1								
AENS AC SYSTEM DATA								
From	То	Resistance	Reactance	Bus	Active	Reactive		
Bus	Bus	(Ohm)	(Ohm)	#	Power	power		
					(kW)	(kVAr)		
1	2	0.0	0.0567	2	10	1.0		
2	3	0.0	0.0625	3	30	10		
3	4	0.0	0.0586	4	10	4		

 TABLE F.2

 AENS Synchronous Generators Parameters

Description	Parameter	Machine # 1
Machine rating	Р	60 kW
Voltage	V	400 V
Armature resistance	r _a	0.003 pu
d-axis reactance	X _d	2.24 pu
q-axis reactance	X_q	1.02 pu
d-axis transient reactance	X' _d	0.17 pu
d-axis sub-transient reactance	X'' _d	0.12 pu
q-axis sub-transient reactance	X''q	0.13 pu
d-axis transient time constant	T' _{do}	0.028 sec
d-axis sub-transient time constant	T'' _{do}	0.007 sec
q-axis sub-transient time constant	T''qo	0.007 sec
Inertia constant	Н	0.1028 sec

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