Adaptive Load Control in Islanded Microgrid System using Intelligent Circuit Breaker

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **Adaptive Load Control in Islanded Microgrid System using Intelligent Circuit Breaker**, submitted by **Avinash Arya**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bona fide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Adaptive load control, islanded microgrid, intelligent circuit breaker, demand response, game theory.

Well-designed demand response is expected to play an essential role in operating power systems by minimising economic and environmental costs. However, the current conventional system is run without much information on the benefits of end-users, especially the small ones, who use electricity. This thesis proposes a framework of operating power systems with demand models including the diversity of end-users' benefits, namely adaptive load control (ALC). Since there are a huge number of end-users repleted with various preferences and conditions in energy demand, the information on the end-users' benefits needs to be added up at the system level. This leads us to frame a paradigm the system in a multi-layered way, including end-users, load serving entities, and a system operator. Contrary to this, the information of the end-users' benefits can be uncertain even to the end-users themselves ahead of time. This information has been discovered incrementally as the actual usage approaches and occurs. Due to the several levels of uncertainty along the decision-making, the risks from the uncertainty of information on both the system and the end-users need to be managed. The methodology of ALC is based on Non-zero sum game theory that utilises interactive communication between the system, load serving entities, and end-users. Under certain conditions, a power system with a large number of end-users can balance at its optimum efficiently over the horizon of a day ahead of operation to near real time. With the right information exchange by each entity in the system, a power system can reach its optimum including a variety of end-users' preferences and their values of consuming electricity.

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ABBREVIATIONS

AC	Alternating Current
ALC	Adaptive load control
CERT	Consortium for Electrical Reliability Technology Solutions
DC	Direct current
DG	Distributed generation
DR	Demand Response
IEEE	Institute of Electrical and Electronics Engineers
MG	Microgrid
PV	Photovoltaic
RE	Renewable energy

CHAPTER 1

INTRODUCTION

1.1 Microgrid

A localised source of electricity and groups of loads that normally operates with the traditional centralised grid (macrogrid) is Micro-grid. Microgrid is connected to and synchronous with the centralised grid. It can disconnect and function autonomously.

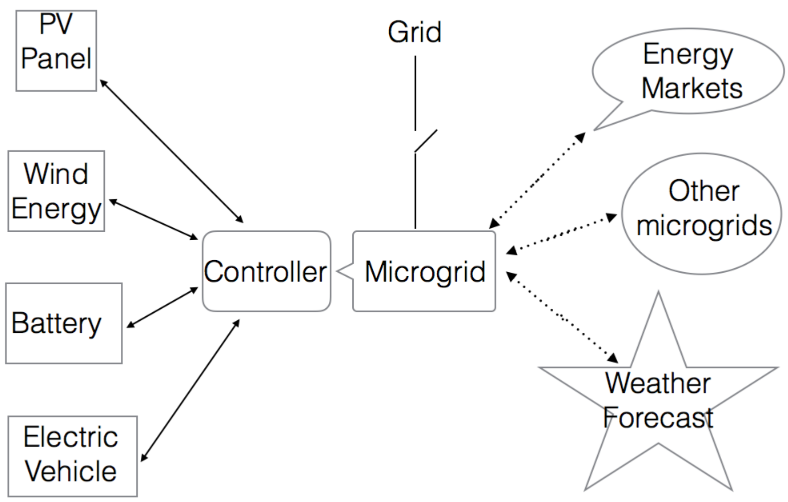

Figure 1.1: Microgrid system

1.1.1 Microgrid Definitions

Below are the definition wordings from the U.S. DOE MEG and the CIGRE 6.22 WG.

U.S. Department of Energy Microgrid Exchange Group: “A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode."

CIGRE C6.22 Working Group, Microgrid Evolution Roadmap: “Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded."

CIGRE C6.22 Definition Qualifiers: “Generators covers all sources possible at the scales and within the context of a microgrid, e.g. fossil or biomass-fired small-scale combined heat and power (CHP), photovoltaic modules (PV), small wind turbines, mini-hydro, etc. Storage Devices includes all of electrical, pressure, gravitational, flywheel, and heat storage technologies. While the microgrid concept focuses on a power system, heat storage can be relevant to its operation whenever its existence affects operation of the microgrid." For example, the availability of heat storage will alter the desirable operating schedule of a CHP system as the electrical and heat loads are decoupled. Similarly, the pre-cooling or heating of buildings will alter the load shape of heating ventilation and air conditioning (HVAC) system, and therefore the requirement faced by electricity supply resources.

Controlled loads, such as automatically dimmable lighting or delayed pumping, are particularly important to microgrids simply by virtue of their scale. Inevitably in small power systems, load variability will be more extreme than in utility-scale systems. The corollary is that load control can make a particularly valuable contribution to a microgrid.

Note:

1. No reference to actual generation
2. No reference to other distributed energy resources technologies involved.
3. Sometimes microgrid involves complex combination of resources.

There are two major types of microgrids:

1. customer microgrids or true microgrids (μgrids)

2. Milligrids (mgrids)

μgrids are those microgrids which is entirely on one site, akin to a traditional utility customer and mgrids are the ones that involve a segment of the legacy regulated grid.

1.1.2 Advantages of microgrid operations

1. Improved energy efficiency, minimisation of overall energy consumption, reduced environmental impact, improvement of reliability of supply, network operational benefits such as loss reduction, congestion relief, voltage control, or security of supply and more cost efficient electricity infrastructure replacement to the customers and utility.
2. There is also a philosophical aspect, rooted in the belief that locally controlled systems are more likely to make wise balanced choices, such as between investments in efficiency and supply technologies.
3. Microgrids can coordinate all these assets and present them to the megagrid in a manner and at a scale that is consistent with current grid operations, thereby avoiding major new investments that are needed to integrate emerging decentralised resources
4. Microgrids have been proposed as a novel distribution network architecture within the SmartGrids concept, capable to exploit the full benefits from the integration of large numbers of small scale distributed energy resources into low-voltage electricity distribution systems.

1.1.3 Islanded Microgrid

Microgrids comprise low voltage distribution systems with distributed energy resources, such as photovoltaic power systems and wind turbines, together with storage devices. These systems are interconnected to the medium voltage distribution network, but they can be also operated isolated from the main grid. From the customer point of view, microgrids provide both thermal and electricity needs and in addition enhance local reliability, reduce emissions, improve power quality by supporting voltage and reducing voltage dips and potentially lower costs of energy supply. From the utility point of view, application of distributed energy sources can potentially reduce the demand for distribution and transmission facilities. Clearly, distributed generation located close to loads will reduce flows in transmission and distribution circuits with two important effects: loss reduction and ability to potentially substitute for network assets. Furthermore, the presence of generation close to demand could increase service quality seen by end customers. Microgrids can provide network support in times of stress by relieving congestions and aiding restoration after faults.

The development of microgrids can contribute to the reduction of emissions and the mitigation of climate changes. This is because available and currently developing technologies for distributed generation units are based on renewable sources and micro sources that are characterized by very low emissions. Technical challenges associated with the operation and control of microgrids are immense. Ensuring stable operation during network disturbances, maintaining stability and power quality in the islanding mode of operation requires the development of sophisticated control strategies for microgrid's inverters in order to provide stable frequency and voltage in the presence of arbitrarily varying loads. This paper's objectives are to demonstrate the transients of a microgrid due to intentional islanding process and to illustrate the maintenance of stability of the microgrid in the isolated mode of operation for varying loads and climate conditions.

1.2 Renewable energy integration

Renewable energy is energy collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat. Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services.

Renewable energy resources exist over wide geographical areas, in contrast to other energy sources. Rapid deployment of renewable energy and energy efficiency is resulting in significant energy security, climate change mitigation, and economic benefits. The consequences of a recent review of the literature inferred that as greenhouse gas (GHG) emitters begin to be held liable for damages resulting from GHG emissions resulting in climate change, a high incentive for risk alleviation would provide powerful incentives for deployment of renewable energy technologies. In worldwide popular supposition reviews there is solid support for advancing inexhaustible sources such as solar power and wind power.

Renewable Energy integration has increased the uncertainty in the power networks. Hence proper planning, monitoring, analysis and control is required to ensure reliable and efficient operation of the power grid.

The essential building pieces of the smart grid are communication systems, control algorithms and efficient sensor systems. These help in managing power demand, improving grid reliability and security and reducing carbon footprint.

1.3 Literature Review

Paper [1] describes graph representation of the power system network and explains the GA reconfiguration algorithm. Simulation works on the proposed algorithm and gives an optimal solution. Paper [2] is related to networking where game theory has been used for an optimal solution to get an optimal response by switches and controllers. In this paper, formulation of problem along with proposed game theory provides a novel solution.Paper [3] provides an overview of conventional load shedding and developed method compares the proposed method with the conventional load shedding scheme. Reference[4] describes the T and D (Transmission and Distribution) losses as per sample studies carried out by independent agencies including TERI. With the setting up of State Regulatory Commissions in the country, accurate estimation of T and D Losses has gained importance as the level of losses directly affects the sales and power purchase requirements and hence has a bearing on the determination of electricity tariff of a utility by the commission. Paper[5] describes the influence of electrical load model of electrical power system. Several model has been described in this.

1.4 Motivation

As mentioned in section 1.1 and 1.2, MG structures have increased due to its capability of enhancing the observability and controllability of power distribution systems. The objective of adaptive loss control is to improve demand response with the ability to work with grid and without grid (islanded mode) and simultaneously cope up with the customer requirements. These action would be done by centralised controller using game theory where none of the customers would be in loss. Therefore, there shall be win-win situation for all. Most of the load control strategies (detailed literature review on section 1.3) concentrates on reconfiguration algorithm in power system network.

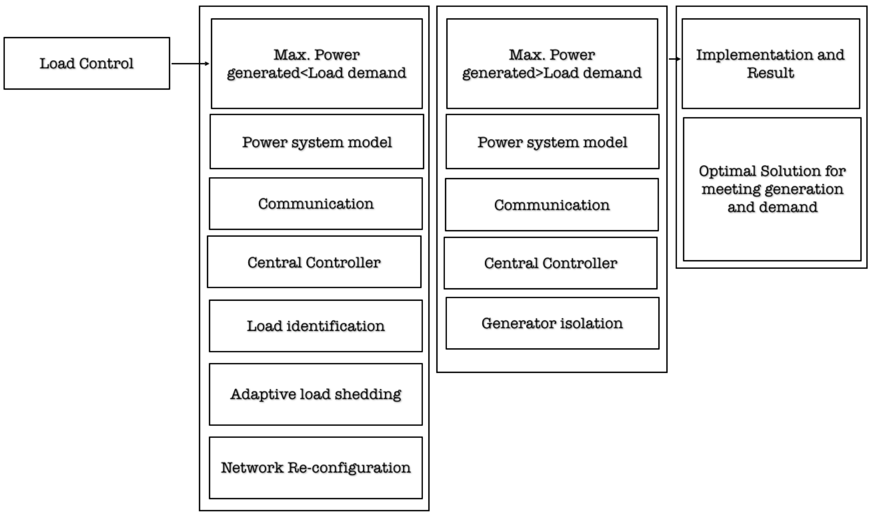

Figure 1.2: Project motivation

1.5 Objective and scope

The objective of this work are the following

1. We propose a framework that comprehensively includes the objective of end-users and based on several preferences, game theory works on pay-off function to obtain an optimal solution.

2. Formulation of a strategy for load control shall be implemented on real-time for microgrid reconfiguration.

The scope of the work narrows down to load control where there is no formal agreement between customer and the utility regarding the usage of loads. Also there is a centralised controller which operates circuits breakers and physics of a power system network was approximated to a linear model with only active power supply and demand. However, priority based function can also be included in pay-off function to have the optimal solution round the clock.

1.6 Organisation of thesis

Primary aim of the work is to have an effective communication of circuit breakers to the centralised controller to reach an optimal solution.

Chapter 2 gives an brief background of load control and game theory. Different types of game theory has been addressed in this chapter. Non-zero game theory plays a role to obtain an optimal solution using the pay-off function.

Chapter 3, Mathematical formulation of problem and methodology to solve this issue has been presented. This chapter uses the pay-off function which takes care of the power system constraints.

Chapter 4, working of intelligent circuit breaker has been explained with centralised and distributive mode of controlling.

Chapter 5, the mathematical formulation to determine the optimal circuit breaker status is presented and simulated for several cases. These cases have been analysed, simulated and implemented in this chapter.

Chapter 6 concludes the thesis with a summary including important conclusions, contributions of this work and the scope of future research.

CHAPTER 2

Adaptive load control in microgrids

2.1 Adaptive load control

The period of cheap fossil fuel energy is attracting to a nearby: fuel costs are winding up noticeably progressively unstable as worldwide request expands, the science behind dire ecological impacts of continued carbon emissions is generally accepted, and national energy security permeates political discussions. Society places extraordinary expectations on sustainable power sources such as wind and solar, but these are non-dispatch-able : they produce predictable but variable quantities of power.

On hourly and daily timescales, other forms of power generation or energy storage has been balancing non-dispatch-able power generation. On windless days energy is being imported from neighbouring states, and on windy days, excess energy is exported. The state with the hydro-powered generation, can effectively act as energy storage: hydro power generation is relatively easy to start and stop to balance wind, and while it is stopped, energy is stored as water fills reservoirs. All state don't have necessary resources, and the risk and integration problems that come with high penetration of renewables has stimulated a flurry of research in microgrids.

Microgrids are basically islandable partitions of a huge power network paired with an added layer of intelligence. The two foremost advantages of microgrids are the ability to effectively integrate micro distributed generation, and the ability to island intentionally. The first is accomplished in light of the fact that the microgrid appears like a single producer/consumer to the rest of the power grid. The Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid Concept paper claims that "the CERTS MicroGrid concept eliminates dominant existing concerns and the consequent approaches for integrating distributed energy resources (DER).The second advantage of microgrids is the ability to disconnect and function in an island mode, weathering catastrophic failures on the grid. Islanding capability provides an increased user reliability to because microgrid would not be dragged into a brownout or blackout along with the rest of the grid.

Microgrids, in any case, do not specifically solve the problem of balancing load and generation. Non-dispatchable sources of energy is still being required to balance energy storage and backup generation on large scales. Indeed, on islanded microgrids (and small power grids in general), regulation is also a problem on shorter timescales. In the event that a cloud were to pass over a photovoltaic array connected to the vast interconnect power grid, the drop in power would go virtually unnoticed. Yet, on an islanded microgrid, where an era from a PV array makes up a noteworthy portion of the generation, a cloud passing overhead could cause a major problem. Other generation or energy storage must be available to provide a fast influx of energy.

2.2 Game Theory

Game theory is “the study of mathematical models of conflict and cooperation between intelligent rational decision-makers." Game theory is mainly being used in economics, political science, and psychology, as well as logic, computer science and biology. Originally, it addressed zero-sum games, in which one person’s gains result in losses for the other participants. Today, game theory applies to a wide range of behavioural relations, and is now an umbrella term for the science of logical decision making in humans, animals, and computers.

There are a few types of game theory:

2.2.1 Cooperative / Non-cooperative

A game is cooperative when the players are able to form binding commitments externally enforced.If players cannot form alliances or if all agreements need to be self-enforcing, game is called as non-cooperative.

2.2.2 Symmetric / Asymmetric

A symmetric game is a game where the pay-offs for playing a specific strategy depend just on alternate methodologies utilised, not on who is playing them. If the identities of the players can be changed without changing the pay-off to the strategies, then a game is symmetric.

2.2.3 Simultaneous / Sequential

An essential subset of sequential games consists of games of perfect information. A game is one of perfect information if, in extensive form, all players know the moves beforehand made by every single other player. Simultaneous games can not be games of perfect information, in light of the fact that the conversion to extensive form converts simultaneous moves into a sequence of moves with prior moves being unknown.

2.2.4 Combinatorial games

Games in which the trouble of finding an ideal procedure originates from the multiplicity of possible moves are called combinatorial games. Cases incorporate chess and go. Games that involve imperfect or fragmented data may also have a strong combinatorial character, for instance backgammon. There is no brought together theory addressing combinatorial elements in games. There are, however, mathematical tools that can solve specific problems and answer general questions.

2.2.5 Stochastic outcomes

Individual decision problems with stochastic outcomes are sometimes considered "one-player games". These situations are not considered game theoretical by some authors.They may be modelled utilising similar tools within the related orders of choice hypothesis, operations research, and areas of artificial intelligence, particularly AI planning (with vulnerability) and multi-agent system. Despite the fact that these fields may have different motivators, the mathematics involved are substantially the same.

2.2.6 Metagames

These are games the play of which is the development of the rules for another game, the target or subject game. Metagames try to expand the utility value of the rule set developed. The theory of metagames is identified with mechanism design theory.

2.2.7 Differential games

Differential games such as the consistent interest and evasion game are continuous games where the advancement of the players' state variables is administered by differential equations. The issue of finding an ideal system in a differential diversion is firmly identified with the optimal control theory.

2.2.8 Pooling games

These are games prevailing over all types of society. Pooling games are repeated plays with changing payoff table in general over an accomplished way and their equilibrium strategies usually take a form of evolutionary social convention and monetary tradition. Pooling game theory emerges to formally recognise the interaction between optimal choice in one play and the emergence of forthcoming payoff table update path, identify the invariance existence and robustness, and predict variance over time. The hypothesis depends on topological transformation classification of payoff table update over time to predict variance and invariance.

2.3 Zero Sum and Non-Zero Sum Game Theory

Zero-Sum Games

At the point when initially taking in the fundamental ideas of Game Theory, the notion of a zero-sum game is probably one of the simplest topics to understand. In these sorts of games, there are generally true winners and losers, yet those terms can have distinctive implications. The real defining characteristic of a zero-sum game is that the sum of all gains by a player or group of players is equal to the sum of all losses for every possible outcome of that game.

Games like checkers and arm-wrestling are simple examples of two-player zero-sum games, since at the end of a standard game, there is a single winner and a single loser with the winner being “up 1 game" and the loser being "down 1 game."

As a side note here, ties are conceivable in zero-sum games. For instance, in an arm-wrestling match, both players may decide to call it a draw if an adequate measure of time passes without one being able to defeat the other. This still satisfies the conditions of a zero-sum game since the payoff to both players is the same that is, neither player wins or loses.

Non-Zero-Sum Games

When one player’s gain does not necessarily mean another player’s loss (and vice versa), the situation becomes more complex. These sorts of games are considered as non-zero-sum games, because the gains and the losses in the game do not always. One classic example of a non-zero-sum game is the Prisoners’ Dilemma. In this game, even though both players are acting in their best interests in mind to determine their most ideal outcomes, the gains of one player are not equally offset by the losses of the other. add up to zero. Another significant viewpoint that sets non-zero-sum games apart from zero-sum games is that non-zero-sum games don’t have to be completely competitive they can contain wide range of degrees of cooperation. Contingent on how much participation is allowed in the game, the strategies of each player can change quite a bit.

2.4 Summary

This chapter introduces the concept of adaptive load control and game theory. Integration of communication technology and automation to the power systems can lead to adaptiveness in load management. Important features of intelligent circuit breaker are to communicate with the controller and to give an effective solution. This work mainly concentrates on load control which works with non-zero sum game theory and all circuit breakers work at its maximum efficiency.

CHAPTER 3

Formulation and methodology of adaptive load control

3.1 Constraints in Power System Network

Here is several constraints in power system network

1.Power Balance Equation

2. Power generation limits

3. Transmission limit overloading constraints

4. Frequency limit range

5. Voltage limits

3.2 Defining variables

Let there be M intelligent CBs connected to form a network representing one or multiple logical/physical domain. For simplicity, we assume uniformity among circuit breakers, though it is not a constraint for this formulation. Controllers are referred by the CBs when power flows arrive at them so that forwarding rules or Forwarding Information Base (FIBs) can be updated. The controllers need to update the FIBs of the switches regularly and ensure QoS in the networks. Let the M CBs receive new flows randomly forming a non-uniform load scenario in the network at any time instant T. Assuming CB i receives Pi power flow and average load that can be handled by one controller is C, the minimum number of controllers required is:

$$Leastintegerfunction(k) = \frac{sumofpowerflows}{C}$$

The above argument is justified, if the load on the network/CB is known a-priori which is not possible in practice. Moreover, with the dynamic changes of load, value of k also changes dynamically. Our aim is to obtain the optimal value of k dynamically and optimally map k controllers (place) to M intelligent CBs. Controllers communicate with each other using a communication protocol. As the load on the network increases, one or more new generators can be added to handle the load, resulting in change of placement of the existing CBs. However, if the load on the network decreases, one active generator can be deleted resulting in change of placement of the surviving CBs. This process of addition/deletion of controller is captured through the following optimisation problem:

min f(k,c),

s.t., $Pg, min < Pgi < Pg, max$, $\forall$ i $\in$ I,

where f is a non-linear function of the number of CBs k and cost c (both CAPEX and OPEX) associated with each CBs. Note that, k and c are inter-related, and c could be a function of k. Pgi is power generated by generator i , and I is the set of all active generators operating in the network. Generated power should be within minimum and maximum thresholds (Pg,min and Pg,max). Eqn. (2) is a global optimization problem in which the objective and constraints are conflicting with each other. Solution of Eqn. (2) should be such that the number of the controllers (k) which can be used is unique and optimum. Apart from this, the mapping of CBs to controllers should ensure requirements. However, as load changes, obtaining an unique k is not possible, which can be used for all load conditions. Moreover, a centralized solution is advisable due to scalability, controllability and fault-tolerance issues. We therefore attempt to solve.

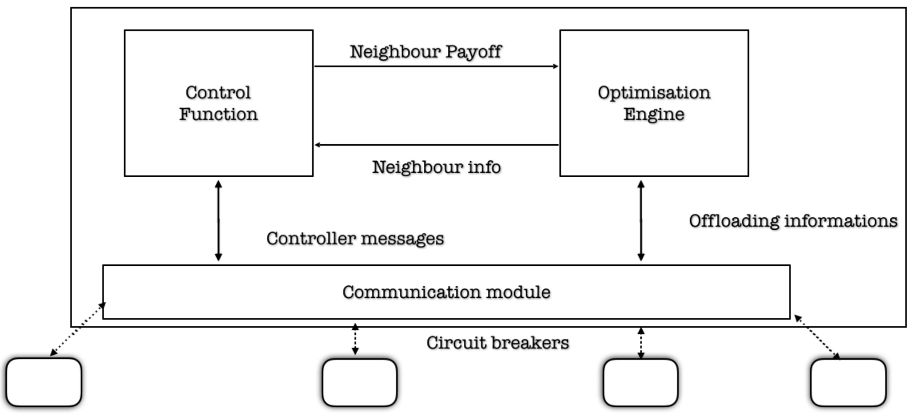

Figure 3.1: Proposed module for adaptive load control

3.3 Assumptions

1. Frequency of the network is always constant.
2. Voltages are within the limits.
3. Transmission lines are never being overloaded.

3.4 Methodology

The set of individual and global optimisations are equivalent, if the solution is unique and optimisation solution exists for all possible load conditions. However, as mentioned before the load changes dynamically and hence obtaining a unique solution is not viable. Therefore, we argue that for an initial condition, we can solve the global optimisation with a reasonable accuracy (level of accuracy can be user defined) or load variation and obtain k - optimal controller number for a particular traffic condition and then start the network with k controllers. As time progresses and load in the network changes, such that new CBs can be added or an existing CBs can be isolated. Therefore, it is a joint global- individual optimisation method of solving a multi-objective and multi-constraint optimisation. In this thesis, our focus is on the solution of the individual optimisation problem, which we solve using a non-zero-sum game. We use a non-zero-sum game to obtain the best possible solution, as an optimal solution is not viable all the time. Hence, neither there is a single optimal strategy that is suitable to all others, nor a predictable outcome. Note that, non-zero-sum games are also non-strictly competitive, rather they are cooperative for a common cause. We now discuss the non-zero-sum game which we propose to solve the above individual optimisation problem. In this, each active controller is assumed to be a player and plays according to a set of rules. Each controller computes a payoff (f_x)[5], which is a function of the existing utilisation and delay as defined:

$$f_x(V,P) = P_i(0.4V_i + 0.6V_i^2)$$

where P_i is the power injected at bus i and Vi is the voltage at bus i. Note that, each CB computes its payoff function fx and takes its decision independently. Moreover, de-

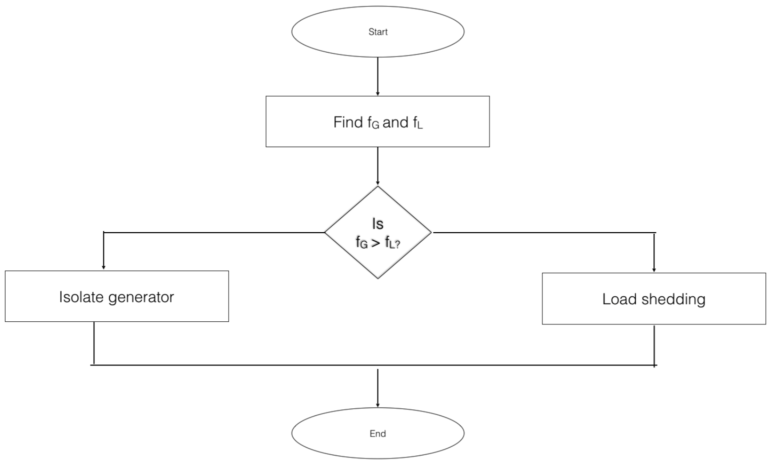

Figure 3.2: Flowchart for load control

cisions are taken at different controllers at different time instants, i.e., an asynchronous mode of operation. As the load in the network changes, power injected at buses and voltage at buses also change and hence the payoff. These values are being used by controllers and also being compared to previous values to operate circuit breakers.

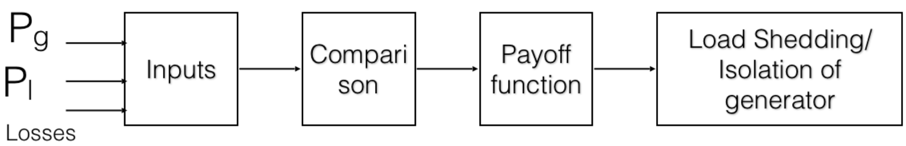

Figure 3.3: Methodology of applied theory

3.5 Summary

Pay-off function uses instantaneous voltage and power values to determine pay-off value which gets compared with previous values to achieve an optimal solution. Proposed theory gives a win-win result for the entire network. In any optimisation problem, there are multiple solution but non-zero sum game theory leads to one of the optimal value. These values are being used for controlling circuit breakers.

CHAPTER 4

Intelligent circuit breaker for islanded microgrid

4.1 Intelligent circuit breaker

Maintaining close control of electric power consumption is an increasingly important element of building services, both in order to reduce the energy costs related to consumption and to improve environmental sustainability. Automatic control of the building loads, based on the power they demand, is an optimum solution for effective cost reduction. The aim of these control systems is to moderate the demand for electric energy by avoiding non-coordinated operation of the loads.

For example, during a hot summer day, building air conditioning systems might start working all at the same time, resulting in peaks in consumption and possible problems with energy supply. The building operator may need to increase the contracted level of power with consequent increase of fixed costs. And in the worst cases, to prevent the overload protection from tripping, the plant must be over-dimensioned.

A traditional dedicated load control system normally requires the installation of a large number of dedicated control devices, with increasing costs and complexity as the number of loads increases.

Whereas low voltage circuit breakers have traditionally switched loads, new communication standards such as IEC 61850 have created a framework for smart grid communication that includes large users of low voltage power such as industrial and commercial buildings and ships.

This has opened up the potential for a new generation of low voltage circuit breaker that not only switches loads but manages power consumption. That was the reason a developed new generation low voltage circuit breaker has taken a major step forward in the principles of control, connectivity, performance and ease of use.

4.1.1 Control

Control over loads is a high priority for large consumers of low voltage power. By prioritising the switching off and on of loads, an operator can limit the power consumption to a maximum level and limit energy bills and reduce the risk of blackout.

The conventional method for switchboard control is to equip circuit breakers with complex communication systems and programme the supervision software. However, expectations are changing and today's operators want flexibility at low cost. The key is to include monitoring, instrumentation and communication in a single unit, even down to a power supply that can be connected to any AC or DC voltage. By removing external and add-on units, the cost, engineering and space required for these are eliminated.

Equipment with touch screen technology and web-based applications can be accessed locally or via smartphones, tablets or desktop computers all without the need for specific programming. This means that a modern circuit breaker provides an economic way for a small plant to increase its monitoring capabilities or for a large plant to simplify local supervision and maintenance.

By using an inbuilt algorithm that monitors power usage over time and determines the average, a smart circuit breaker will control a built-in load list and limit the power consumption to a maximum level set by the operator. This means that the breaker will automatically take low priority loads offline, saving utility bills without the need for additional monitoring systems.

And by building measurement of voltage, current, power, energy and power quality, an operator can identify the root cause of increased power outages or reduced service life of cables and capacitors without installing additional instrumentation.

4.1.2 Connectivity

Since the introduction of IEC 61850 for smart grids, operators have been upgrading their installations on a piecemeal basis to avoid the cost and disruption of a step change. Circuit breakers introduced today now need to be compatible with the existing legacy system at the facility where they will be installed but also with the new standard, so itâĂŹs vital that new technology is compatible with the seven most popular global communication protocols.

Another aspect of connectivity is the compatibility of a new unit with the existing infrastructure. Common bus configurations can be vertical or horizontal with anything from one to four bus runs and operators like the flexibility of choosing the location of the neutral position. Minimising the length of copper bus is an important consideration. As a result, the new circuit breaker is designed to fit the most common bus configurations for simplicity, its terminals can be rotated from horizontal to vertical in the field for maximum flexibility and each terminal is sized to fit the standard width of bus bar for that current. Plus, it's possible to choose the neutral position and the largest model is available with a choice of neutral conductor sizes to allow for the correct sizing of bus bar and the opportunity to reduce construction costs.

At the rear of the units, the terminals can be rotated from horizontal to vertical in the field for maximum flexibility, but they have been designed to fit the most common bus configurations for simplicity. Each terminal is dimensioned to fit the standard width of bus bar for that current. One, two or three terminal stabs ensure easy connection of up to four bus runs, ensuring easy connection and installation while minimising bus bar stock.

4.1.3 Performance

A challenge in many installations is how to deliver high performance while using limited space and materials. Intelligent circuit breaker has four frame sizes, each of which is only as wide as required by its current rating. This gives operators the opportunity to optimise their use of space and materials. Rated at 1,600 A to 6,300 A, the breakers' design and use of quality materials allows for high performance in a small size.

With increased current-carrying capacity in a small size, the units overcome the potential issue of overheating with a built-in module that activates cooling fans.

By using new generation Rogowski sensors, the circuit breaker measures performance to high precision to 1 percent accuracy for current, 0.5 percent for voltage and 2 percent of power and energy.

4.1.4 Ease of use

The smartphone and mobile communications revolution has transformed expectations of control systems. Today, operators can purchase web-operated security systems that send audio visual alerts when movement is detected. Tablets are now out-selling laptops and new ways of working are seeing industrial touch screens introduced across many industries, including oil and gas, utilities and elsewhere.

By introducing touch screen technology and web-based apps that allow intuitive access to information and programming in ten languages that enable control from remote locations, the new generation of control technology is simpler to use and more intuitive than previous generations.

Safety is a primary consideration too and by creating a circuit breaker that keeps personnel separate from the operating parts and is lockable to prevent unwanted operation during maintenance. The withdrawable version even has guide rails for simple and accurate positioning. And building on the safety aspects, the breaker is significantly smaller and lighter than previous models.

4.1.5 Managing large quantities of low voltage power

By introducing intelligent circuit breaker, It has created the world's first low-voltage circuit breaker that can be used for energy management and smart grid communications. It is designed for facilities that use large amounts of low voltage power. Applications include industrial and commercial buildings, data centres and on board ships.

The breaker integrates energy management and off the supply to non-essential equipment at times of peak demand. This not only saves energy but also helps prevent blackouts, which are often caused by peak demand exceeding supply. Intelligent decision making is achieved through an in-built controller using complex algorithms to decide when to switch power on and off.

For an individual building, using intelligent CB in place of traditional breakers can lead to a reduction in peak power demand of up to 15 percent. Replacing an existing breaker with the intelligent CB is technically simple and due to energy savings, it will typically pay for itself within a year.

A compact and flexible installationOne installation where the intelligent CB is proving its worth is on board a state-of-the-art diesel-electric ferryboat equipped by Italian electromechanical construction specialist IMESA. It was the only switchgear that would deliver selective circuit breaking capability with short circuit breaking capacity of 50 kA at 600 V AC as well as fit within an extremely compact space and a horizontal bussing distribution system.

Thanks to the unit's compact size and ability to be mounted in the horizontal position, it was possible to fit five circuit breakers in a single column, saving 45 percent of the footprint of a conventional distribution switchboard.

4.2 Summary

Relays used for conventional power distribution grids are not fully effective. In order to understand the protection challenges for a microgrid, knowledge of microgrid operation, during the pre-fault and post-fault period, is necessary. Intelligent circuit breaker which communicate with a central controller can also be used for protecting the microgrid. In case of a excess/lack of load demand in the microgrid, the Intelligent circuit breaker alerts the central controller which in turn will open/close the circuit breaker.

CHAPTER 5

Case study, Implementation and simulation results

5.1 Modelling and simulation

In this chapter we apply the short-term scheduling methods of Adaptive Load control on 8-bus standalone power system [1] and the IEEE 14-bus test system. We apply the methods proposed in Chapters 3 for scheduling of generation resources and demand. Real-time functional clearing adjusts the scheduled amounts in a moving horizon based on the bids that are submitted by supply and demand entities.

5.2 System reconfiguration

The system studied here is based on the 8-bus standalone power system and the IEEE 14-bus test systems. All parameters has been taken as per IEEE standard [6]. Several cases has been tested in MATLAB simulink which provides an expected results.

5.2.1 8-Bus Standalone power system

Since the test system does not include the specifics of the loads, we configure the flexible loads based on statistics and inference. There are four generators in this 8-bus system. For simulation, circuit breakers are placed for generator 1, generator 2, load 5, load6, load 7 and load 8 i.e. generator 3 and generator 4 are always connected to the network.

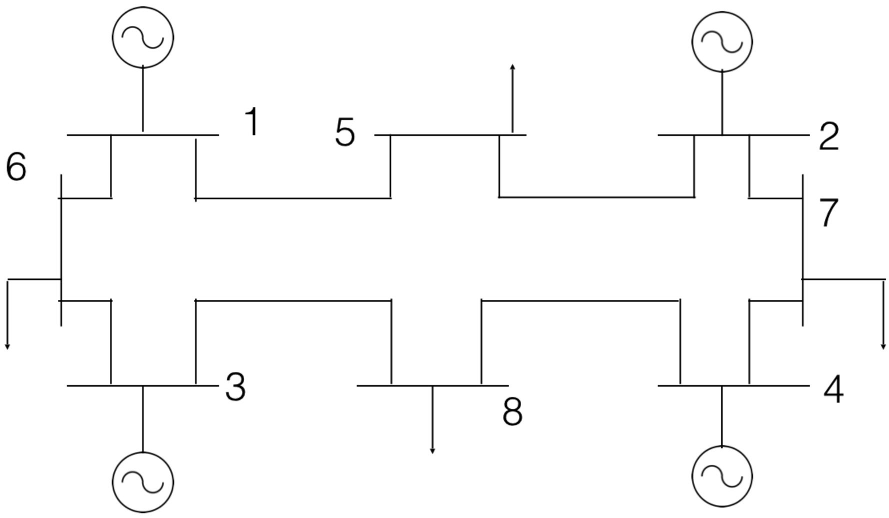

Figure 5.1: 8-Bus Standalone power system network

5.2.2 14-Bus IEEE test bus system

Since the test system does not include the specifics of the loads, we configure the flexible loads based on statistics and inference. There are four generators in this 14-bus IEEE system[6]. For simulation, circuit breakers are placed for generator 1, generator 2, load 5, load6, load 7 and load 8 i.e. generator 6 and generator 8 are always connected to the network.

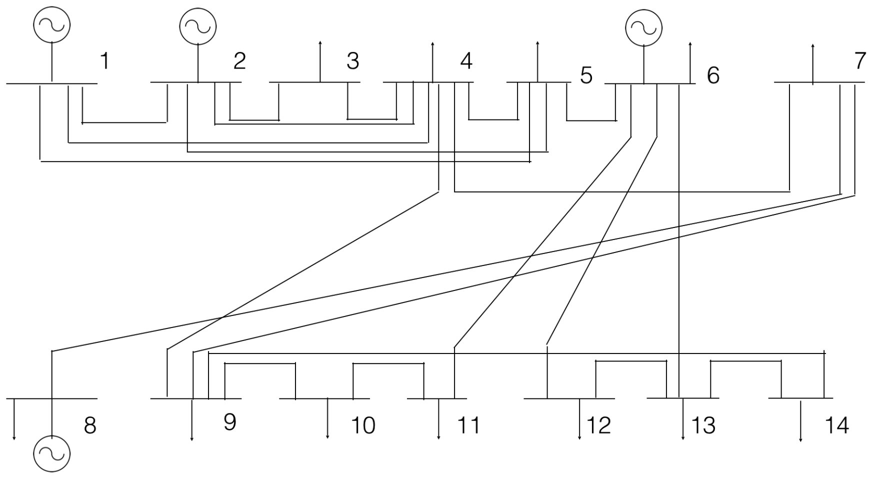

Figure 5.2: IEEE 14-Bus power system network

5.3 Simulation Results:

5.3.1 8-Bus Standalone power system

Case 1:

Power generated is less than addition of load power and losses in the system. As per the methodology used in chapter 3, initial conditions are mentioned in table 5.1 and also final statuses of circuit breaker have been mentioned in table 5.1.

Table 5.1: 8-Bus Standalone power System- Case 1

Circuit Breaker	Initial Condition	Final Condition
GenSigCB1	1	1
GenSigCB2	1	1
LoadSigCB5	1	1
LoadSigCB6	1	1
LoadSigCB7	1	0
LoadSigCB8	1	1

To meet load demand and power generation, both the generators shall be connected to the network in this case. And as the load power demand is more, one load has to be shed. Based on the methodology used in chapter 3, load connected to bus is isolated from the system.

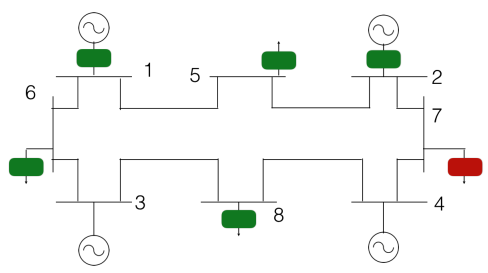

Figure 5.3: Real time model of 8-bus system for case 1

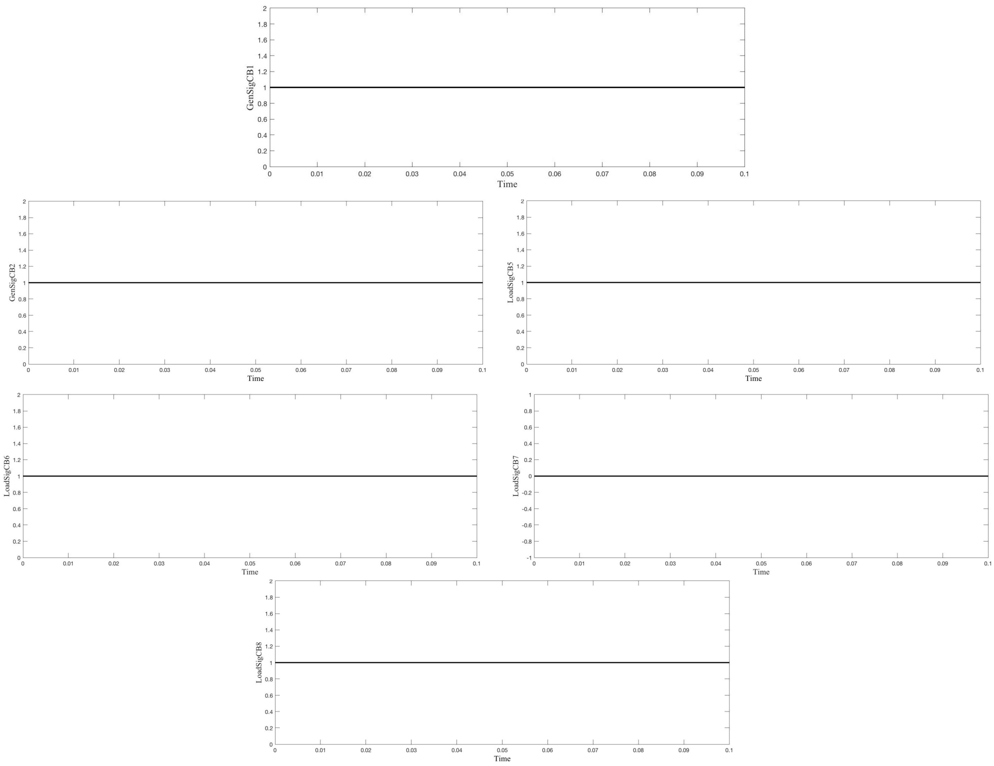

Figure 5.4: Signal to load circuit breakers 1,2,5,6,7,8 in case 1 respectively

Case 2:

Power generated is more than addition of load power and losses in the system. As per the methodology used in chapter 3, initial conditions are mentioned in table 5.2 and also final statuses of circuit breaker have been mentioned in table 5.2.

Table 5.2: 8-Bus Standalone power System- Case 2

Circuit Breaker	Initial Condition	Final Condition
GenSigCB1	1	1
GenSigCB2	1	0
LoadSigCB5	1	1
LoadSigCB6	1	1
LoadSigCB7	1	1
LoadSigCB8	1	1

To balance load power demand and power generation, one generators is sufficient to provide required power. Therefore, generator is isolated from the network. And as the load power demand is being fulfilled by the generator 1, all the load will be connected to the power system network.

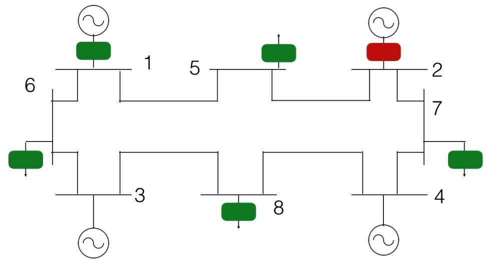

Figure 5.5: Real time model of 8-bus system for case 2

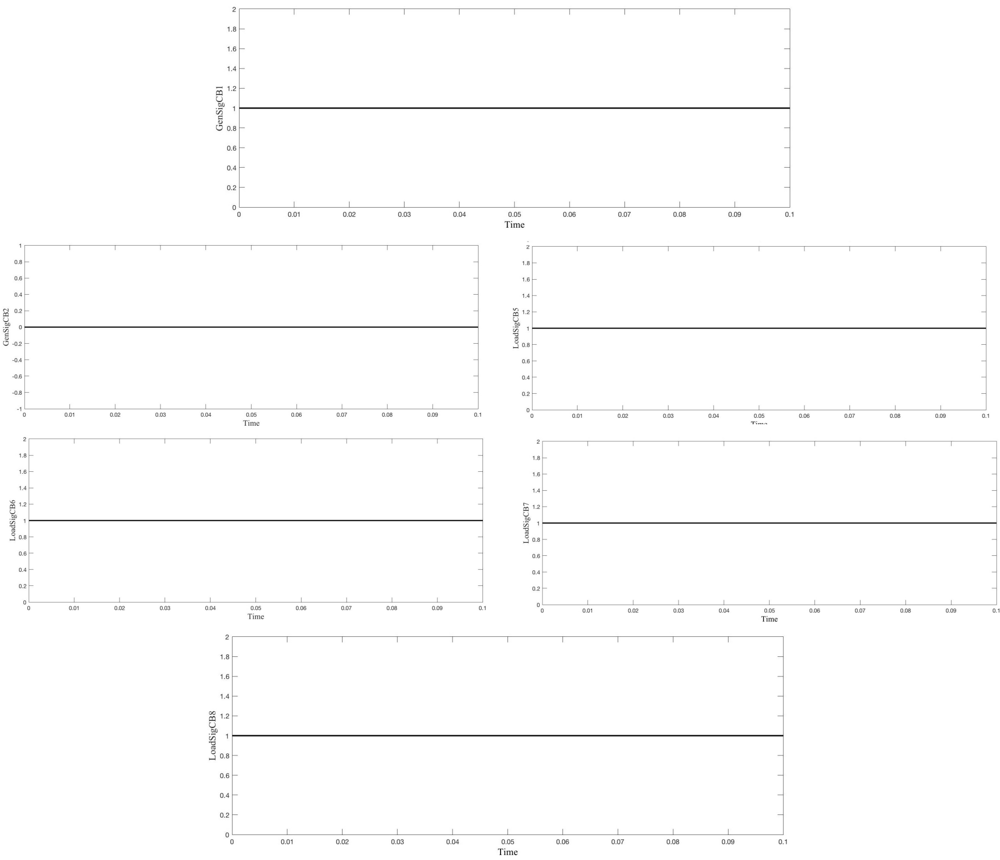

Figure 5.6: Signal to load circuit breakers 1,2,5,6,7,8 in case 2 respectively

5.3.2 14-Bus IEEE test bus system

Case 1:

Power generated is less than addition of load power and losses in the system. As per the methodology used in chapter 3, initial conditions are mentioned in table 5.3 and also final statuses of circuit breaker have been mentioned in table 5.3. To meet load

Table 5.3: IEEE 14-Bus Standalone power System- Case 1

Circuit Breaker	Initial Condition	Final Condition
GenSigCB1	1	1
GenSigCB2	1	1
LoadSigCB5	1	1
LoadSigCB6	1	0
LoadSigCB7	1	1
LoadSigCB8	1	1

demand and power generation, both the generators shall be connected to the network in this case. And as the load power demand is more, one load has to be shed. Based on the methodology used in chapter 3, load connected to bus is isolated from the system.

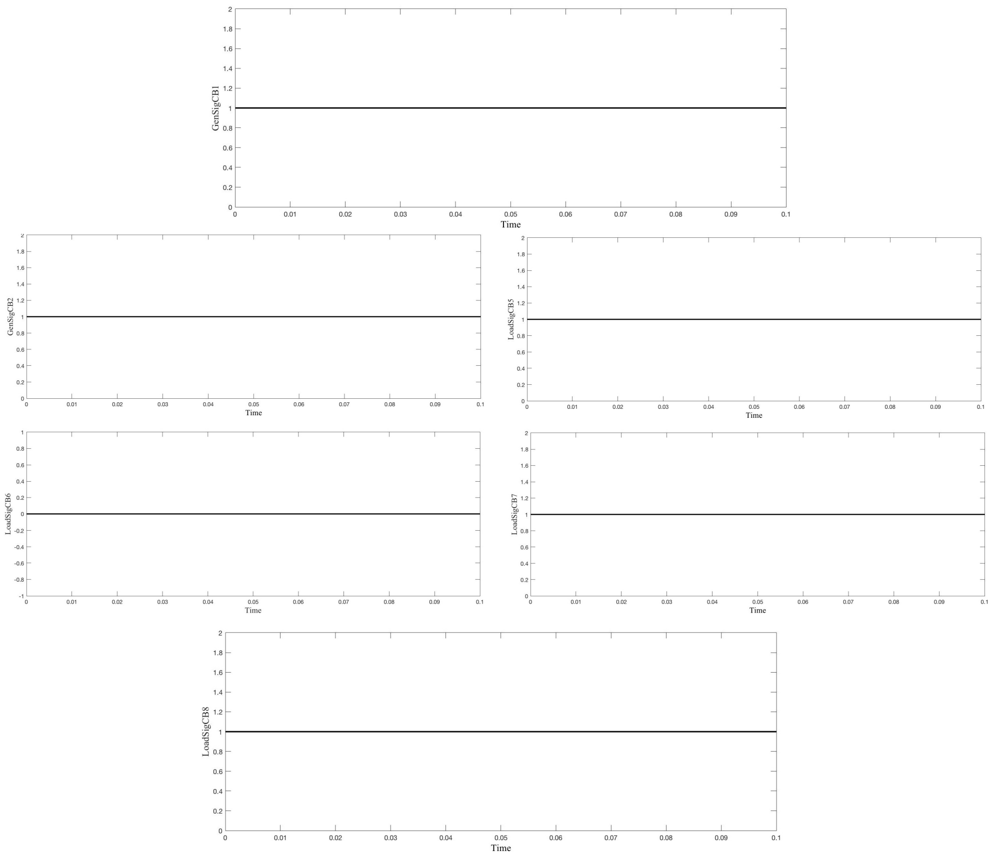

Figure 5.7: Signal to load circuit breakers 1,2,5,6,7,8 in case 1 respectively

Case 2:

Power generated is more than addition of load power and losses in the system. As per the methodology used in chapter 3, initial conditions are mentioned in table 5.4 and also final statuses of circuit breaker have been mentioned in table 5.4. Balancing load power demand and power generation, one generators is sufficient to provide required power.Therefore, generator is isolated from the network. And as the load power demand is being fulfilled by the generator 1, all the load will be connected to the power system network.

Table 5.4: IEEE 14-Bus power System- Case 2

Circuit Breaker	Initial Condition	Final Condition
GenSigCB1	1	1
GenSigCB2	1	0
LoadSigCB5	0	1
LoadSigCB6	0	1
LoadSigCB7	0	1
LoadSigCB8	0	1

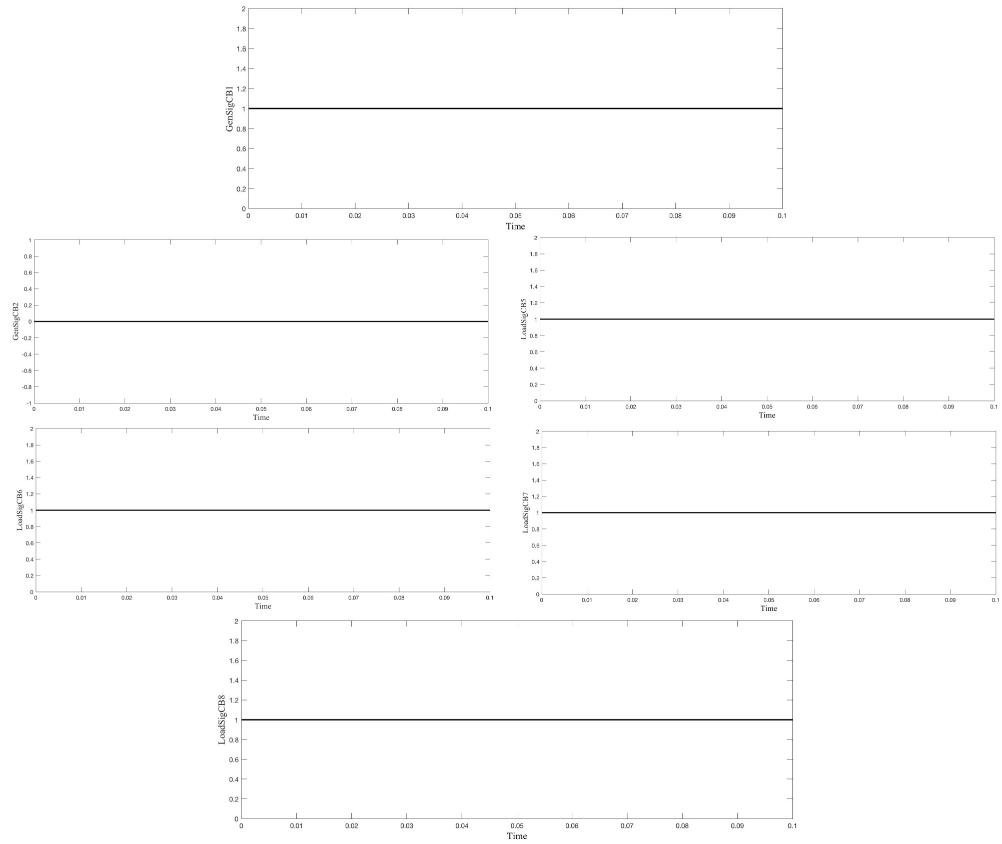

Figure 5.8: Signal to load circuit breakers 1,2,5,6,7,8 in case 2 respectively

Case 3:

Generated power and load demand is perfectly balanced.As per the methodology used in chapter 3, initial conditions are mentioned in table 5.5 and also final statuses of circuit breaker have been mentioned in table 5.5. In this case, generator 1 is unable to

Table 5.5: IEEE 14-Bus power System- Case 3

Circuit Breaker	Initial Condition	Final Condition
GenSigCB1	1	1
GenSigCB2	1	1
LoadSigCB5	1	1
LoadSigCB6	1	1
LoadSigCB7	1	1
LoadSigCB8	1	1

feed required power but working with generator 2, load requirement is fully satisfactory. Therefore, all generators and loads will be connected.

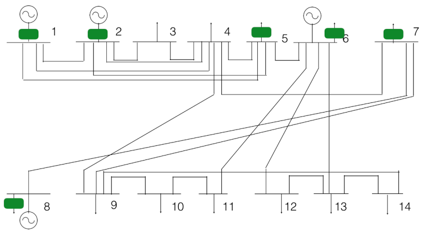

Figure 5.9: Real time model of 14-bus system for case 3

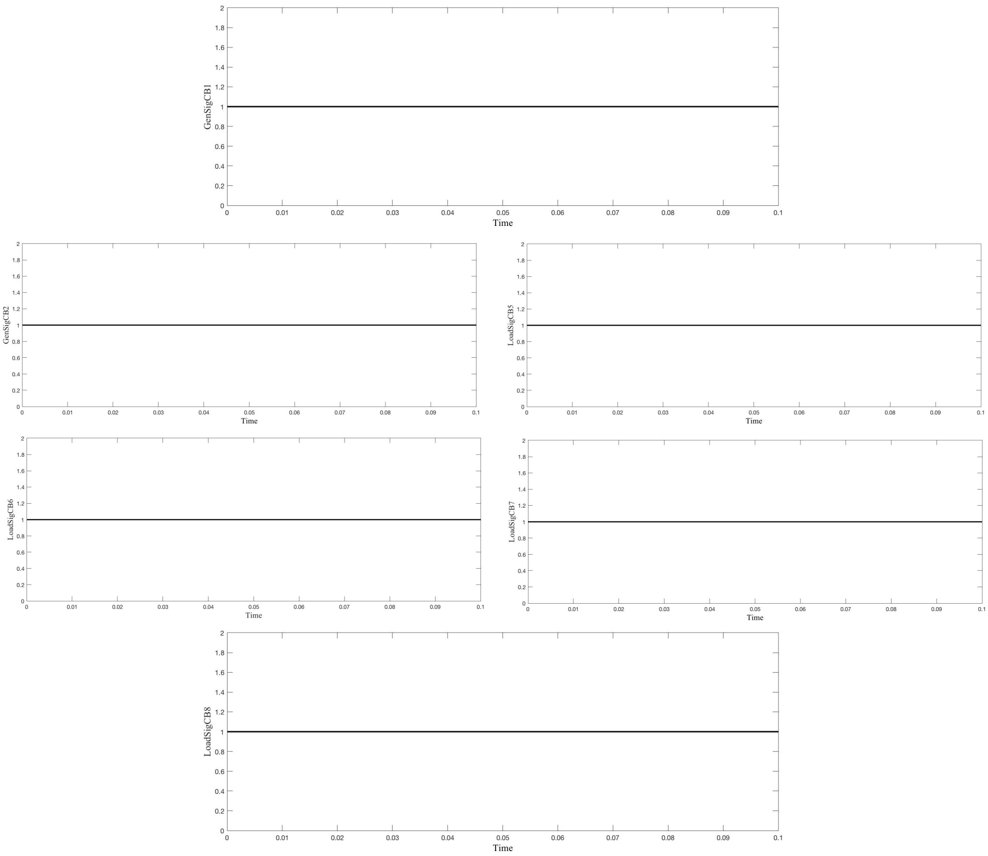

Figure 5.10: Signal to load circuit breakers 1,2,5,6,7,8 in case 3 respectively

5.4 Summary

Non-zero sum game theory' s pay-off function decides the status of circuit breakers connected to generators and loads. Based on different cases, circuit breaker status is either 1 or 0 which corresponds to 'on' or 'off' respectively. If a single generator is able to feed the load requirement, second generator is isolated (case-2) whereas load requirement is more than the generation, loads get isolated to maintain power balance in the network. Sometimes, both generators are required for power balance (case-1 and case-3).

CHAPTER 6

Conclusion and future scope

6.1 Conclusion

Motivated by the efforts of including more demand resources into power systems yet failing to include the end-users' benefit in the current system operation, this thesis provides a framework of operating a power system with end-users' benefits, namely adaptive load control (ALC). In order to represent a large number of end-users in the system where the system supply and demand are scheduled to be balanced at its optimum, we consider load serving entities to play a critical role of aggregating end-users' demand in ALC. Coordinating the objectives of a large number of different end-users and power producers in the system subject to the system network requires a careful design of information exchange scheme among the entities. We note that the information on the condition and external factors of the system, end-users, and generators varies along the timeline of operating and planning the system. For this reason, the information exchange framework needs to be designed differently over various time horizons, and needs to be determined according to the risks of uncertainty of this information. ALC provides a multi-layered (from end-users to load serving entities to the system operator), multi-temporal (ranging from a long-term capacity and energy decision making to a short-term scheduling including day-ahead clearing and near-real-time adjustment) information exchange framework that relates the decisions made by each entity over different time horizons. The decisions of each entity and the information on the system condition were modelled based on Non-zero sum game theory. The thesis provides a numerical example where we design an ALC framework that is specific to the characteristics of the loads and generators of the system. Another example shows that ALC can efficiently schedule a large number of end-users with generators a day ahead of operation, and adjust the scheduled amounts in near real time even when the system condition has changed from what was expected. The biggest contribution of this thesis is in proposing and showing the proof of concept of a system operation framework, which enables the choices of end-users that have different energy consumption preferences and loads with physical dynamics. We show the conditions under which the system optimum can be achieved with various objectives of the entities coordinated by the system operator.

Our ALC framework suggests changes in policy regarding system operation. For day-ahead scheduling, the inter temporal dynamics and constraints of local supply and demand units, including end-users, should be well incorporated in optimising the system's objective. We showed that information to be exchanged in different time horizons, e.g., day-ahead and real-time clearing, should be designed differently. The types of loads and their physical characteristics should also be of concern when scheduling these resources with the rest of traditional supply units, and especially with more uncertain and volatile renewable generation resources. The information exchanged between load serving entities and end- users has implications on the service products of LSEs, such as demand subscriptions suggested in. Moreover, due to the generality of the ALC framework, the information exchange protocol can be applied to other components in a power system as well.

6.2 Future scope

There is much future work ahead in order to relax many assumptions we made to show the proof of concept. The objectives of load serving entities were approximated since we assumed perfect competition and no gaming among them. There is a centralised controller which operates circuits breakers. They should communicate each other to reach optimal solution by using distributed controlling algorithm. Physics of a power system network was approximated to a linear model with only active power supply and demand. However, for extension of the short-term scheduling, priority based function can also be included in pay-off function to have the optimal solution round the clock.

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