Multi-Agent Based Techniques for Coordinating the Distribution of Electricity in a Micro-Grid Environment

Samuel J. O. Miller
The University of Southampton, United Kingdom

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Abstract

By the year 2050, the UK must transition to a low carbon economy via an 80% reduction of all carbon emissions. In order to ensure that this challenging low carbon emissions plan is met, not only will energy need to be generated and used more efficiently, but technologies that use cleaner energy, such as the electrification of home heating and vehicles, will need to be introduced. This increase in demand for electricity will need to be balanced with additional supply, however the current national grid is not capable of sustaining this increase. Therefore a more dynamic and efficient two-way national grid will be required which incorporates intermittent renewable resources, micro-generators, micro-storage devices and agent managed microgrids. Fred Schweppe, a recognised world leader in the field of electric power, at Massachusetts Institute of Technology from 1960 onwards, researched ways in which a dynamic national grid could be implemented. However at the time the technologies available were limited. This paper compares the current state of the art techniques at solving some of problems Schweppe identified, describes the agent coordination algorithms that are used, and suggests some future research opportunities on applying agent coordination algorithms, that have not previously been used, to microgrids.

1 Introduction

One of the main concerns of the 21^{st} century is the transition to a low carbon economy via an 80% reduction of all carbon emissions by the year 2050 (Gov, 2009). As the population increases, and supplies of non-renewable gas and coal reserves become depleted, more efficient uses of energy will be required in order to sustain the growth and development of future generations. This paper gives a detailed description of the need to shift to a more dynamic national grid in order to increase the efficiency of electricity generation, and compares the research conducted by Schweppe et al. against the current state of the art research for tackling this problem.

This paper is organised as follows: Section 2 gives an introduction to the area of research, describing the current national grid and the reasons why a more dynamic grid is needed. Section 3 details the research conducted by Schweppe et al. and their solutions to the problems they identify. Section 4 compares the current state of the art techniques for improving the national grid against Schweppe's research and details the agent coordination algorithms that could be used. Section 5 concludes.

2 Background Research

To reduce carbon emissions and ensure that the UK low carbon emissions plan is met, not only will energy need to be generated and used more efficiently, but technologies that use cleaner energy will need to be introduced. The residential sector accounts for 25% of all UK carbon emmissions, the majority of which is a consequence of heating living spaces and water (Gov, 2009). Currently gas is used in heating, however the transition to lower carbon energy generation will see an increasing demand for electric heating technologies such as ground-source and air-source heat pumps (Dep, 2009).

Another major source of emissions comes from the transport sector, which contributes a fifth of all UK green-house emissions (Gov, 2009). To reduce these emissions, a shift from conventional vehicles, to ultra-low carbon vehicles (ULCV) such as hybrids, electric vehicles and hydrogen fuel cell vehicles, will be experienced. Due to these factors the demand for electricity will increase dramatically over the coming decades in order to alleviate these rising concerns. The problem is that due to the current national grid, the increasing demand for electricity will only result in more carbon emissions. Therefore to resolve this situation and ensure that the targets for 2050 are met, lower carbon generation technologies using renewable resources, such as wind and solar, will be required.

Integration of renewable resources into the electricity system is obviously a good thing. However due to the intermittent nature of the renewable resources, (i.e. wind turbines are dependent on wind, which fluctuates greatly between seasons, weeks and days), the complexity of actually integrating these technologies is increased. This is primarily because it is harder to satisfy fluctuating demands with intermittent technologies. Failure to maintain a balance of supply and demand can result in adverse affects to the electricity system which could result in nationwide blackouts. Therefore if renewable resources are to be integrated into the national electricity system, the current national grid will need to evolve to compensate.

2.1 Current National Grid Structure

The national grid, (also known as the national transmission network) is a nationwide infrastructure, consisting of two distinct parts, that enables the transportation of electricity from generators to end users (Nat, 2010). The first part involves generating the electricity in a small number of large power stations and inserting it onto the transmission network; the backbone of the grid that consists of heavy duty cables and pylons capable of carrying very high voltages. The second part consists of the regional distribution networks which, using a series of transformers, reduce the voltage of the electricity to a suitable level for end users, see figure 1.

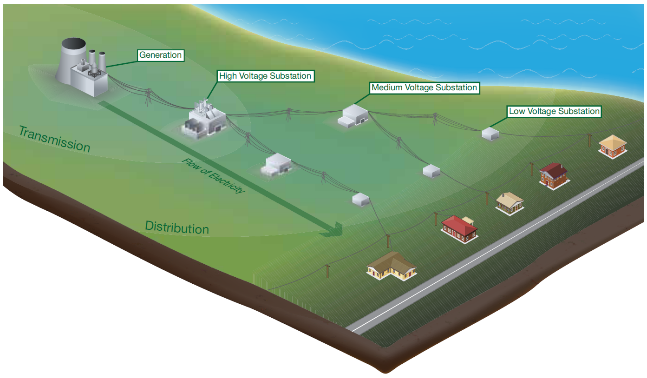

Figure 1: The Current National Grid Structure, used from (Dep, 2009)

The national grid is currently a one way system; electricity is transported from generators to end users with little dynamical techniques. In order to supply increasing demands during peak times of the day, more electricity must be injected into the system. For example during an advert break of certain television programmes, millions of people nationwide turn on their kettles for a hot beverage. This creates a surge of demand which must be balanced with additional supply. The traditional approach is to turn on extra generators which, although are extremely reliable, tend to come at a cost; high carbon emissions.

With the addition of more and more localised and renewable generators, and the plan to reduce carbon emissions, the national grid will have to change the way it meets fluctuations in demand. Renewable generators produce little or no carbon emissions. However they are intermittent and cannot always be switched on or ramped up to meet the peak demands if the renewable resource they use to generate electricity is scarce. Therefore a change to a more dynamic two-way system will be required that is able to dynamically manage the rising demands for electricity and integrate renewable generators.

2.2 A Need For A Dynamical Grid

To be able to meet the rising demand of electricity while making generation more efficient, the national grid will have to evolve into a two-way dynamic system that is able to produce cleaner energy at lower costs; a smart grid. As non-renewable resources become increasingly scarce over the next decade, more and more renewable micro-generation systems will be added to the grid in order to meet the rising demands. Integrating distributed generation decreases the amount of energy lost via transportation because the distance the electricity travels from generator to end user will be significantly reduced. However these micro-generation systems will be intermittent, therefore distributed techniques for managing these devices will have to be employed.

Managing the rising demand of electricity does not necessarily lie solely with the suppliers and distributors. Changes to the way end users receive information about their energy use will eventually increase the effectiveness of the smart grid. Currently most end users pay a fixed price per unit of electricity. However the cost to actually generate this electricity greatly fluctuates due to many factors including, time of day, demand and availability. If a more dynamic real-time pricing system was used that adjusts the cost of the price per unit of electricity, then end users would have more control over how they use their electricity.

During peak times of day the price per unit of electricity is higher, therefore providing end users with this information would give them an incentive to turn off non-essential electrical devices, such as washing machines or tumble dryers, and save money. This would encourage end users to mange their usage more effectively which would balance the demand fluctuation and reduce the need to use extra high cost generators. Smart Meters are the proposed devices that will provide real time information about energy use to end users, and the government has committed to install them in all homes and small businesses by the year 2020 (Gov, 2009). With smart grid, end users may even be able to opt for certain packages that automatically switch devices on and off depending on demand, therefore balancing the demand fluctuations even more efficiently.

With the introduction of ULCV's, the demand for electricity will increase further as more and more people switch to cleaner transport. A technique known as vehicle to grid (V2G) could be employed which uses the vehicles as micro-storage devices. Therefore if there is a surplus of electricity being generated by local micro-generators, it could be stored for future use. Furthermore if there is a high demand for electricity in a particular area, the micro-storage devices could provide electricity back to the national grid, once again alleviating the need to use extra generators. Using distributed micro-storage devices allows electricity generation to be decoupled in time between supplier and end user, therefore during off peak hours when electricity generation is cheaper, it could be stored in these devices for use during peak hours when electricity is more expensive, benefiting not only end users but suppliers as well.

However if these micro-storage devices are all charged at the same time, they will create a sudden increase in demand which will have to be met by additional supply using high cost generators (Vytelingum et al., 2010b); the same problem as before. Therefore, the way the future smart grid performs as a dynamical distributed electricity network will require micro-storage, micro-generators, suppliers and end users to be managed in a more intelligent and distributed fashion to ensure that the most efficient use of the system is maintained.

3 Schweppe's Idea Of A Dynamic Electricity Grid

The idea of a dynamic electricity grid has been around for longer then one might think (Schweppe, 1978). It was thought about long before carbon emissions and efficient use of electricity were even an issue; unlike today. The main driving force of using a dynamic electricity grid came from an engineer called Fred Schweppe. Schweppe was born in 1934 and actively researched the area of electricity and the use of a dynamic electricity grid at Massachusetts Institute of Technology from 1960 onwards. He speculated that in the future electricity use would have to become more efficient due to increasing electricity demands and that the current national grid was not capable of sustaining such an evolution.

Schweppe identified three key areas of the current electrical system that could be changed in order to produce a more dynamic electricity grid: creating a system where supply and demand are in a state of equilibrium (Schweppe et al., 1980), pricing electricity in a more dynamic way over space and time (Bohn et al., 1984), and limiting the peak-power-demand of a group of buildings (Williams and Schweppe, 1986). The main focus of this section is to review and discuss these key areas.

3.1 Homeostatic Utility Control

The traditional electricity system, as it was 20 years ago and still largely today, uses an approach where supply follows demand. This means that end users are allowed to request as much energy as they require and pay a flat rate per unit of energy they consume, that varies infrequently. This is however a poor model of how the actual electricity system works. The cost of electricity generation depends largely on time of day, month or year, available supply and current demand. However these fluctuations in cost are not passed onto the end user of the electricity. Schweppe et al. (1980) identified the following as criticisms of the traditional electricity system:

Fuel Inefficiency As a result of rapidly following the demand fluctuations, generators are being rapidly ramped up and down. This is an inefficient way of generating electricity because of the extra costs involved when changing generating capacities. A more flat and constant approach would increase fuel efficiency.

Peak Load The large ratio between peak and average loads on the system means that extra generators need to exist in order to supply the peak demand periods. These extra generators often have substantial costs to run and are therefore very inefficient.

Fixed Prices Since prices for electricity are mainly fixed, this discourages end users to implement their own generation facilities because there is no incentive to do so (i.e. cheaper electricity costs).

One way to increase the efficiency of generating electricity would be to use a system where demand follows supply. This would mean that to flatten out the peak demand periods and thus increase fuel efficiency, demand would be reduced by actively not supplying it. Although this would allow generators to run at a constant output and produce electricity at minimum cost, it would not be acceptable to have an intermittent electricity supply. Therefore to create a more efficient and reliable system, a dynamical way in which supply and demand coexist in a state of equilibrium is required (Schweppe et al., 1980).

Homeostatic utility control allows the constant fluctuations of supply and demand to be stabilized providing all the advantages of both supply follows demand and demand follows supply, while avoiding most of the disadvantages associated with them. Three distinct functional developments are required for the successful implementation of this technique. The first is a mechanism to balance supply and demand using both automatic generation control (AGC), where supply follows demand, and frequency adaptive power energy rescheduler (FAPER), where demand follows supply. The second is the switch from fixed pricing of electricity to a more dynamic approach where end users pay a price for electricity that reflects closely the cost for generating it over time. The third is a way to notify the end user of these fluctuating electricity costs so that they can more effectively manage their own electricity consumption. The device proposed was called a marketing interface to customer (MIC), however the current term for such a device is called a smart meter, see section 2.2.

3.2 Optimal Pricing In Electrical Networks

One of the criticisms of the traditional electricity system was targeted at the fixed price of electricity that end users pay. This does not reflect the actual cost of generation, since the cost to generate electricity fluctuates depending on a number of factors, see section 3.1. In order to implement homeostatic utility control (Schweppe et al., 1980), Schweppe et al identified that a more dynamical way of pricing should be used; spot pricing (Bohn et al., 1984). It provides a way to price electricity that reflects the underlying physical and engineering properties of electricity and how it is generated, distributed and managed.

Schweppe et al. develop a model to describe how the price to generate electricity is affected by certain factors. The model consists of four aspects, each of which affects the overall price in different ways. The first aspect describes how the generation of electricity will be modelled. The output from a generator depends on the maximum output the generating unit can achieve, the marginal generating cost (dependent on the cost of maintenance, fuel price and heat rate) and the availability of the unit at a particular time. The second aspect models the demand of individual customers, each of which acts independently. Their demand depends on many contributing factors such as time of day, weather and the price of electricity. They are modeled as wanting to maximise their expected profit, (i.e. they want to spend the least amount of money for the most amount of electricity).

The third aspect models the transmission lines that are used to transport and distribute the generated electricity. For each unit of electricity transfered along a transmission line, less then one unit can be used due to loss of energy via heat. In order to maintain a safe level of operation, each transmission line has an energy balancing constraint. If this constraint is violated by either inadequate or excessive generation, then system wide blackouts may be experienced, therefore the model conserves this constraint. Finally, to optimise the entire model and thus find the optimal spot pricing for the network and the operational decisions, the standard welfare criterion is used which attempts to maximise the consumers' plus the suppliers' surplus, subject to the aforementioned constraints.

Using this model allows the electricity generated to be priced in a more dynamic way that reflects the actual costs for generating the electricity. It allows electricity pricing to be dependent on spatial properties of the network (i.e. the cost of electricity for a particular end user is increased the further away they are from the generating unit) as well as temporal aspects relating to fluctuating demands throughout the day, week or month. Relaying these fluctuating prices of electricity to the end user allows them to have more control over their electricity demand. During peak times, when prices are high, they could reduce their own demand and save money, consequently balancing out the overall demand of the network and increasing the efficiency of generating the electricity.

3.3 Limiting Peak-Power-Demand

The traditional approach to compensate for peak demands for electricity is to ramp up additional generators that require a large cost to operate and often produce large amounts of unwanted byproducts. Williams and Schweppe (1986) propose a technique that attempts to smooth the fluctuation in demand throughout the day, therefore reducing the need to switch on the extra high cost generators and allows generators to operate in a more stable fashion resulting in a more efficient and less costly generation of electricity.

The main theory behind limiting peak demand is to apply a global constraint on the resource (i.e. peak electricity) that is available. This theory is applied to an environment where several buildings are associated with each other, for instance a campus or industrial site, and thus their common objective is to limit the peak demand used by the entire site. Since each building has common interests, the problem revolves around redistributing the demands so that the peak demand is more balanced. One decentralised approach is to allocate a fixed power supply to each building that optimise's the global constraint, however this is not able to accommodate an environment with dynamically changing demands for electricity use and thus is not an appropriate solution for the future electricity network.

Each building is represented as an autonomous agent with a well defined objective function. An agent has a number of resources available to it in the form of the rights to consume power during each of several time intervals. However individual rights to consume power do not correspond to the individual agents consumption needs, therefore consumption rights can be exchanged between agents. Since the total peak-power-demand is the sum of the individual agents consumptions, and the common objective of all the agents is to reduce and balance this peak demand, then the agents consumptions can be cooperatively altered without violating or changing the peak demand constraint.

The number of agents that are likely to participate in the exchange will be relatively small in this context (Williams and Schweppe, 1986). All the agents will have an influence on the exchange mechanism, however none of the agents will dominate it. Therefore cooperative mechanisms can be applied in which all of the agents can satisfy their objective functions fairly, without any one agent receiving a much higher utility then the others.

One approach for the exchange mechanism involves using a bidding structure in which agents give resource offers and requests using some unit of price. Each agent has their own objective function that they wish to optimise but in order to reduce the global constraint of peak-power-demand, the global objective (i.e. to balance out the demand) needs to be optimised. With this mechanism, the global objective is the sum of the individual objective of each agent, however there are two fundamental problems:

1. The global objective attempts to redistribute resources. However since each agent has only their own local objective function that they wish to optimise, there is no incentive for any agent to supply resources unless they have an excess.

2. In order to optimise the global objective and redistribute resources, accurate knowledge of each agents individual objective function is required. However knowing each agents objective function is a breach of an agents

privacy and defeats the point of having autonomous agents in the first place.

Therefore a simpler mechanism was proposed for varying the rights to consume power involving the use of a simple bartering system, where every exchange of one resource is accompanied by a balanced exchange of some other resource. To make sure that the exchanges are compatible with each other, an arbiter is used to reconcile incompatible bids so that feasible exchanges that are equitable for each agent are established.

This overcomes the two problems mentioned previously. The supply incentive is overcome because bartering is being used to exchange one resource for another resource, (i.e. any transaction must involve more then one resource, instead of just one resource and a price), therefore during each transaction both agents are effectively suppliers and consumers since they are both receiving and sending resources. The privacy and global optimisation problem is addressed because a bartering system can operate without requiring the offers and requests to be related to individual objective functions. Each agent can still retain their own incentives, however in order to satisfy their objective functions, they may need to participate in transactions that don't always give them high utility, since each transaction requires that an exchange of resources takes place.

4 Comparison Of Agent Based Techniques

Schweppe had some very interesting points of view about how to change the electricity system to make it more efficient and dynamic. However most of his research was either theoretical or could not be implemented due to restrictions of the technology at that time. During the last decades there has been major advancements in the areas of agent-based technologies, therefore this section compares the current state of the art for a more dynamic electricity grid and details which of the problems identified by Schweppe have been solved as a result.

4.1 Microgrids

The proposed solution to Schweppes vision of a dynamic national grid, that manages electricity efficiently, is to evolve the electricity networks into decentralised migrogrids that use agent based technologies to manage them. A microgrid, or smart grid, consists of micro-generators, micro-storage devices, electrical devices, smart meters and end users connected in a decentralised way. The idea is that each microgrid is connected to major electricity generators, such as nuclear or coal stations, much like the current system. However the difference is that each microgrid has the ability to be disconnected and isolated from the national grid (i.e. working in island mode) and continue to balance the supply and demand using autonomous agents to manage the electricity flow around the decentralised network.

Using microgrids can be seen as a software alternative to the traditional hardware based protection systems which isolate parts of the national grid if blackouts or malfunctions occur. Using microgrids instead to isolate parts of the national grid not only allows greater flexibility about where the boundaries of the isolated network are, but also allows a more intelligent management of the electricity within the microgrid when it is being isolated.

This section comprises a comparison that details how the current state of the art techniques solve the problems proposed by Schweppe and is structured as follows: Sections 4.1.1 and 4.1.2 compare the techniques by Bohn et al. (1984), Williams and Schweppe (1986) and Schweppe et al. (1980) with the current state of the art techniques.

4.1.1 Optimal Pricing Strategies

When the microgrid is connected to the national grid, the electricity that it needs to meet demand can either come from the national grid, local micro-generators or local micro-storage devices. Using Bohn et al. (1984) ideas for optimal pricing of electricity, when the price for the electricity is high, due to demand distributed across the entire national grid, local generators could be used to supply the demand of the microgrid. Furthermore if the demand is particularly high, micro-storage devices could also be used to supply. However determining when to either charge the micro-storage devices, use electricity from the national grid or from micro-generators is an issue.

The solution proposed by Bohn et al. (1984) uses a simple bartering system so that agents have an incentive to trade the rights to consume power, see section 3.2. Recently there have been solutions to this problem which use different methods for the trading of electricity within the microgrid (Vytelingum et al., 2010b), (Dimeas and Hatziargyriou, 2004) and (Vytelingum et al., 2010a).

Vytelingum et al. (2010b) propose a technique for overcoming this issue involving agents in a distributed microgrid. Each agent represents either a consumer or supplier and are selfish individuals that only want to minimise their individual costs. They may also have some form of storage available to them. The aim of the technique is to create a Nash equilibrium such that the agents within the microgrid converge to profitably efficient behaviour, knowing when best to charge their storage device, when to use their storage profile, or when to consume electricity. To do this the agents must adapt over time to become more aware of the repeating daily patterns of demand and supply. In doing so the agents adaptively change their own storage profiles each day to their perceived optimal strategy.

This technique even allows agents to sell some of the electricity in their storage device back onto the national grid, if there is an increase in demand, meaning that end users, represented by agents, could potentially profit when they have a surplus of electricity. End users with a storage device of 4kWh, would be able to achieve savings of up to 13% on average for their electricity bills if this agent based technique is implemented within the UK. Furthermore only 38% of UK households would need to own such a storage device for an equilibrium to be experienced and social welfare to be maximised.

Dimeas and Hatziargyriou (2004) propose a solution using an English auction protocol for the exchange of energy within a microgrid. Trading starts when the grid operator announces the buying and selling prices of energy to the microgrid, whereupon the local consumption units announce their demands of energy for the next 15 minutes; this is the negotiation period and takes 3 minutes. Production units accept or decline offers made by the consumption units. However if after the negotiation period, no production unit has accepted an offer, the energy must be bought from the national grid. Therefore this method is not always suitable if the microgrid must be isolated from the national grid for extended periods of time as it could fail to meet the demands of the consumption units.

Another such solution has been proposed by Vytelingum et al. (2010a) which solves the problem of congestion and fluctuating demands by using a continuous double auction (CDA), an auction which allows multiple agents to continuously make offers until a transaction (i.e. a possible buyer and seller) is found, to price the electricity. The assumption, equivalent to Bohn et al. (1984), is that each agent is selfish and only has their own interests to maximise. Furthermore they assume that the agents will not truthfully reveal their consumption patterns or reserve prices; This approach differs from current mechanisms that exist in the wholesale electricity market.

They introduce several techniques which advance the state of the art and solve the problem of a dynamic electricity pricing market. The market mechanism manages congestion within the system using DC flow approximations to price the electricity. Thus the electricity is priced dynamically meaning that priority transactions, when resources are limited, are satisfied first. A balancing system is introduced that ensures buyers pay a fair price for unexpected demand and that generators are compensated accordingly. Moreover it generates the fluctuating prices in real-time thus agents have more of an incentive to bid truthfully in the market.

Overtime the mechanism for congestion transmission line pricing evolves to increase the efficiency of the proposed electricity market, thus allowing the market mechanism to achieve close to the optimal allocations. Furthermore a new technique called dynamic location marginal prices (DLMP) is introduced that indicates endemic levels of congestion indicating possible future infrastructure improvements. DLMP could also indicate where potential boundaries of a microgrid could be altered to either include or exclude these areas of high congestion allowing for greater control over the electricity network. Simulation results have shown that this market mechanism produces a 99% efficiency for pricing electricity and transmission line management, allowing end users to maximise their own benefits with potential profits.

4.1.2 Achieving a State of Equilibrium

Balancing demand and supply will greatly increase the efficiency of the electricity system and will benefit not only end users but also electricity suppliers. Williams and Schweppe (1986) attempt to balance the supply and demand by achieving a Nash equilibrium. As a Nash equilibrium is reached, the balance between supply and demand is smoothed out resulting in a more stable electricity supply and a decreased use of the expensive extra generators, thus the peak-power-demand is also reduced. The solutions proposed by Schweppe et al. (1980), where supply follows demand and demand follows supply, can also be seen as trying to smooth the balance between supply and demand. This problem has been addressed by Vytelingum et al. (2010b) whereby each agent constantly changes their consumption rates and storage profiles to acquire equilibrium.

In order to achieve a balance between demand and supply, the generators need to be adjusted to compensate for fluctuating demands. Oyarzabal et al. (2005) provide an algorithm which automatically adjusts the power schedules of the generators within an isolated microgrid based on a number of factors: renewable generators that are often intermittent, fixed schedule generators (i.e. those that are also linked to heat demand links or contracted schemes), resource availability (i.e. the wind speeds for turbine generation) and the maximum and minimum power producing limits of the generators. Taking all these factors into account, the algorithm is able to efficiently manage the generators within a microgrid leading to more a efficient and cost effective electricity generation.

The problems proposed by Schweppe et al. (1980) (i.e. fuel inefficiency, peak loads and fixed prices) have been addressed in the previously mentioned literature. Fuel inefficiency and peak loads have been reduced by smoothing the peak-power-demands so that extra generators do not need to be used (Vytelingum et al., 2010b), and by integrating micro-generators and micro-storage devices into the microgrid (Pipattanasomporn et al., 2009) and (Oyarzabal et al., 2005). Fixed pricing of electricity is an issue because it does not reflect the actual costs generating it however the solutions proposed by Vytelingum et al. (2010a) and Dimeas and Hatziargyriou (2004) give robust solutions.

This section has presented several state of the art agent frameworks and market mechanisms for solving some of the problems proposed by Schweppe et al. (1980). Only the framework for the systems have been presented; The coordination algorithms that are used to control the agents have not been specified. Therefore the following section comprises the agent coordination algorithms that have been used in an electricity microgrid environment, as well as some potential coordination algorithms that are yet to be used.

4.2 Agent Coordination Algorithms

Coordinating agents in a microgrid environment requires a coordination strategy that is able to cope with distributed agents that communicate and act in a decentralised way. The contract net protocol (Smith, 1980) is one such algorithm that is used in the microgrid environment (Jiang, 2006). The protocol starts by an agent, a, requesting a certain resource, r, in this case electricity, from the other agents. Each agent may or may not make an offer, o to supply r to a for a certain price. a chooses the o that maximises its own utility function and thus a contract is made between a supplier and consumer.

The advantage of using contract net is that it is a very simple protocol and thus is computationally inexpensive. However the one major disadvantage is that it does not allow complex negotiation strategies such as counter proposals. Thus if a does not accept any offers or the other agents do not make any offers, then a contract can not be made and a will not receive any resources. This could have unacceptable consequences if the electricity supply to a particular agent, and thus a particular device that this agent represents, is interrupted because the device may stop working resulting in a blackout of part of the microgrid.

To overcome this issue, allowing for more complex behaviour, Vytelingum et al. (2010a) use a CDA to manage the microgrid by pricing the flow of electricity. A CDA permits multiple buyers and sellers to compete in the electricity market for resources. The protocol is continuous because it allows agents to continuously make offers in the market and improve upon those offers until a potential buyer and seller is matched. This complex strategy overcomes the issues of a contract net protocol because it allows agents to negotiate with each other resulting in each agent eventually being satisfied.

An interesting approach to managing agents in this electricity microgrid environment, that has not previously been used, is coalition formation (CF) (Shehory et al., 1997). Coordinating groups of agents, referred to as coalitions, has already been investigated extensively within game theory, however this is in a centralised manner. CF coordinates agents in a decentralised manner allowing agents to form coalitions whereby within their coalition they act cooperatively to achieve some combined utility. Agents only form coalitions if they perceive that forming the coalition will increase their own utility, therefore only beneficial coalitions are formed.

Since agents form coalitions to cooperatively interact, a possible application for CF would be to apply it to a part of the microgrid that has common objectives, such as an army base or university campus. For instance, you may want to limit the peak-power-demand in a certain area of the microgrid, therefore using CF, agents can form a coalition in that area and cooperate effectively. After the agents have achieved their combined goal, they can disband and form other coalitions. The advantage of using a CF approach is that coalitions can be formed and broken, therefore agents that cooperated previously, do not necessarily have to cooperate in the future. Therefore in the case of limiting peak power on a microgrid, the boundaries of the area that the peak power is being limited can be changed just by forming larger or smaller coalitions creating a more dynamic and efficient electricity grid.

Another possible application of CF is to use it to manage a virtual power plant (i.e. a group of distributed microgenerators and micro-storage devices that act as a functioning power plant). Virtual power plants have already been used by PowerMatcher to manage a microgrid and field tests have been carried out which prove that virtual power plants are an effective way of combining intermittent microgenerators and micro-storage devices (Roossien, 2009). If CF is used in conjunction with a virtual power plant, the common goal of the a particular coalition would be to meet fluctuating demands with uninterrupted supply, thus using CF, the agents would form beneficial coalitions and, using the techniques proposed by Vytelingum et al. (2010b), be able to dynamically decide where electricity is needed, which generators should be used at what times, and when to the store the electricity.

A recent successful coordination strategy for coordinating agents in a decentralised manner, called max-sum, has been proposed by Farinelli et al. (2008) and could be a suitable technique for coordinating agents in a microgrid environment. The max-sum algorithm calculates the best possible actions for each agent based on their utility relationships using a bipartite factor graph. Messages are passed around the factor graph until each agent has received a message from all of its neighbours, at which point the best action for each agent is chosen. Max-sum can be seen as an extension of DPOP (Petcu and Faltings, 2005), however it overcomes DPOP's disadvantage of scaling exponentially with the number of agents and is thus a much better algorithm to coordinate multiple agents in a microgrid. Max-sum coordinates agents cooperatively and therefore like CF, the possible applications for it are limiting peak-power-demand within a part of the microgrid with common objectives, like an army base or university campus.

Kumar et al. (2009) also propose an extension of DPOP which deals with the exponential scalability and have already applied it to a microgrid environment. It too uses message passing between agents and is able to manage the flow of electricity in real time around a distributed network that contains many cyclic paths, outperforming the standard binary decision diagram (BDD) that has been used previously to manage electricity. Thus there is definite potential in applying the max-sum algorithm to successfully manage multiple agents in a microgrid.

5 Conclusions

The current national grid that distributes electricity around the UK will be insufficient to sustain the growing population and increasing electricity demands of the future. This is largely due to the one-way nature of the system and the inefficient way it deals with fluctuating demands. A more dynamic two-way system, where micro-generators and micro-storage devices are incorporated into the national grid using agent based techniques to manage the system autonomously, is required in order to meet the rising demands for cleaner more efficient electricity.

The need for a more dynamic grid was identified by Schweppe around two decades ago when the need for a more dynamic electricity grid was not prevalent. He participated in research that tried to overcome the current issues with the national grid by using agent based techniques. He identified three key areas of the national grid which need to be evolved: creating a system where supply and demand are in a state of equilibrium (Schweppe et al., 1980), pricing electricity in a more dynamic way over space and time (Bohn et al., 1984) and limiting the peak-power-demand of a group of buildings (Williams and Schweppe, 1986).

Schweppe's solutions and techniques have been compared to the current state of the art, identifying solutions which have been improved as a result of two decades worth of progress in the field of artificial intelligence. Along with the frameworks of the microgrids proposed in the literature, the coordination algorithms used to manage the agents within the microgrid, such as contract net and continuous double auction, have been reviewed and compared. Max-sum and coalition formation have been suggested as potential coordination algorithms to manage the agents of the microgrid with applications such as limiting peak-power-demand in a university microgrid.

As a result of this papers research it is apparent that a smarter electricity grid is definitely feasible with the current state of the art techniques proposed in the literature, however more experimentation needs to be completed in order to test the long term stability of a microgrid electricity system. Future possible research to consider would be implement the max-sum and coalition formation algorithms and test the efficiency of each one at managing a microgrid consisting of multiple micro-generators, micro-storage devices and end users.

To implement the coalition formation algorithm effectively it needs to be extended so that it can cope with incomplete information. It is easy to form coalitions in a centralised manner when complete information about each agent is known since the centralised repository can compute the most optimal formation of a coalition. However when a decentralised approach is used, forming a coalition is harder because each agent only knows a limited amount of information making it harder to compute a beneficial coalition.

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