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Fair electricity transfer price and unit capacity selection for microgrids

Di Zhang [a], Nouri J. Samsatli [a,b], Adam D. Hawkes [c], Dan J.L. Brett [a,c], Nilay Shah [b], Lazaros G. Papageorgiou [a,*]

[a] Centre for Process Systems Engineering, Department of Chemical Engineering, University College London, London WC1E 7JE, UK
[b] Centre for Process Systems Engineering, Imperial College London, London SW7 2BY, UK
[c] Energy Futures Lab, Imperial College London, London SW7 2AZ, UK

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ABSTRACT

Microgrids are defined as an area of electricity distribution network that can operate autonomously from the rest of the network. In order to achieve the best economic outcomes, the participants in a microgrid can benefit from cooperation in microgrid design and operation. In this paper, a mathematical programming formulation is presented for fair, optimised cost distribution amongst participants in a general microgrid. The proposed formulation is based on the Game-theory Nash bargaining solution approach for finding optimal multi-partner cost levels subject to given upper bounds on the equivalent annual costs. The microgrid planning problem concerning the fair electricity transfer price and unit capacity selection is first formulated as a mixed integer non-linear programming model. Then, a separable programming approach is applied to reform the resulting mixed integer non-linear programming model to a mixed integer linear programming form. The model is applied to a case study with a microgrid involving five participants.

1. Introduction

Given that global electricity demand is increasing by 2.4% each year, and is accompanied by rising global emissions of greenhouse gases, the current centralised generation system may benefit from being re-evaluated (Colson and Nehrir, 2009). Decentralised energy resources (DER) are a class of technologies that could help in this regard, and are emerging as a potentially important feature of future power systems and as an alternative or complement to centralised generation. A number of concepts have emerged in recent years in relation to deployment and control of these DERs, including 'smart grids' and 'microgrids'. These concepts represent a significant departure from the top–down and asset-intensive nature of current electricity systems, and capitalise on the availability of new generation equipment and information and communication technologies (ICT) systems to facilitate the use of many small-scale energy resources to serve burgeoning demand. It has been demonstrated that such technology can provide economic benefits through avoidance of investment in upstream infrastructure, security and reliability benefits through interconnection and coordinated control, and environmental (and additional economic) benefits through the use of low carbon/low pollutant generation and co-production of heat and power. The detail of the smart grid concept remains only loosely defined at present based on specific focuses whilst there is no agreed universal concept yet (Sun et al., 2010; Zhang and Du, 2010). It is apparent that it is likely to include active control of small scale energy resources. The context of this paper is that the technical aspects of such control have benefitted from research attention (Hernandez-Aramburo et al., 2005; Lasseter, 2011; Piagi and Lasseter, 2006), but the economic incentive for participants to become involved has not. Therefore this paper strives to begin addressing this gap by considering a fair economic settlement scheme for participants in a microgrid, which is a special case of the smart grid concept.

1.1. Unit capacity selection in microgrids

A microgrid can operate in either grid connected or islanded mode[1] when there are external faults and/or to gain economic

* Corresponding author. Tel.: +44 20 7679 2563.
E-mail address: l.papageorgiou@ucl.ac.uk (L.G. Papageorgiou).

[1] Islanded mode means no electricity can be obtained from grid.

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advantage. As a relatively small-scale localised network, a microgrid can include loads, generators, energy storage devices, and network control systems. It operates and fulfils the local energy demands according to its own protocols and standards (Lidula and Rajapakse, 2011; Siddiqui et al., 2005). The distributed generators applicable for a microgrid can comprise a range of existing and emerging technologies. Examples include combined heat and power (CHP), micro turbines, wind generators, photovoltaic arrays, fuel cells and also some well established technologies, such as small hydro. Energy storage devices can be applied to balance the demand with generation. Batteries, fly-wheels and super-capacitors are more appropriate for microgrids amongst the available energy storage technologies (Huang et al., 2008).

Microgrids have been developed for a number of reasons: they can provide better power quality and reliability in case of blackout or other problems on the external network; they may have economic and environmental benefits when emissions credits are considered because they can utilise more low carbon energy sources such as wind and solar energy; and they are localised which implies that some transmission infrastructure and associated costs may be avoided. Additionally, primary energy consumption could be reduced when combined heat and power (CHP) technology is applied (Marnay et al., 2008). Finally, microgrids also have the inherent advantages of being interconnected via a local or private network, so the participants can cooperate with each other thus increasing equipment utilisation and providing yet more benefits.

Several studies have considered how to design the capacity of a microgrid system to minimise the annual cost of meeting demand (Asano et al., 2007; Marnay et al., 2008; Zhang et al., 2008). A computer program that optimises the equipment arrangement of each building linked to a fuel cell network and the path of the hot-water piping network under the cost minimisation objective has also been developed (Obara, 2007). Energy management systems and optimal scheduling have been produced to generate an optimum operation plan for microgrids (Bagherian and Tafreshi, 2009; Mohamed and Koivo, 2010; Morais et al., 2010). Hawkes and Leach (2009) presented a linear programming cost minimisation model for the high level system design and corresponding unit commitment of generators and storage devices within a microgrid. Sensitivity analysis of total microgrid costs to variations in energy prices has been implemented and the results indicate that a microgrid can offer a positive economic proposition. This model provides both the optimised capacities of candidate technologies as well as the optimised operating schedule. King and Morgan (2007) performed a baseline analysis estimating the economic benefits of microgrids, and it indicates that a good mix of customer types would result in better overall system efficiency and cost savings. However, for all of these models, the objective function is to minimise the total cost for the whole microgrid; the costs to respective participants are not considered. This raises a problem that design and operation of the microgrid are based on the mutual interest of all participants instead of the self-interest of each participant. This approach could be improved, because there is the possibility that some participants will not benefit from the microgrid, whilst others do benefit. Therefore a fair method for settlement between microgrid participants is essential for the success of this concept.

1.2. Fair settlement using Game theory

Microgrids can be considered as collaborative networks. Microgrid participants may have their own objectives and constraints which make them compete with other participants, but they will also recognise that they can be better off via cooperation. Cooperation amongst microgrid participants can provide better economic outcome than being isolated from each other with pure self interest. The asset utilisation will be increased and the average capital cost for each participant could also be decreased. A number of collaborative planning schemes with different assumptions and different areas of application have been reviewed by Stadtler (2007).

Game theory is a powerful tool for studying strategic decision making under cooperation and conflict conditions (Fudenberg and Tirole, 1991). It attempts to mathematically describe people's rational decision making behaviour under a competitive situation, where the player's benefits depend on his or her own choices as well as the choices of the other players. Nash (1950) presents the equilibrium point of finite games, where all players adopt the strategy which gives them the best outcome given that they know their opponents' strategy. In essence, Nash equilibrium is defined as a profile of strategies such that each player's strategy is an optimal response to the other players' strategies. Game theory has been applied in diverse areas, such as anthropology, auction, biology, business, economics, management–labour arbitration, politics and sports. Yang and Sirianni (2010) set up a framework for sharing regional carbon concentration under global carbon concentration cooperation. In the area of energy economics, Carpio and Pereira (2007) proposed a decision-making model for competitive electric power generation between different subsystems in Brazil based on Nash–Cournot equilibrium with the objective of maximising regional benefits. Using an agent-based approach incorporated with Game theory, Sueyoshi (2010) investigates the learning speed of traders and their strategic collaboration in a dynamic electricity market. Whilst in the area of supply chain management, Game theory is utilised to help understand and predict strategic operational decisions. There are two recent reviews on the application of Game theory in supply chain management, and both non-cooperative and cooperative games are discussed (Leng and Parlar, 2010; Ohnson et al., 2004). Nagarajan and Sosic (2008) reviewed some applications of cooperative Game theory to supply chain management with the focus on profit allocation and stability. Zhao et al. (2010) proposed a cooperative game approach, and is considered to help the coordination issue between manufacturers and retailers in supply chain using option contracts. An option contract model is developed, taking the wholesale price mechanism as a benchmark. Leng and Parlar (2010) apply both the non-cooperative Nash and Stackelberg equilibrium, and coordination with cost-sharing contracts, to achieve the maximum system-wide expected profit.

Game theory has been applied to find the 'fair' solution, although there are different measures of fairness. The fair solution suggests that all game participants can receive an acceptable or 'fair' portion of benefits. As Leng and Zhu (2009) discussed, an appropriate side-payment[2] contract can be developed to coordinate the participants in a network. Various side-payment schemes to coordinate supply chains are reviewed, and a procedure for such contract development is provided and applied. It has the assumption that all side-payment contracts in the discussion are legally possible, whereas some of them could be illegal and will be prohibited in practice. Rosenhal (2008) provides a cooperative game that provides transfer prices for the intermediate products in the supply chain to allocate the net profit in a fair manner. It applies when the market prices for the products are known and when the values differ. In the work of Ertogral and Wu (2000), the fairness is defined as facilities burden sharing. A benchmark is set first, then the respective participant cost is compared with this benchmark and the objective is to minimise the absolute deviation of the difference. In this way, the sum of the unfairness is minimised, but the result shows that the fair solutions sacrifice one third on average in solution quality. Nash bargaining framework from cooperative Game theory has been applied for 'fair' solution in different areas. It has been applied by Yaiche et al. (2000) for bandwidth allocation of services in high-speed networks. Ganji et al. (2007) develop a discrete stochastic

[2] Side-payment is defined as an additional monetary transfer to improve the chain-wide performance.