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Keywords future power systems, zones of control, auctions

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Economic zones for future complex power systems

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ABSTRACT

This paper examines the economics of the electricity market out to 2050. We propose a flexible zoning concept, built up around economic and technical layers, in networks of the order of hundreds of thousands or millions of nodes. The Economic Layer runs auctions to determine the electricity to be delivered and prices. The Economic Layer delivers suggestions after a fixed ordering, starting with suppliers and demands that generates the lowest overall system cost, then second-lowest overall network cost etc. These suggestions are delivered to the Technical Layer that checks for feasibility in terms of technical constraints. The first match between the ranked suggestions and non-violation of technical constraints is chosen. We demonstrate why this paper should be considered for future power systems. This paper extends previous work on reactive power exchange by introducing market considerations in zoning mechanisms for active power exchanges. We also exhibit the potential for much higher price resolution in distribution networks via our concept of economic zoning.

Key words: Future Electricity Networks, Network Designs, Flexible Zones, Auctions

1. Introduction

In order for society to meet its challenging CO₂ reduction targets it is essential for energy systems to be decarbonised. There are many possible trajectories that can be envisaged for this transition and all of them require radical changes to the way electric

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power is generated, transmitted and distributed not least due to the additional burdens presented by the electrification of heat and transport. One vision relies upon carbon capture and storage, interconnectors and large scale nuclear power coupled with heavy reinforcement of the grid infrastructure. A competing vision favours high levels of decentralisation of both generation and control using fast intelligent network management systems for dynamically defined sub zones of the network. This latter vision relies on flexibility on the demand and generation side, as well as the network, to deliver decarbonisation and promises to require much lower levels of network reinforcement. This decentralisation leads us to consider localised markets to assist with this flexibility. These markets could be for energy and for ancillary services. One consequence of this asset light, flexibility heavy vision is that it will result in a relatively higher network asset utilisation. This means that we would expect the network to place more frequent constraints on the flow of energy between generators and loads. Therefore this paper examines the possibility of a commercial-technical approach to local markets and network management by finding efficient market arrangements that can be delivered without infringing network constraints.

The rest of the paper is organized as follows: section 2 describes the role of economic zones in future networks with high degrees of operational flexibility and autonomy in decision making, reviews the current literature and highlights the paper's contribution in this area. Section 3 reviews current electricity markets drawing examples from the USA. Section 4 presents the concept of flexible zones within our framework. Section 5 presents our results. An illustrative example is given. Section 6 discusses our framework and alternative uses of it. Finally, section 7 discusses possible extensions.

2. Economic Zones in an Autonomic Power System

Existing networks are not designed to cope with the challenges of high uncertainty and complexity that future networks are expected to face and are away from being ready to support the degree of controllability that may be required by 2050. Conventional networks are largely defined according to history, geography and legislation (McArthur et al., 2012). They are often treated as independent networks, however, their operation cannot be considered autonomous as network management does not currently involve significant artificial intelligence and learning mechanisms.

The Autonomic Power System (APS) project focuses on the electricity network of the year 2050 (Alimisis et al, 2013; McArthur et al., 2012; Piacentini et al., 2013). This project investigates if the foreseeable network challenges of 2050 can be met by a fully distributed intelligence and control philosophy. The APS is envisaged as a self-healing, self-optimizing and self-protecting (hereafter self*) system. While these concepts are

often discussed in Smart Grid applications, the APS vision of network control and operation goes far beyond that (McArthur et al., 2012).

An integral part of the APS research agenda is zones of control. A zone can be considered as a group of nodes and edges corresponding to physical elements, e.g. busbars and power lines (McArthur et al., 2012, p. 4). Although the zone sizes are not fixed, actual transmission networks can comprise thousands of buses, and can be segmented in dozens of zones consisting of hundreds of buses each. In conventional networks, these zones are able to exchange power and share constraints at their boundaries. However, these zones are static and do not change. The novelty of the APS concept in this area lies in the fact that these boundaries can be dynamic (hereafter flexible). This allows systems to achieve optimisation of multiple operations, but importantly, learn and adapt by themselves to new situations, such as due to a change in renewable generation or a network fault. This is a step forward compared to the current approach and respective control algorithms. A key aspect of the APS zoning approach lies in the increased operating flexibility at the transmission level, but this can also be extended and developed at the distribution level.

So far in the APS narrative (Alimisis et al, 2013), the flexibility offered by flexible zoning accounts for technical operating constraints. In this paper, we include such considerations with respect to distribution network zones. We introduce the idea of economic zones in distribution networks as a collection of network nodes carrying monetary bids for energy not accounting at first for any technical constraints, but aiming to choose the lowest (possible) cost suppliers to match demands' willingness to pay (WTP) to minimize overall network costs. Lowest cost is achieved in the long run by making use of energy auction bids³.

This paper focuses on the distribution level and introduces two layers of control, each operating separately within zoning structures defined by either technical or economic criteria – we refer to these as the Technical Layer and the Economic Layer. The Economic Layer runs auctions to determine electricity to be delivered (hereafter quantity) and prices without taking into account technical constraints derived by the Technical Layer. The Economic Layer delivers suggestions after an initial ordering, starting with suppliers, connected supply and prices, demand, connected willingness to pay (WTP), that generates the lowest overall system cost (defined as suggestion 1, hence, independent of technical constraints, the collection of bids and therefore, the solution (quantity and

³ In auction terms, see this as optimality (reversed) where a mechanism/algorithm searches for the solution that minimizes total overall network costs.

prices) that the Economic Layer prefers the most⁴), second-lowest overall network cost (suggestion 2) etc. These suggestions are delivered to the Technical Layer that checks for feasibility in terms of technical constraints. The first match between the ranked suggestions and non-violation of technical constraints is chosen.

Our Layers can be seen as two flexible zoning structures in a network containing, for example, of order 5,000 nodes (in a region significantly smaller than the PJM⁵ region in the USA), where the Technical Layer and Economic Layer combine suppliers and demands and set zones from period to period after checking technical and economic conditions.

From a graph theory point of view (Chen, 1997), buses in transmission networks can be viewed as nodes (Chai, 2001) and therefore also as control points for setting (regulating) the price. The resolution of buses in the distribution network is much higher. Therefore in this paper we consider price control nodes (cleared in the auction) to be critical power flow and voltage control points, such as substations and large or aggregated suppliers and consumers. In order to provide an indication of these numbers, Table 1 summarises the current number of substations in the UK for voltage levels of 400kV, 132kV, 33kV, 11kV and 400/230V (ENA, 2015). For the discussion in this paper we are focusing our analysis in the distribution network at 11kV. This would result in a minimum of 4,800 nodes with 5,000 to 30,000 customers each, but higher resolutions are possible.⁶

Given vastly increased computer resources in the year 2050, these high resolutions for price formation could be considered, if necessary (because the increased transactions costs of higher price resolution would be very low). The deployment of smart grid solutions and technologies such as smart meters can facilitate price formation at higher resolution levels and also enable the active control of demand, generation and storage, providing improved network operational visibility. The rightmost column of the table depicts the typical number of customers supplied at every voltage level. An indication of the amount of visibility that will be required in future networks is the Government's Smart Metering Implementation Programme aiming to roll out 53 million smart (electricity and gas) meters in Great Britain by the end of 2020 (DECC, 2013).

⁴ In auction terms, see this as optimality (reversed) where the Economic Layer is a mechanism that searches for the solution which minimises total overall network costs.

⁵ The area of PJM covers more than 3,000 nodes and has a demand roughly three times that of Great Britain. We could also compare the 5,000 nodes to Great Britain (GB) that have 14 demand zones. For the GB as well, one could use a 33kV or a 69kV network (Frontier Economics, 2009).

⁶ Higher resolutions of prices would require the possibility of separate prices at lower voltage levels. This is theoretically possible, but raises issues of how competitive the price resolution might be at lower voltages as the number of potential bidders declines. The benefits of such finer resolution of prices may not outweigh costs at lower voltages.

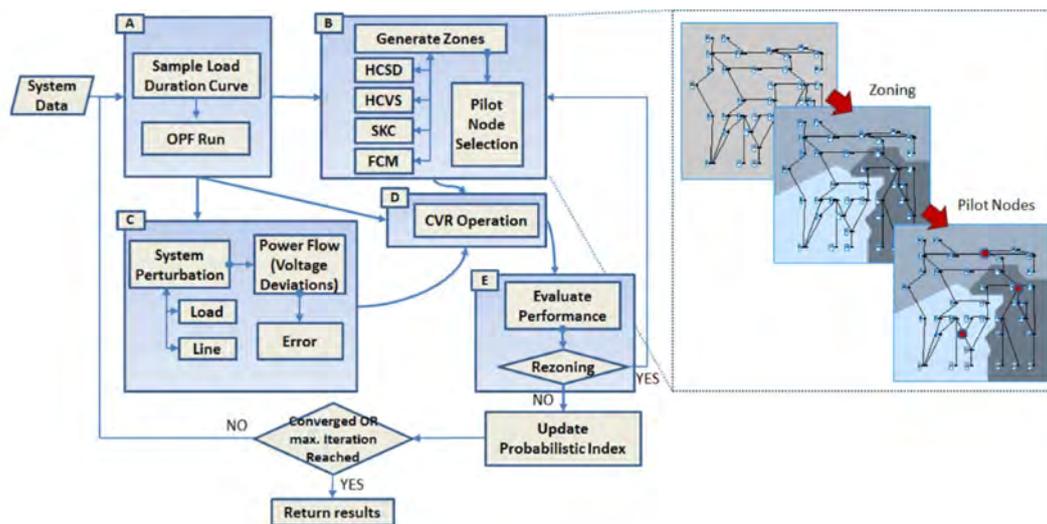
Table 1: Potential number of nodes in a network

Substation Type		Typical Voltage Transformation Levels	Approximate number nationally	Typical Number of Customers Supplied
Grid	Grid Supply Point	400kV to 132kV	380	200,000/500,000
	Bulk Supply Point	132kV to 33kV	1,000	50,000/125,000
Primary		33kV to 11kV	4,800	5,000/30,000
Distribution		11kV to 400/230V	230,000	1/500

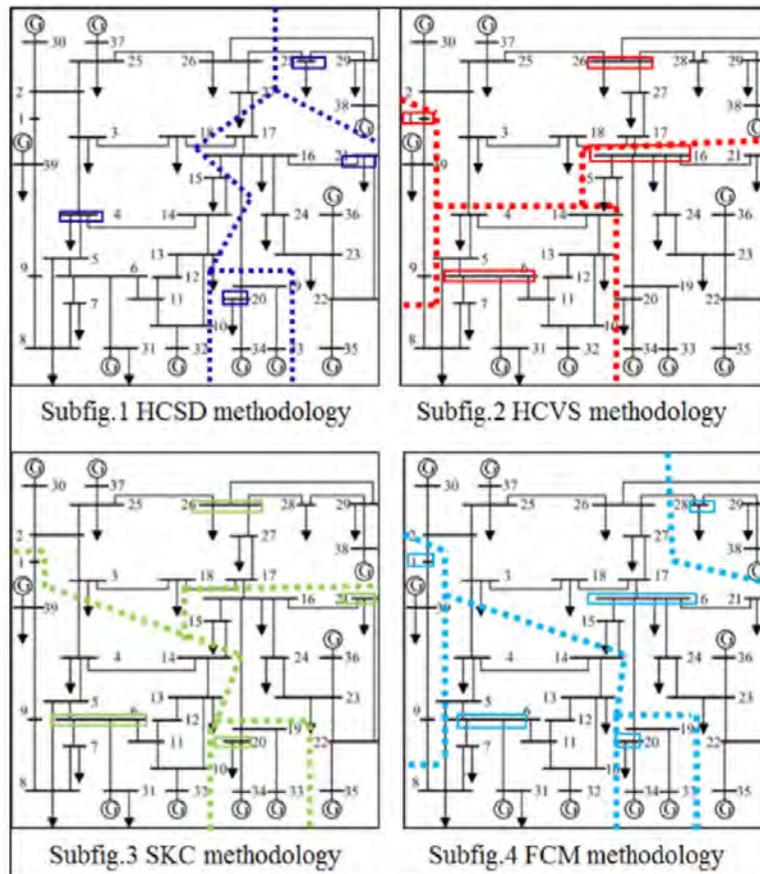
There is literature on how to optimize electricity flow and/or minimize cost at the transmission level (McArthur et al., 2012; Alimisis et al., 2013; Hogan, 2002). However, work at the distribution level is scarce, presumably due to a lack of ideas on how a zoning structure can work at this level, and limited computer power to calculate quantities and prices at thousands of nodes. There are papers that look at the distribution level - two papers are good starting points for our discussion. AER (2011) examines the model as used at the transmission level in PJM and transfers it to the distribution level. The author suggests an almost identical model to the PJM model used in practice, but modifies it to include a premium price for renewable distributed generation. However, the paper does not include congestion variables (AER, 2011, p. 101). This is key point in our paper.

Alimisis et al. (2013) discusses a flexible zoning structure at the transmission level but doesn't consider markets. In Alimisis et al. (2013) it is proposed that zones are extracted as peer entities with potentially dynamic boundaries that appropriately respond to a control algorithm. A multi-layer analysis involving three layers i.e. observation, behaviour and computation is used to derive the nodes' dependencies. The layers provide information to the zone determination technique, which in turn informs a partitioning method about prevailing dependencies and constraints. Alimisis and Taylor (2015) take this analysis one step further and propose a novel generic framework to assess different zoning methodologies in the context of co-ordinated voltage regulation (CVR). The framework is shown in Fig. 1a. Fig. 1b shows the zoning outcomes and pilot node identification for a New England 39-bus test network used as a case study. At each iteration, blocks A and C effectively generate a system state, while blocks B, D, and E solve and evaluate the performance for that state. More specifically Block A generates a random state and solves a system-wide optimal power flow algorithm. Block B integrates a zoning methodology into the framework. Block C creates voltage deviations and

provides the CVR with a voltage deviation vector-target to act upon. Block D contains the CVR strategy and block E evaluates the control decisions and decides if re-zoning is required. Even though Alimisis and Taylor (2015) focuses on the performance of four examined zoning methodologies — Hierarchical clustering with single distance (HCSD), hierarchical clustering with VAR control space (HCVS), spectral k-way (SKC), and fuzzy C-means (FCM) —, the proposed framework is generic and may accommodate any possible control model reduction methodology, data acquisition technique or control scheme. Furthermore, it takes into account the robustness of the zoning methodologies when topological changes occur to the network, as a change in topology can affect zones' homogeneity of control and both inter- and intra-zone coupling. This is particularly important in the APS concept. In the APS goals are set and are then autonomously mapped on to objectives. For example, a goal could be to integrate a certain amount of wind energy over a number of hours. An objective arising from this could be to charge energy storage devices without violating line voltage constraints. The APS self* operation will thus determine appropriate zones of control and control algorithms to be deployed in the zones according to the objectives and the network would have to decide how to achieve the varying goals autonomously by re-configuring zones and changing the algorithms used in real-time while also taking into account past performance data.



(a)



(b)

Fig. 1. Technical zones in transmission a) Proposed framework for zoning methodology assessment (b) Zoning outcomes and pilot node identification (Alimisis and Taylor, 2015).

Alimisis et al. (2015)'s focus is on the transmission level and not the distribution level, it investigates reactive power and not energy and there is no market part of their design. In this paper we focus on real power and discuss market design.

On economics, the closest paper to this one is Binetti et al. (2014). This studies an auction at the distribution level. The auction presented in their paper is an algorithm built on graph theory. Each unit on the network submits two bids: one bid for how much it has to spend to increase its generation from current value, and one bid for how much it can save by reducing its generation from the current value. Neighbouring units communicate and reach a consensus on final values for adding and moving an amount of power. Compared to the design presented in this paper, the authors do not use a conventional auction/market as seen the economic literature. Auctions/markets, rightly, worry about coordination of prices by market participants and explicitly forbid the sort of coordination discussed by Binetti et al. In our set up we use many bidders, and there is no negotiation between bidders after the auction has concluded.

We contribute to the literature on network design, by extending the work of McArthur et al. (2012) and Alimisis et al. (2015) to include distribution and at the same time to add economics to these papers' control and operation algorithm. Following McArthur et al. (2012), we use the framework to assess different zoning methodologies and following Alimisis et al. (2015), we use a zoning technique. However, and compared to McArthur et al. (2012) and Alimisis et al. (2015), we introduce economic set-points (quantities and prices) - our Economic Layer's suggestions – that work for thousands of nodes. From defined criteria, our Technical Layer gives us the optimal technical solution for a given economic solution. This interaction in technical terms at this more complex level has not been done before and has practical use in the context of suitably fast computer power, as we might expect in the year of 2050 and as assumed in this paper.

3. Current electricity market – the USA

The use of zones in the electricity system for technical and economic reasons already exists today. The North American electricity system is one example. The USA is of particular interest because of the use of nodal pricing. However, the use of nodes only covers the market at the transmission level, not at the distribution level. We want to introduce technical and economic zoning structures based on pricing nodes at the distribution level and we want to exploit an auction framework at this level.

Transmission

Most of the North American electricity market is split into regions and zones. Seven regions can be identified where each region is controlled by a regional transmission organization or independent system operator (RTO/ISO). PJM is one of these RTO regions, with an aggregate capacity of 167 GW (PJM, 2014a). PJM serves all or part of the state of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. These regions can be seen as our zoning structures, both zones of control and economics. In term of zones of control, the RTOs/ISOs use dispatch algorithms to decide how each available resource should be operated given demand and constraints. The system dispatch is set, so that costs are minimized (FERC, 2012). PJM is built up around 3,000 nodes in the network down to 69kV (PJM, 2014b). PJM employs nodal pricing where there is a price for each node (locational marginal price, LMP). The schedules and LMP are set in the day-ahead market and the real-time market. In the day-ahead market, schedules and prices are set for each hour one day ahead (FERC, 2012),

whereas the real-time market corrects for any differences between the schedule day-ahead and actual demand, subject potential constraints, unplanned outages etc. The day-ahead market uses auctions to set schedules and prices. The participants are generators that offer to sell electricity and demand-serving utilities that bid to buy electricity. The real-time market does not use market-based mechanisms (it uses existing bids) and can be seen as an administrative procedure. Actual conditions will vary from that forecast in the day-ahead market, so RTOs/ISOs adjust technical and economical operation accordingly. Supply and prices are set at the more than 3,000 nodes throughout PJM (Frontier Economics, 2009).

RTOs/ISOs also trade across regions. PJM has interconnections with, for example, Midwest ISO (MISO) and New York ISO (NYISO), where it imports and exports electricity. Cross-border trading is based on agreements between the regions. PJM and MISO as well as PJM and NYISO coordinate schedules and prices intended to reduce uneconomic flows between the regions. The agreement between PJM and MISO requires a joint clearing of schedules and prices, whereas the clearing process happens separately between PJM and NYISO (Groomes and Rustum, 2013). Transmission service request access is required from each region (Groomes and Rustum, 2013).

Distribution

PJM is responsible for the real time operation of the transmission grid within its area, while the operation of the distribution systems underneath it is undertaken by private utilities (about 75%), municipal utilities and cooperatives. However, besides defining the regional market, PJM has no duties in the distribution system. Each distribution utility is responsible for its own network and for undertaking the necessary investments. A consumer price is a combination of different components, including inter alia, wholesale power costs and the charges for transmission and distribution services. The transmission level wholesale prices are calculated at the 3,000 nodes, regulated by FERC, whereas the prices final distribution system customers pay are billed directly by the local utility to the consumer (Thomas et al., 2014). Each distribution service price is subject to price control and has to be approved by the state public utility commission (Thomas et al., 2014).

Things to discuss from the current system

The current nodal system at the transmission level effectively defines zones within the distribution system. This is problematic. It is also the case that there are boundary problems between PJM and other regional power markets. These regions and the zones

they give rise to are historically pre-defined and static. This lowers the flexibility to fully optimize the system. Trading across borders is used, but trades are based on fixed working agreements between regions. Furthermore, a transmission service request is required which is not market based. More importantly from our point of view, the transmission system contains 3,000 nodes, but if it was possible, more nodes (combined with more flexible zoning areas) could provide the necessary conditions for efficient trade (Newbery, 2006).

The distribution level is part of the zoning structure defined at the transmission level and therefore, it shares its problems. It operates independently of the transmission level and in a system that is not based on how to optimize power flow or economics. Further, the distribution system does not use auctions to determine supply, demand and hence prices. It is a procedure approved by central bodies and therefore, it is not market based.

The zoning structures presented in this paper and its flexibility will increase system reliability and allow us to potentially increase price resolution by an order of magnitude, relative to today⁷. This involves better supply and demand matching at each very narrow location (effectively an LMP) to ensure the lowest cost.

4. Applying Economics in Technical Zones

Based on section 2, we need a flexible network at the distribution level to meet both the economic and technical challenges of the future. We might think of this as central dispatch, but compared to current systems it is a mechanism that alone runs and tests the network.⁸ Hence, compared to current systems, where economic and technical constraints are controlled and actions are taken by the transmission and distribution system operators, it is a mechanism/an algorithm that controls and approves what actions and solutions to take. It is a self* network. The network is based on nodal pricing, a price at each node, with around 5,000 nodes in the GB case. Auctions determine schedules and prices. We operate using two zoning structures: zones defined from an economic point of view on the basis of submitted bids through an auction (the Economic layer) and zones defined from a control point of view and subject to technical constraints (the Technical Layer).

⁷ 5000/3000 nodes in GB vs PJM, in systems where demand is three times higher in PJM than GB. This gives a factor of 5 times greater price resolution.

⁸ The price resolution process is run independently from the operation of the network in the sense that distribution grid owners cannot gain advantages for their own facilities (e.g. generation and storage) participating in the real energy auctions we describe.

Definitions

To define a zone from a control point of view, we use the argument of the authors in Alimisis et al. (2013, p. 260): *'a zone can be thought of as a physically connected collection of power elements that form a union that is strongly self-contained in terms of actions directed within the zone and by extension loosely affected from actions outside its boundaries, though not an electrical island, and can still be managed as a single group computationally to deliver a sufficiently optimised operation in real time, with regards to an hierarchy of objectives.'*

Economic zones can be thought of as *a conceptual collection of nodes defined by bids for energy at a given price. Economic zones are not subject to technical constraints, but are formulated as a result of a process that tries to minimize cost and therefore, minimize consumer prices by properly matching supply and demand.*

Methodology

This paper argues in favour of localised zones – which are based on nodes in the distribution system where an algorithm searches to optimize power flow and at the same time searches to minimize cost. Although computer power resolution in price formation could scale up to millions of customers, this could be impractical from a controllability point of view and the additional monetary benefits of running an auction of that size might be questionable considering the infrastructure required and the additional computational complexity.

The authors in McArthur et al. (2012) have already proposed that zones can be extracted as peer entities with potentially flexible boundaries that appropriately serve a control algorithm. A multi-layer analysis involving three layers i.e. observation, behaviour and computation is used to derive the nodes dependencies. The layers provide information to the zone determination technique, which in turn informs a partitioning method about prevailing dependencies and constraints. In Alimisis et al. (2015), the authors take this analysis a step further and propose a novel generic framework to assess different zoning methodologies particularly against CVR.

Even though Alimisis et al. (2015) focuses on the performance of four examined zoning methodologies, it takes into account the element of robustness when topological changes occur to the network, as a change in topology can affect zones' homogeneity to control and both inter- and intra-zone coupling. This is particularly important for the concept of this paper as the Technical Layer reacts to the Economic Layer and vice versa. As multiple bids can be submitted, the network conditions can significantly change and

zones need to be optimised against robustness to topological changes. The criteria suggested in Alimisis et al. (2015) for technical zoning refer to Controllability inside the zone, Interdependency between zones and the Relative Size of zones. Although in that paper the network size used as a case study was limited, the same criteria and consequently the same methodology can also be used if more complex networks are to be zoned, as in the case of the distribution system.

The Economic Layer is controlled by auctions that deliver quantities and prices. Suppose the Economic Layer begins by considering all bids as being submitted in one zone. It only reacts on the bids submitted in the auctions in order to ensure lowest cost. The bids are submitted by suppliers and demands. The suppliers submit cost/potential prices to charge the consumers. The demands submit their willingness to pay (WTP) for electricity. From the submitted bids, the Economic Layer will suggest set-points to the Technical Layer in combinations from (1) a set that generates lowest overall cost (suggestion 1), (2) a set that generates second-lowest overall cost (suggestion 2) etc. The Technical Layer then checks if the combination generating lowest cost can be met without violating power and voltage constraints. If it doesn't violate the constraints, this combination is chosen. If it does, then the next best solution suggested by the Economic Layer will be checked etc. The Economic Layer could in theory be resolved every minute and bidders could submit offers and bids in real time, hence, submit new offers and bids or resubmit offers and bids every second of the day. This would mean that an auction clears and determines quantities and price at each node every minute based on offers and bids submitted either in real time or valid for fixed for a period (e.g. one week). Larger, more liquid, energy auctions could set quantity and prices to be delivered by supplies and demands, for example, 6 months ahead, if desired. This would allow reasonable price expectations of future nodal prices to be formed. Figure 2 and 3 show the interactions between the layers as a decision tree.

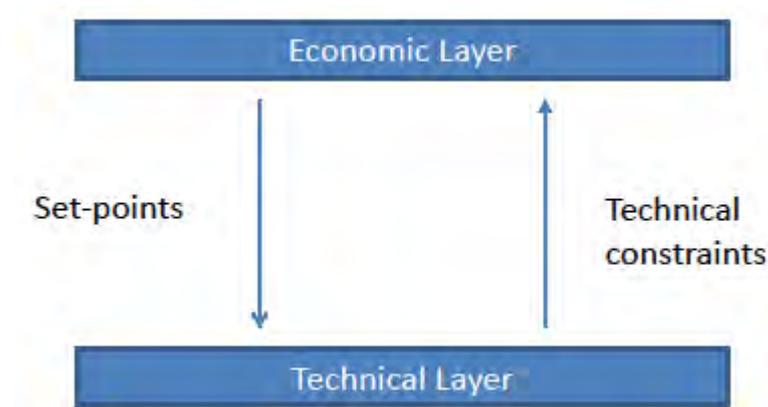


Fig. 2. Interaction between Technical and Economic Layers.

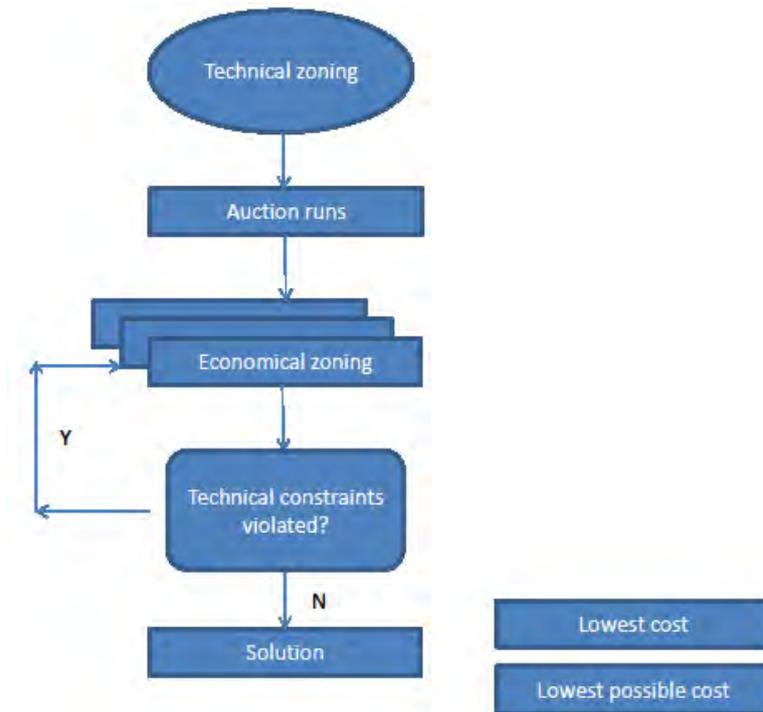


Fig. 3. Decision tree in distribution.

More precisely, the algorithm is as follows:

1. The Technical Layer will inform the Economic Layer about overall demand and supply requirements.
2. In order to determine quantities and prices, the system (not a supplier or a demander) runs an auction. The quantity and price are determined for every minute, and expected prices for future periods can also be computed.
3. The Economic Layer will look at the submitted bids and deliver a number of suggestions, starting with lowest overall cost (suggestion 1), second-lowest overall cost (suggestion 2) etc. The Economic Layer delivers as many suggestions as there are combinations of the supplies and demands that meet the demand and supply equilibrium to the Technical Layer.
4. The Technical Layer will check each suggestion to see if they can be delivered in technical terms, starting with suggestion 1. If suggestion 1 can be met based on defined technical criteria, it is chosen. If not, suggestion 2 will be checked etc.
5. The algorithm will continue until a solution is reached.

5. An example

The network used to illustrate the proposed approach is shown in Fig. 4⁹, with bidding supplies and demands marked as S and D. The network is a modified version of an existing UK network considering anticipated changes in 2050 such as:

- **Increased Complexity.** Reverse power flow is more likely to occur as a result of the large penetrations of distributed generation and energy storage. The topologies of networks will be more complex due to the increasing use of soft open points i.e. power converter devices that are able to regulate active and reactive power flows between interconnected lines, and potentially more frequent network reconfigurations.
- **Increased Uncertainty.** Load and generation profiles are expected to be more volatile and less predictable calling for the adoption of new techniques such as real time thermal rating and demand side response (DSR).
- **Increased size.** Networks with larger sizes or in larger geographic areas need to be considered especially as the numbers of controllable devices will increase and with it the need for enhanced observability and measurements.
- **Increased Decentralisation and Active Participation.** Future distribution networks are likely to be more decentralised due to the increasing number of distributed generation, microgrids, virtual power plants and community energy systems. More customers are expected to participate in the form of DSR and as producers.

⁹ This is a modified version of an 11kV UK distribution network. It consists of two primary substations and four 11kV feeders. Energy storage systems, soft open points and distributed generation has been included in order to simulate a future network configuration. D1-D6 are single or aggregated loads. S1, S3, S4 and S5 are individual supplies rated at 10MVA, 5MVA, 7.5MVA and 22.5 MVA respectively. S2 is a 2.5MVA/6 MWh energy storage system. Soft Open Points (SOP1-3) are rated at 3.5MVA each. They are used to regulate power flows between their end-points to satisfy requirements that could be triggered by events during network operation and/or as a result of power set-points suggested by auctions.

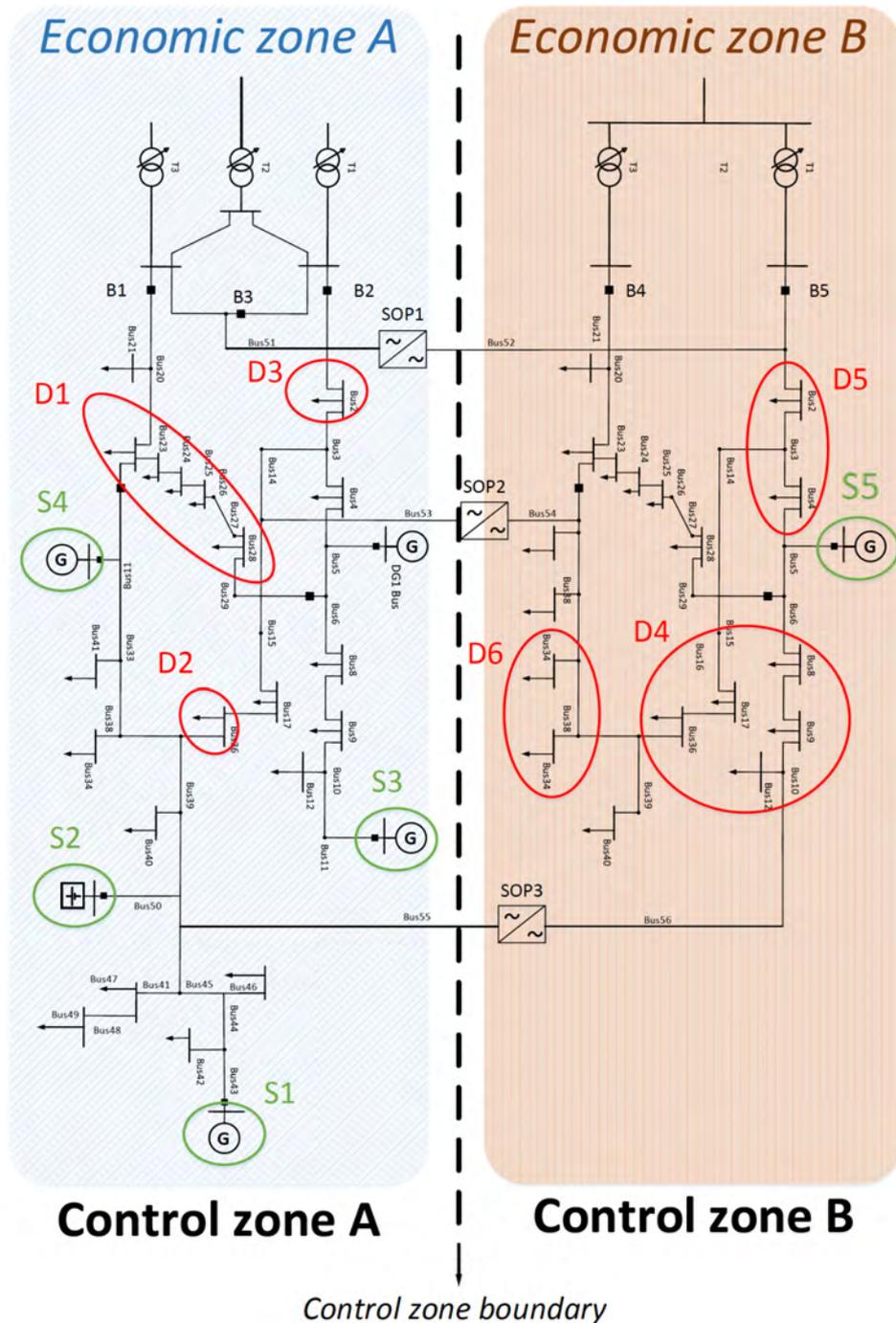


Fig. 4. The Technical Layer checks the set-points for feasibility, 11 kV network.

In the network considered there are two obvious zones of control: Control zone A and Control zone B, in this case interconnected by means of three soft open points (SOP1-3). We define SOPs according to Cao et al. (2016, p.36): ‘*Soft Open Points (SOPs) are power electronic devices installed in place of normally-open points in electrical power distribution networks. They are able to provide active power flow control, reactive power compensation and voltage regulation under normal network operating conditions, as well as fast fault isolation and supply restoration under abnormal conditions*’. In a future

scenario of enhanced renewables penetration these Zones could refer to communities that, although connected to the main grid through the 33/11kV substations, would operate in a way that could result in demand being satisfied by local generation. This could be driven by the need to absorb low carbon energy locally to avoid transmission losses, or due to the fact that in the future the substations would have reached their nominal capacity; therefore, instead of network reinforcements, Operators have deployed ‘smart’ solutions like energy storage and DSR schemes implemented through market operations.

Although the boundaries in the example, between technical zones are obvious i.e. Control zone A and Control zone B, a similar approach to the one followed in Alimisis and Taylor (2015) and described in the previous section can be followed to determine the optimal zoning from a technical perspective¹⁰ in more complicated networks resulting in any number of control zones. Although in this particular case these result in the obvious zones depicted in Fig. 4, they can also be used if more complex networks are to be zoned.

In terms of the actual power exchange this is practically unregulated i.e. power can flow between any supplier and any consumer, provided this is technically feasible from a network operation perspective, as long as total supply always meets the total demand. Priority will be given for this power equilibrium to be maintained locally i.e. breakers B1-B5 and SOP1-SOP3 operation will be co-ordinated in a way that results in minimum power being exchanged with the 33kV network. From an economic point of view we can assign any demand to meet any supply and therefore economic zones can be determined from a cost optimisation point of view. However, this will result in the issuing of set-points inside the technical zone, therefore, new zone suggestions must also fulfil technical criteria such as line and SOP ratings.

Now, we will show how our Economic and Technical Layers work. An example is given. Suppose our area is built up in two zones of control –Control zone A and B (initial zones are the last period’s optimal power flow), where there are 11 bidders participating in the auction – six demands (D1-D6) and five suppliers (S1-S5)¹¹. Three demands and four suppliers are in Control zone A and three demands and one supplier in Control zone B. Suppose the initial zoning structure is set where power flow is optimised. Assume the Technical Layer has informed the Economic Layer that overall demand in Control zone A is 12.5 MW and 10 MW in Control zone B. The initial Economic Zones will match the Control zones as shown in Fig. 4. Table 1 shows the submitted offers and bids in

¹⁰ This analysis is beyond the scope of this work. In this paper we base our technical zoning on the criteria suggested in Alimisis and Taylor (2015), which refer to Controllability inside the zone, Interdependency between zones and Relative Size of zones.

¹¹ For example, S1 and S3 could be individual suppliers, S3 and S5 renewable generators, and S2 storage facilities.

Economic zone A. For example, the table shows that Demand 1 has submitted a WTP of 120 pence for 5 MW (for 1 minute). The auction is resolved for each minute.

Table 1: Submitted offers and bids in Economic zone A

Demand	MW	Cost (pence/MW)
Demand 1	5	120
Demand 2	2.5	100
Demand 3	5	90
Suppliers	MW	Cost (pence/MW)
Supplier 1	2.5	140
Supplier 2	5	130
Supplier 3	7.5	130
Supplier 4	12.5	90
Supplier 4	2.5	80

Table 1 shows that Supplier 4 has submitted two separate bids: a bid to deliver 12.5 MW at a price of 90 pence; and a bid to deliver 2.5 MW at a price of 80 pence. Since we are in an environment of many demands and suppliers, take the bid to deliver 12.5 MW and suppose, for example, that Supplier 4 is an aggregation of 13 smaller suppliers - 12 have submitted a bid of 1 MW and one has submitted a bid of $\frac{1}{2}$ MW, all MWs at a price of 90 pence/MW. Other suppliers and demanders could be seen in a similar way.

Using a two-sided uniform-price auction¹², Supplier 4 delivers 12.5 MW to Demands 1, 2 and 3 at a price of 90 pence. Before using the flexible zoning structure, the cost in Economic zone A alone would be 1125 pence (12.5 MW*90 pence).

Table 2 shows the offers and bids in Economic zone B.

Table 2: Submitted offers and bids in Economic zone B

Demand	MW	Cost (pence/MW)
Demand 4	5	80
Demand 5	2.5	50
Demand 6	2.5	40

¹² A uniform-price auction is a multiple object format, where the price is found at the intersection point of the supply and demand curve (Krishna, 2009).

Suppliers	MW	Cost (pence/MW)
Supplier 5	12.5	50
Supplier 5	10	40
Supplier 5	10	40

Again, using a two-sided uniform-price auction Supplier 5 delivers 10 MW to Demands 4, 5 and 6 at a price of 40 pence. At this price, the energy cost in Economic zone B alone would be 400 pence (10 MW*40 pence). Together with Economic zone A, total energy cost would be 1525 pence.

Now, suppose that Supplier 5's submitted bid of 12.5 MW can be delivered to Economic zone A at a price of 50 pence and Demand 5 can be placed in Economic zone A and Demand 2 in Economic zone B. Imagine that the zoning structure re-configures to include Supplier 5 in zone A, Demand 5 in zone A and Demand 2 in zone B. Now, for zone A and B, we have Table 3 and 4.

Table 3: Submitted offers and bids in Economic zone A after a re-configuration

Demands	MW	Cost (pence/MW)
Demand 1	5	120
Demand 3	5	90
Demand 5	2.5	50
Suppliers	MW	Cost (pence/MW)
Supplier 1	2.5	140
Supplier 2	5	130
Supplier 3	7.5	130
Supplier 4	12.5	90
Supplier 4	2.5	80
Supplier 5	12.5	50

Table 4: Submitted offers and bids in Economic zone B after a re-configuration

Demands	MW	Cost (pence/MW)
Demand 2	2.5	100
Demand 4	5	80
Demand 6	2.5	40

Suppliers	MW	Cost (pence/MW)
Supplier 5	10	40
Supplier 5	10	40

In line with this the Economic Layer delivers the following two new suggestions to the Technical Layer, in addition to the result of the initial zoning. The first, in Table 5, reflects the results of Tables 3 and 4.

Table 5: Suggestion 1 – lowest overall cost

Zones	MW	Cost (pence/MW)
<u>Economic Zone A (new zone)</u>		
Demand 1	5	120
Demand 3	5	90
Demand 5	2.5	50
Supplier 5	12.5	50
<u>Economic Zone B (new zone)</u>		
Demand 2	2.5	100
Demand 4	5	80
Demand 6	2.5	40
Supplier 5	10	40
Total cost		1025 ¹³

The Economic Layer has suggested a lowest cost of 1025 pence. To suggest the second-lowest overall network cost, the Economic Layer places one of Supplier 5's submitted bids of 10 MW in Economic zone A, Demand 2 and Demand 4 in Economic zone A and Demand 3 and Demand 5 in Economic zone B. Now, for Economic zones A and B, we have Table 6 and 7.

Table 6: Submitted offers and bids in Economic zone A after a second re-configuration

Demands	MW	Cost (pence/MW)
Demand 1	5	120
Demand 2	2.5	100
Demand 4	5	80

¹³ $12.5*50+10*40 = 625+400= 1025$ pence.

Suppliers	MW	Cost (pence/MW)
Supplier 1	2.5	140
Supplier 2	5	130
Supplier 3	7.5	130
Supplier 4	12.5	90
Supplier 4	2.5	80
Supplier 5	10	40

Table 7: Submitted offers and bids in Economic zone B after a second re-configuration

Demands	MW	Cost (pence/MW)
Demand 3	5	90
Demand 5	2.5	50
Demand 6	2.5	40
Suppliers	MW	Cost (pence/MW)
Supplier 5	12.5	50
Supplier 5	10	40

This second reconfiguration gives rise to a new suggestion from the economic layer shown in Table 8.

Table 8: Suggestion 2 – second-lowest overall cost

Zones	MW	Cost (pence/MW)
<u>Economic Zone A (new zone)</u>		
Demand 1	5	120
Demand 2	2.5	100
Demand 4	5	80
Supplier 4	2.5	80
Supplier 5	10	40
<u>Economic Zone B (new zone)</u>		
Demand 3	5	90
Demand 5	2.5	50
Demand 6	2.5	40
Supplier 5	10	40

Total cost		1400 ¹⁴
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The Economic Layer has now delivered three suggestions – a lowest cost of 1025 pence, a second-lowest cost of 1400 pence and the initial zoning structure at a cost of 1525 pence.

Now, the Technical Layer checks the set-points for feasibility. Suggestion 1 results in supply S5 increasing its power output as a response of a request generated in a different zone i.e. Control Zone A. Furthermore S1-4 would need to re-adjust their outputs to meet the demand that is not participating in the auction. This in essence constitutes a re-configuration of the control zones. As S5 now provides power to all Demands participating in the auction this could now result in two different zones of Control as shown in Fig. 5a, provided controllability is maintained using flexibility provided by assets such as the SOPs. However, based on power flow calculation, in this conceptual example this would result in the power between the two zones exceeding the nominal capacity of SOP1. Hence, the Technical Layer rejects Suggestion 1. Suggestion 2 is examined which results in the zoning shown in Fig. 5b. As there is no exceeding of technical constraints throughout the network, Suggestion 2 is therefore feasible. Suggestion 2 is accepted by Technical Layer.

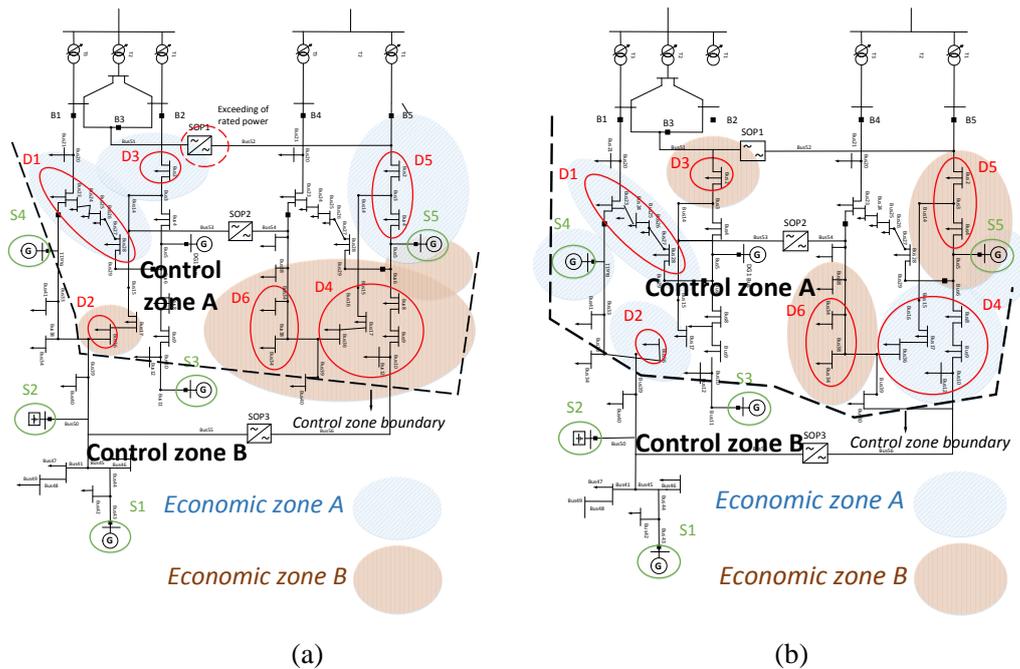


Fig. 5 Suggested zones after re-configuration a) Suggestion 1 b) Suggestion 2. The reader is encouraged to refer to section 4 paragraph 2, above, for a definition of control and economic zones.

¹⁴ $12.5 \times 80 + 10 \times 40 = 1000 + 400 = 1400$ pence.

6. Discussion

We have shown that locational marginal prices (LMPs), auctions and our flexible zones could be the way towards a lowest cost electricity system. Importantly, our set-up can improve on the outcome in a world of pre-defined, fixed and/or static electricity networks. That said, there could be a mismatch between the lowest system cost, and what is possible taking into account control and operation is. Using economics to drive zone re-configuration could result in drastic changes in the setting of control zones, however, provided the enhanced flexibility offered by assets in 2050 we have shown that this could be a viable option.

The use of zones can be analysed three ways: (1) only in terms of control and operation without taking into account the economics when determining zones; (2) only in terms of economics without taking into account the control and operation technique when determining zones; (3) a mix between control and operation and economics when determining zones.

Approach (1) is analysed in Alimisis et al., (2013) and Piacentini et al., (2013), (2) is an alternative approach to the problem and approach (Krishna, 2009) (3) is the most desirable scenario, and what has been analysed in this paper.

6.1. Feasibility

One might wonder whether or not our economic set up could be used after an optimisation of control and operation. The answer is yes. The control and operation set boundaries for the power flow. If the Technical Layer allows room for lower overall cost, our algorithm aims to find it. If not, we already have the lowest possible cost. In any case, the market (boundaries and bidders) decides which configuration ensures lowest feasible cost.

6.2. Number of zones

Then we may ask: What is the minimum/maximum number of zones? Following the discussion above, the minimum or maximum number of zones is determined by the Technical and Economic Layers. The Economic Layer will determine prices and therefore, who are the cheaper suppliers. The Technical Layer determines the number of zones. The number zones depend on bids, demand and constraints.

7. Extensions

In this paper, we presented a method that can secure a lowest cost in a system made up of many local power zones. Our zoning structure reacts if the control and operation allow/require it. However, this does not necessarily suggest that it should be like this. There could be a welfare improvement and lower cost by letting control and operation follow the economics. A further extension could be to take the technical part of this paper and look at it through a Multi-Agent System (Cameron et al. 2015) at the distribution level and add economics. The aim of such a follow-on paper should be to demonstrate that network conditions, including market constraints and considerations, can be used not only to determine the most appropriate control and communication architecture from a technical perspective, but also to trigger architectural changes in the Technical Layer in order to maximize economic benefits.

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