LEVERAGING LOCATION AWARENESS FOR DISTRIBUTED ENERGY RESOURCES: SELF-ORGANISING ENERGY COMMUNITIES

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ABSTRACT

Integration of small-scale distributed energy resources into low-voltage networks requires a smart approach. A self-organising network of distributed energy resource controllers can derive network topology information that may be used for smart control decisions. This paper illustrates a multi-agent distributed control system that uses location information to solve a voltage problem, and demonstrates its full closed-loop application on a real-time distribution network model.

INTRODUCTION

The rise of two technologies typifies the changing nature of low-voltage distribution networks: photovoltaic (PV) generation and electric vehicles (EVs). PV generation may not match use patterns, arrays may be oversized for a building's energy needs to maximise feed-in tariff incentives, and a considerable proportion of energy may be exported. Voltage rise, reverse power flows and degraded power quality may result. EVs may cause network issues (primarily thermal overloading of transformers and voltage drop) where uptake reaches a third of customers, or even lower[1]. Thermal and voltage issues are exacerbated by distance from transformer busbars as line impedance plays an increasing role; connection phase affects unbalance, and clusters of devices will impact more heavily than if they were uniformly distributed. Consequently, electrical location is important.

APPROACH

Coordination between PV and other distributed generators (DGs), EVs and other small-scale distributed energy resources (DERs) can mitigate some of the concomitant issues; this work approaches the task by examining location as a factor exacerbating electrical problems, but also as a tool towards their solution.

The structure of a Multi-Agent System (MAS) is used, where devices exist as autonomous entities within a networked multi-stakeholder context, each capable of its own control.

We use line voltage rise and drop as an example of the importance of location, and show how a multi-agent, distributed control system may use a variety of techniques to derive network information and learn about their surroundings. Knowledge of location is developed into an awareness of operational context, including electrical connection topology and location of other DERs. This forms a self-organising, communicating and coordinating energy community which, in turn, facilitates integration of distributed energy resources into a smart grid.

ELECTRICAL IMPACT OF DISTRIBUTED ENERGY RESOURCES

Voltage and thermal issues due to heavy loading are exacerbated by distance from transformer busbars due to the increased power loss from the resistive nature of LV distribution networks. Connection phase affects unbalance, and clusters of devices will impact more heavily than if they were uniformly distributed[2]. The network location of DGs may be important when dispatching generation in aggregate form in Virtual Power Plants.

The impact of location within a radial electrical distribution network was examined using the 3-phase low-voltage network model described in [3] and illustrated in Figure 1. The figure shows domestic customers connected at 230V through two transformers to the 33kV network. One feeder was disaggregated into its individual customers and extended to reflect network growth, increased demand, and new generation equipment. A 4-wire representation was created for unbalanced and transient analysis. As in [1] and [2], the addition of high EV penetration caused undervoltage problems, and the addition of small-scale generation caused overvoltage problems. The impacts of devices were location-dependent; a single 3kW EV charger causes a voltage drop as high as 1V when connected at the end of a heavily-loaded feeder, significantly contributing to voltage excursions - but as little as 0.14V when connected adjacent to the busbar. Consequently, a system can use the resistive property of the network to determine the per-device priority of demand-side response control actions according to their effectiveness.

CONTROL PARADIGM

A centralised control system could be pre-programmed with network topology including the location and properties of any DERs. This centralised system could use this information to determine optimum settings to control individual devices. However, this paradigm has several shortcomings – firstly, of scalability and reliability[4]. A database of known network information is problematic: it may be commercially sensitive or protected for security

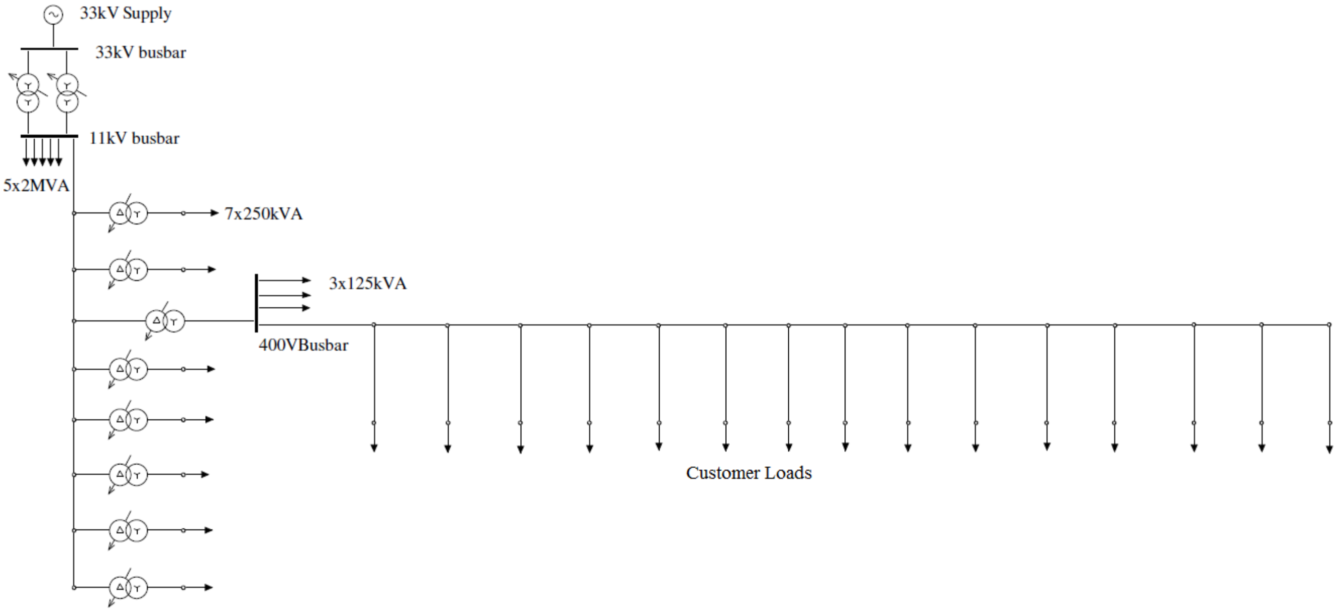

Figure 1: Case Study LV Network (single-line diagram)

purposes. Coordination of multiple system operators is necessary, since the UK system is divided into regional monopolies. Data may not exist to a relevant detail level in all locations. The database must be maintained and updated regularly. Instead, decentralisation fits a multi-stakeholder context where generation, load and network assets have different owners; use of a multi-agent system (where the network topology is derived locally) facilitates this decentralised approach.

LOCATION

Electrical Topology Analogues

As well as referring to location as the point of connection in an electrical network, location can also apply to geographical position or connection to an ICT network. There may be overlap between these locations: for example, we may suppose that two geographically adjacent houses may be connected to the same electric distribution feeder. Location information can be derived from many sources: radio signals from Global Positioning System (GPS) satellites give a precise geographical position; a postal code input upon installation provides an approximate area. Many smart meters are networked via mobile phone towers, which could be grouped by cell ID, or mapped to physical coverage area. These geographical properties can be used as an analogue to electrical location, although proximity is not necessarily a guarantee of a common connection.

ICT network proximity (measured by latency or by common access point hardware) may indicate a common electrical connection. A medium such as powerline communications can be used directly to infer electrical connections between devices.

Electrical network characteristics can be used to identify the nature of connections by using direct on-line measurement. Analysis of signals on the electrical network will show differences in connection phase, as well as identify where devices do not have any common connection.

Multi-Factor Location

Multiple sources of location information can be used together. Strong indicators – such as identifying common signals on the electrical network – can be combined with weaker indicators, such as geographical coordinates or areas, to give both a location and a value for confidence in that assessment. A process whereby the agent learns about the effectiveness of its control actions allows a dynamic multi-factor location system to adjust its confidence in topology. Machine learning may be used in conjunction with assessment of the impact each action. We may create an overlay graph where each edge is allocated a weight that corresponds to the impact an action may have with respect to those nodes. The correctness of the initial tree becomes less relevant than knowledge of what its impacts are as the agent learns from experience.

DECENTRALISED CONTROL SYSTEM

Overview

Figure 2 shows the outline of the control system. The model in Figure 1 was adapted into a 3-phase, 4-wire representation, with one 400V feeder disaggregated to show 15 domestic customers at the remote end; the other feeders were lumped to simplify the model. This was input into RSCAD [5] to produce a real-time simulation of the distribution network via Real-Time Digital Simulator (RTDS) hardware (labelled "Real-Time Network Simulator" in Figure 2). Each of the 15 customers was assigned an analogue output channel to supply live physical voltage signals, and digital input allowing virtual equipment to be switched on or off by its respective controller. Three of the 15 controllers are shown in the

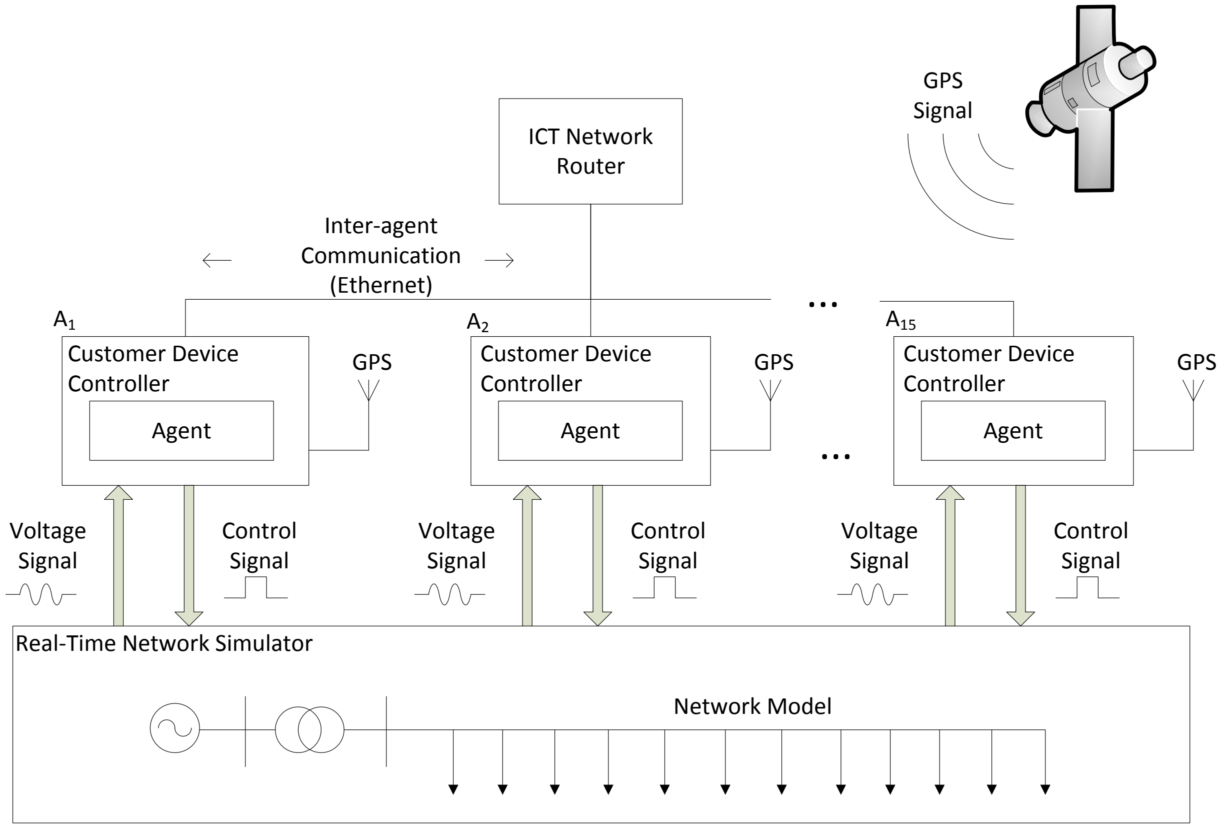

Figure 2: System Outline

figure: the Beagleboard target hardware are inexpensive, small-form-factor embedded computers, each hosting analogue signal acquisition, agent-based control code, and digital output to return control instructions to the simulator for complete closed-loop control. Each controller has a GPS receiver. At the top of the diagram, the ICT network is shown. Each of the controllers is networked via ethernet.

Multi-Agent System

Control agents for customer loads and generators were written in Java using the JADE [6] framework, each hosted on individual embedded computers. Real-time local voltage is measured from an analogue channel. Each controller is GPS-enabled: for the purposes of providing a simple location indicator, the devices in this paper use latitude/longitude coordinates. The ICT network allows the agents to communicate via FIPA-compliant messages. The process of registration and location identification is completed automatically to reduce configuration.

Decentralised Dynamic Graph Creation

Upon startup, a new agent registers with the agent platform and directories. It registers its own geographical coordinates, and requests those of its two nearest neighbours. This allows it to begin to construct a graph of nodes, represented internally as a connection matrix, shown in Figure 3, where the New device is situated between existing devices A_1 and A_2 on the network and the edge is the geographical distance. We exclude self-connections and represent disconnections as ∞. Each agent stores a partial representation of the full network topology.

$$\begin{array}{c} \\ A_1 \\ New \\ A_2 \end{array} \begin{array}{c} \begin{array}{ccc} A_1 & New & A_2 \end{array} \\ \begin{bmatrix} \infty & 112 & 140 \\ 112 & \infty & 50 \\ 140 & 50 & \infty \end{bmatrix} \end{array}$$

Figure 3: New device connection matrix

Representing connections in this graph form already allows the agent to make deductions about the structure of the network: if the distances A_1-New and A_2-New are both less than A_1-A_2, the device is between them (true in the 1D case below, requiring verification in the 2D case due to the possibility of complex geometry); otherwise, it is at the end of the graph. In the case where the New device is not the most remote on the feeder, A_2 has knowledge of a node (e.g. A_3) on the feeder beyond the New device; having found a connection, New announces its existence to A_1 and A_2; if appropriate, A_2 responds with details of A_3.

EXPERIMENTAL PROCEDURE

In this initial case, the 15 remote customers in the network described above were modelled to use 3kW EV chargers with no distributed generation. The customers were connected to a common phase, and it was assumed there were no branches or unusual geometry. The RTDS was started, then the controllers began closed-loop operation using the live voltage signals. 15 agents joined the platform and assessed their location using the technique described above. Illustrating the case of loss of diversity due to a simultaneous EV charging pattern [1], we recorded the system experiencing a voltage excursion dropping below 0.94 p.u., visible at t=500ms in Figure 4.

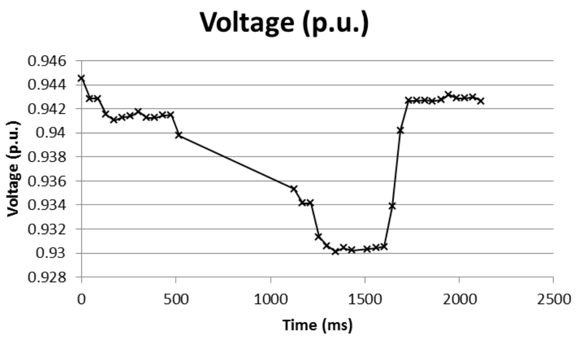

Figure 4: Voltage excursion (end of feeder)

The agents at the end of the feeder measured the analogue voltage signal dropping below the 0.94p.u. limit. Shortly after, agent A_{15} contacted A_{14}, the agent directly above it on the feeder, to request assistance, visible in Figure 5. A_{14} was well-placed to do so, since its impact on voltage is higher than those closer to the busbar. It determined to assist; it reconfirmed the necessity of action (to reduce excessive control actions from voltage transients), then delayed its EV charging for a time, reducing network load. This process occurred for 6 agents requesting assistance from adjacent agents almost simultaneously (not shown), and resulted in 4 controller switching operations. At around t=1650ms, the voltage was restored to within limits.

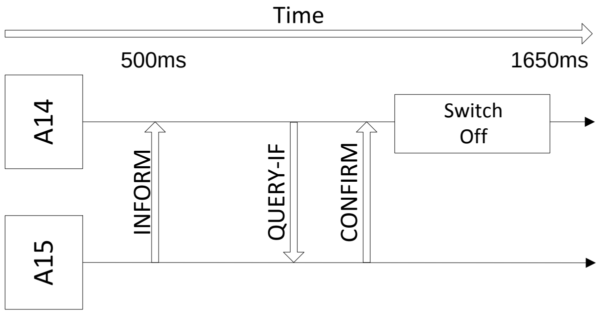

Figure 5: Agent Communication

DISCUSSION

This derived awareness of operational environment results in a reduction in configuration requirements and eliminates the need for a maintained, centralised database of network topology, and allows control to be decentralised.
While GPS coordinates do not provide a complete picture of electrical connections, they can be used as a "first filter" to drastically reduce the search space of connected devices. There is a need to combine this with confirmation of electrical connection, whether by learning (measuring the effect of exerting control) or by direct measurement (such as common signal identification).
Time elapsed to system restoration was around 1100ms, which is sufficient to prevent mandatory disconnection of local DG installed under the UK G83/1 regulations[7].

FURTHER WORK

At present, the system does not use a multi-factor location or learning system, though both geographical and electrical characteristics have been used independently in tests.

CONCLUSION

This work argues that location is an important aspect for the control and integration of distributed energy resources. It identifies various sources of location data. One simple geographically-based location identification technique is developed. We implemented a control system in real-time closed-loop simulation that uses that location data in the process of providing demand-side response to a voltage excursion. The self-organising, communicating and coordinating energy community forms a truly smart distribution system leveraging location awareness for integrating distributed energy resources.

ACKNOWLEDGMENTS

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