Do We Need a New Architecture for Simulating Power Systems?

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Keywords: Agent based Modelling, Multi Agent Systems, Multiscale, Multilayer, Power, Simulation, Smartgrid.

Abstract: The delivery of electric power and organisation of electric power systems is an incredibly complex system, which will become ever more complex with an increased penetration of Distributed Energy Resources (DER), including electric vehicles and renewables. Optimization of such a system using conventional techniques is difficult and fraught with a myriad of issues, so simulation provides a more holistic approach to understanding the evolving issues. We argue that although power simulation frameworks exist they may be inadequate for simulating a more complex and evolving smart power grid infrastructure. A brief overview of research on existing systems is provided and this paper argues for the development of a distributed multi-scale, multi layered hybrid ABM/MAS system.

1 INTRODUCTION

In his work, Watts (2003) characterised power systems as complex systems. Others have followed this work but have focused on using graph based statistical measures to help understand their stability e.g. cascades and other issues. However Holland (1999) suggests that a graph based statistical or mathematical approach gives us no insight as to how patterns e.g. price or power flows in our instance arise. It tells us nothing about emergence in what is a Complex Adaptive System (CAS). This emergence in our context is an important element to understand and enable us to develop (i) policy rules for future system operation and (ii) appropriate short-term technical control measures. Currently only a simulation approach appears to provide us with a route to understanding complex dynamics in these systems.

However, Agent Based (ABM) and Multi Agent System (MAS) modelling could also provide us with an important arsenal in discovering these patterns. Holland also suggests that as we add stochastic mobile agents to the system the potential for new rules and patterns to emerge tends to grow rapidly, resulting in many more persistent states as a result of system emergence. In our case, electric vehicles (EV's) are the stochastic mobile agents of Holland's discussions. Understanding this complex system behaviour seems to be an important ideal for us to achieve. Essentially, our model of the power system has to represent its physical and commercial aspects, including the grid, the market, the generators, the demand, DERs etc. The model also needs to include an ability to represent and study adapting participant behaviours. Therefore, it is now recognized that a more holistic approach is required, one that ultimately requires a more sophisticated simulator. This short position paper presents initial scope/ideas for an ABM/MAS system that meets our needs for an electrical power simulator and can look at complex interactions in a future power system (Smart Grid). It is therefore a concept paper and is not meant to solve and give detailed architectural designs for our framework at this stage.

The paper is organised as follows. In Section 2, relevant examples of academic research on ABM and MAS are presented. Section 3 focusses on ABM/MAS systems used in electrical engineering, while section 4 proposes the conceptual design of a new power system simulator. Finally, Section 5 concludes this paper.

2 OVERVIEW OF ABM/MAS LITERATURE

There have been many surveys on ABM and MAS systems (Heath et al., 2009, Kantamneni et al., 2015, Leon et al., 2015, McArthur et al., 2007) plus many

Howorth, G. and Kockar, I.
Do We Need a New Architecture for Simulating Power Systems?.
DOI: 10.5220/0006917801900197
In *Proceedings of 8th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2018)*, pages 190-197
ISBN: 978-989-758-323-0

dedicated webpages and tutorials outlining what they can do in terms of Agent Communication Languages, openness, programming language choice and so on. Typically, the systems focus on a particular area of research i.e. they are specialised to analyse particular features or behaviour, or have other limitations. Only a few specifically focus on power system applications. There are now over 70 ABM/MAS systems in existence with a typical lifespan of 4-5 years. Only a few of these systems /designs (e.g. Jade (Bellifemine et al., 2007) , Repast (Cardoso, 2009))) have lifespans in excess of 10 years.

Few researchers propose aggregation of systems or components or simple reuse. However, Cardoso (2015) in his paper on SAJas proposes the use of an API to join Repast to Jade, with a justification that "multi-agent based system simulations (MABS) focus on applying MAS to model complex social systems typically involving a large agent population. Several MAS frameworks exist, but they are often not appropriate for MABS". In a similar vein, Gormer et al. (2011) propose the JRep framework for simulating an agent-based airport scenario, linking Repast (ABM) to Jade (MAS). As they note, "existing agent frameworks focus on either the macro or the micro perspective", but don't combine the two. The objective of the proposed combination of an ABM and MAS frameworks will allow us to better understand power system organisation/operation.

3 POWER MODELS IN ABM/MAS

Although there are over 70 ABM/MAS systems in existence few have been developed to address power systems, with categorisation and analysis of MAS applications in power provided in (Sujil et al., 2016). Table 3 in that review summarizes papers that have focused on lower level distributed simulation, while Table 4 provides a useful breakdown of papers that deal with specific power issues e.g. markets, generators etc.

For example, AMES (Repast) (Li and Tesfatsion, 2009), ECMAS (Repast) (Conzelmann et al., 2005), EMLab (Agent Spring) (De Vries et al., 2013) are specific modelling environments that have power system implementations, while "lower level modelling" of multi agent systems using Presage2 is presented in (Chen et al., 2016, Macbeth, 2015). Furthermore, Anylogic (AnyLogic, 2018), which is not specifically designed for power systems, is a proprietary system that could be used and has an architecture design whose logic allows analysts to model not only agents, but also discrete events and also use system dynamics. The agent behaviours can be modelled using JavaScript, but this is too limiting for our purposes, as we require a fully-fledged asynchronous Object Orientated Programming (OOP) language to model complex interactions. More sophisticated agents using Java and Neural Nets which are linked into AnyLogic using a Java Archive file (JAR) have been developed in (Wallis and Paich, 2017). This method requires a greater degree of programmer intervention to link in the various components and is less flexible than our proposed conceptual design.

EMLab has based their system on the Neo4J graph database (Merkl Sasaki et al., 2017), rather than build a Relational Database Management System (RDMS). This is an open source/commercial system used by many to analyse Twitter feeds and relationships. It is a very efficient and can be used to store knowledge maps, power networks and, most importantly, the relationships between agents in different layers and between agents on the same layer. It can in the right circumstances be a faster than a normal database (RDMS). It can also be used to quickly analyse networks and identify problem nodes for example. Due to its features which also fit nicely with the typical representations of power grids (i.e. they are node based) it may be a useful base for a future power simulator framework.

Furthermore, the Mosaik platform (Rohjans et al., 2013) is designed to allow reuse of components like Matlab and other "simulators to create large-scale Smart Grid scenarios". It is written in Python, provides an API for connecting these different simulators including MATLAB, and uses JSON to communicate between packages.

4 AN IDEAL ABM/MAS POWER SIMULATION SYSTEM

An ideal ABM/MAS power simulator would provide the following functionality:

- A design which allows us to understand how different behaviours of the various power system agents (generators aggregators, consumers and policy makers etc.) will affect the system technically and commercially. For example, how will power flows across the system change? How will prices change at various nodes in the system? Will they be too high? Will resulting power flows cause congestion in the system and require new investment?

- Test out new policy rules or potential control algorithms;
- Try out different agent behaviour techniques e.g. policy agent rules, different agent learning paradigms;
- Understand how voltage extremes (which would result in system performance degradation or failure) might be generated by behaviours of participants in the system, which in turn might be driven by policy makers rules;

The framework will also need to have the following features:

- Has both a market and network physical (i.e. power flow) layers that are incorporated into market clearing and bidding representations;
- Is extensible and is truly layer based allowing us the ability to switch in and out different layers and change agent behaviours as needed;
- Easy to use;
- Could be solved in distributed manner so to allow analysis of large scale networks;
- Plug in based while using a Component modularity architecture;
- Have models of agents representing various actors such as generators, loads, electric vehicles, aggregators, storage, atomic and temperature controlled loads, system operators, regulators, and companies;
- To reuse existing software components where ever possible;

4.1 Proposed Architecture

These requirements appear to drive us to a conceptual design that would include the following elements shown in Figure 1.

We discuss the main elements of this proposed architecture in the sections below.

4.1.1 Asynchronicity

A review of ABM surveys and systems shows that ABM (macro level) models are typically synchronous, whereas micro level systems such as Jade (MAS) are typically asynchronous. Youssefmir and Huberman (1997) have investigated the impact of asynchronicity on system performance. Figure 2 below shows such an impact from this paper. Note that the system is usually stable and is punctuated with periods of instability.

Youssefmir and Huberman's paper considers multiple agents who take decisions and act on the system simultaneously in an asynchronous manner to improve their utility. Our problem domain has exactly these characteristics and will incorporate learning and adaptive agent behaviour. Initial experiments on a simple power system model show similar patterns of punctuated bursts of activity followed by "stability".

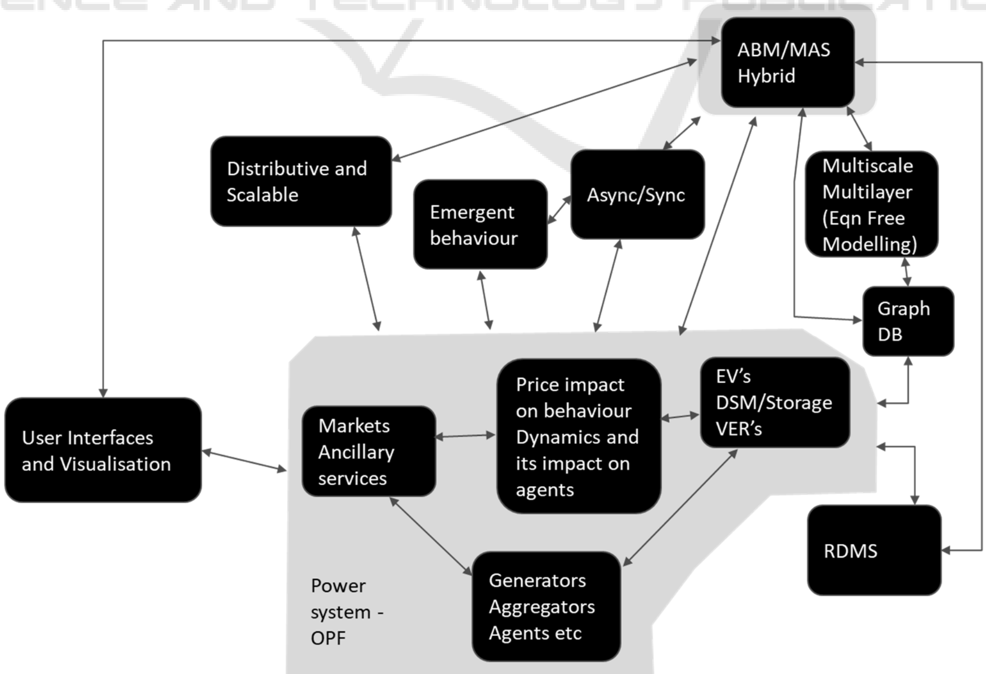

Figure 1: Proposed high-level architecture.

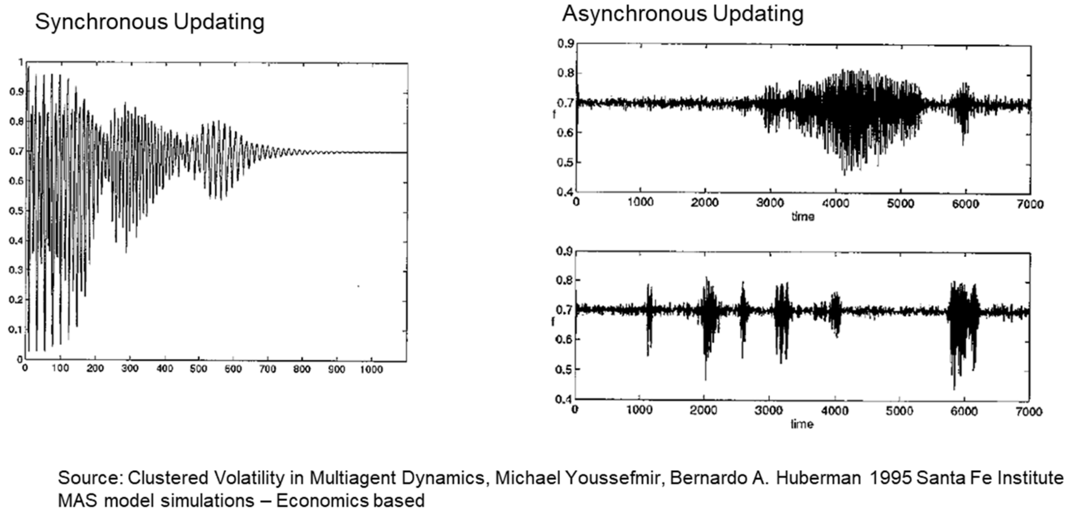

Figure 2: Asynchronicity impacts on system dynamics.

Cornforth et al. (2005) discusses MAS agent update strategies using a cellular automata (CA) framework as a case study. They examine updating strategies associated with some real life systems where the agents behave with different asynchronous update schemes and compare this with synchronous updating. The paper provides results on the dynamics of the CA system, under the different update schemes and shows that the outputs can be significantly different. Again initial experiments on a power system show similar behaviours.

In a future smart grid system, peer to peer (P2P) bargaining/interactions will have an important impact both on local conditions and further afield in the wider power system. By their nature these transactions are asynchronous, but other parts of the system will have synchronous interactions e.g. like market clearing. Designing and testing the interactions between these types of system e.g. P2P and the system operator, will allow us to understand how the system might perform in the future. A simulator with the ability to try out different synchronous/asynchronous protocols does not currently exist in the power domain and would be a useful addition to the power engineers toolkit.

In finance (Jacobs et al., 2004) developed the “JLM stock market simulator” to look at the effect of asynchronous investments on price patterns. Although written nearly 15 years ago, few authors and simulator designers have taken this approach, which as they argue is more realistic. All of the power system simulators that we have investigated assume synchronous investments. We know from our own domain experience, that in the real world, power investors do not act synchronously. In our context, earlier large capital investments in infrastructure may “lockout” later investments, so timing is crucial.

Modelling asynchronous behaviour in our context is therefore extremely important, so we would argue that models that ignore asynchronicity would find it difficult to predict future system states accurately. Our domain has elements of all the examples we cite above. We therefore propose that any future power simulation environment provide a mechanism to switch between modes of synchronization.

4.1.2 Multi-Scale (Equation Free Modelling)

From a CAS perspective, emergence occurs when events in one scale (micro) are propagated to another scale (macro) and vice versa. Capturing those effects (Holland, 1999), is key to identifying and understanding emergent behaviour in systems. In the context of the power domain, we suggest that it is important that system modellers investigate, these phenomena, so that they can design appropriate mitigation strategies. The multi-scale architecture allows us to model these propagation effects. It also fits well with the idea that we need to combine ABM (macro) and MAS (micro) architectures.

However, developing models that can simulate a combination of events that occur at both the second (for generators, EV’s) and the years’ timescale (for investments in infrastructure), are typically computationally inefficient. We require some kind of glue or bridge to join these timescales.

There have been many papers on multi-scale simulations, in recent years, and this provides a potential solution for our specific problem area. However, as we discussed above, our systems typically are "stable" for large periods and are punctuated with bursts of activity. Equation free modelling (DeAngelis and Yurek, 2015, Kevrekidis et al., 2004, Kevrekidis et al., 2003, Kevrekidis and Samaey, 2009, Kevrekidis, 2004, Le Maître and Mathelin, 2010) provides a promising viewpoint/solution for this particular aspect and we believe warrants further investigation, particularly in the methodology to trigger the micro level simulation. In this regard, there have been far less papers focused on this specific aspect, especially in recent years. This approach has not been implemented in the area of power systems simulation and therefore corresponding techniques need to be developed.

4.1.3 Multi-Level

Although there has been growing interest in developing models on multi levels and multi time scales, there still only a few concrete examples (Sarjoughian et al., 2001, Ferreira et al., 2015). The layered approach is discussed in many papers, but typically as a conceptual model, rather than used as a programming paradigm. This layer or multi-level model also fits well with the conceptual model presented by SGAM (Santodomingo et al., 2014) for Smart Grid interactions in power.

We would propose that any new conceptual design adopts a multilayer structure so that it can capture different views of the system represented as layers in a model (see Figure 3), such as a physical layer (devices power nodes, flows, congestion), market layer (prices) etc. We also propose that any new conceptual design allow users to easily add, define or remove layers, to allow experimentation with different designs. This would be easier using a graph database structure as the links in the database would define the layers and their interconnections.

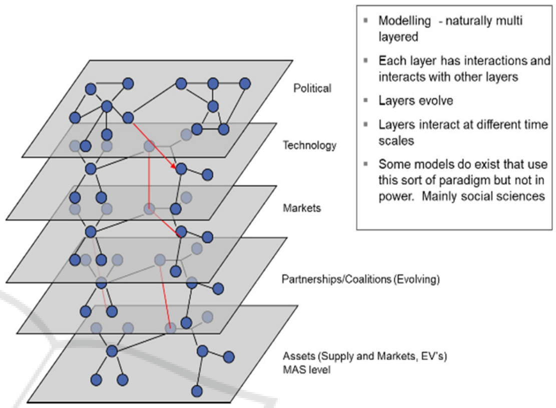

Figure 3: Multi-layer concept.

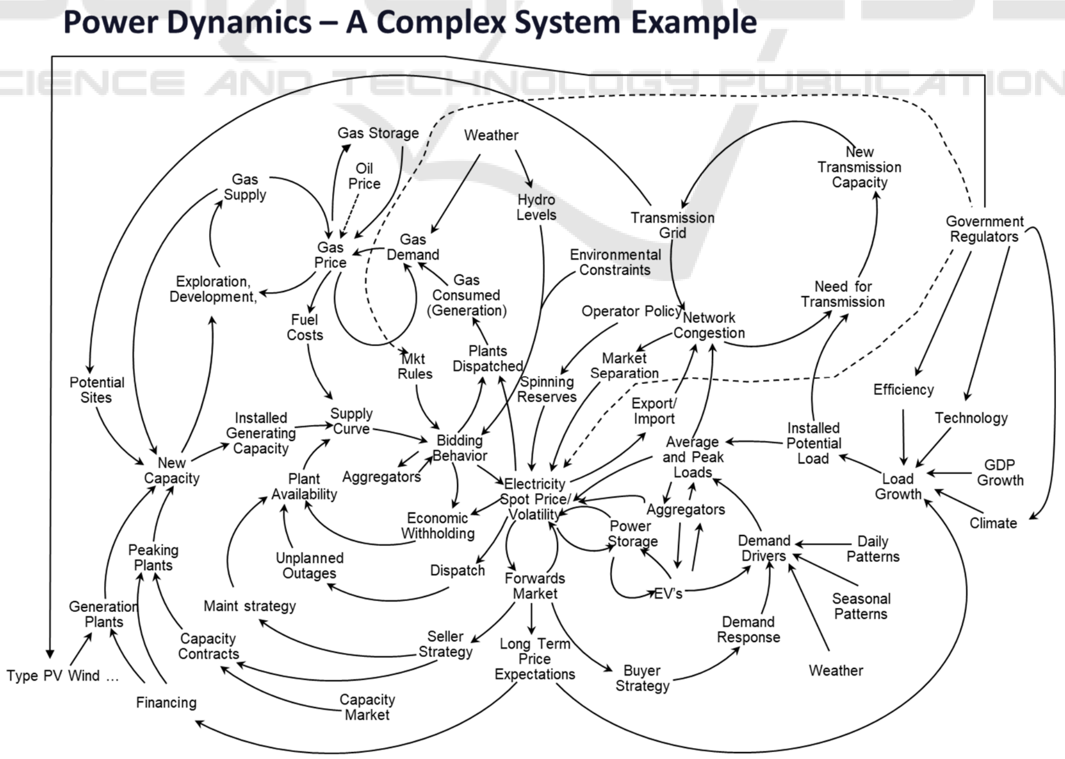

Figure 4: Representation of a power system.

4.1.4 Distributed and Scale

Many of the models we have investigated have been developed using smaller problems and therefore may be difficult to scale. To provide a realistic simulation, our problem space requires that a potential model can simulate tens of thousands of power nodes with thousands of power consuming and producing devices attached to each of those nodes. This drives us to a potential distributed architecture.

4.1.5 Power Simulation Specifics

A power system can be represented as a cause and effect diagram, as shown in Figure 4, which indicates flows, interactions and relationships between actors/agents e.g. generators. Note that that this diagram will evolve through time, e.g. 5-10 years ago EV's would not have existed on this diagram.

Considering this, one of the necessary features of a new proposed architecture is that it can easily allow changes of the relationships and flows.

We take as given that in the power domain that any model would also need to represent power flows and be able to "clear" the market on a large scale. This would necessitate that any framework have a methodology and a database structure/design suitable for power and particularly for designs associated with the evolving smart grid area and its new participants. Links to existing power system simulators e.g. MATPOWER (Murillo-Sánchez et al., 2013, Zimmerman et al., 2011) should be considered.

4.2 The Suitability of Existing Systems

Using a "traffic light" ratings approach for gap and needs analysis we have created a "Navajo blanket" of our power research problem to help us understand how four systems stack up against the requirements for an "ideal" power system simulator (see Figure 5). For brevity we only show one of the "Navajo" blankets" analysed. Extensive experimentation with the various systems discussed above has also been performed and forms the basis of the scores presented in Figure 5.

Each row represents a potential need or requirement for our ideal simulator. The four columns represent the four currently available systems that we are comparing. Scores from 1 – 10 have been given to each cell, with 10 representing that the system meets that current need. This is the equivalent of dark green in the figure. Zero represents that the system does not currently have that functionality. Colours are provided automatically by conditional formatting in

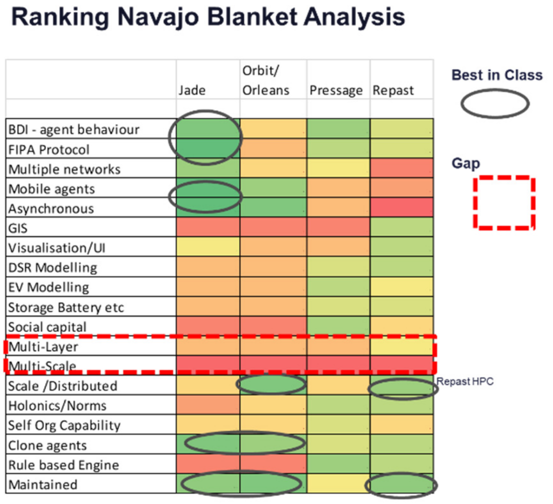

Figure 5: Navajo blanket of an ideal ABM/MAS power simulator.

Excel 2016 using a graduated green - yellow – red colour scale. Although models that are circled in Figure 5 can be regarded as most comprehensive in class, gaps for our requirements remain. Therefore, the above analysis indicates that there is a need for a hybrid ABM/MAS simulator to model electricity systems that fills these gaps.

It is clear from the proceeding sections that there are many useful ideas and components in the existing systems that can be reused, and therefore we would not advocate the complete redesign of a simulation system, but the reuse of large parts of existing simulators (e.g. EMLab, AMES).

5 CONCLUSIONS

This paper introduced current research and advocates for the development of a hybrid ABM/MAS system for power simulation. It presented an initial scope and ideas for this potential simulator. The addition of a multitude of electric vehicles and DER's to the power grid will exacerbate the complexity of the system and suggests that we should develop a distributed multi-scale, multi- layer architecture that will make use of reusable components. We are not advocating that we should build a completely new system, but see a solution in reusing and linking existing simulators, while some changes to their designs to accommodate better asynchronous modelling capabilities will be required. We have looked at a number of systems applicable to our problem domain and found that they lacked the following:

- An easy way to address asynchronicity and its effects on power systems especially at scale i.e. millions of agents;
- A system that models both the micro levels interactions and communications that are likely to occur between Consumers, EV's and system mangers in the longer term without the need to simulate every second for every agent;
- Systems that adequately link OPF to the ABM/MAS environment at scale;

Our proposal therefore adds the following main features to existing ABM/MAS power simulators in the power domain; An asynchronous/synchronous base applied to an existing ABM and MAS simulator; the use of an equation free modelling technique or some other alternative to simulate at the micro scale when required, and an existing large scale OPF model. We are currently looking to design and build this simulator and are developing agent methodologies and detailed interaction protocols using an agent orientated design methodology. Investigations into multiscale methodologies (particularly equation free modelling) are ongoing.

ACKNOWLEDGEMENTS

This research is funded by the UK Engineering and Physical Science Research Council (EPSRC) and the International Strategic Partner (ISP) Research Studentship.

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