A Concept Solution Architecture for Electrical Distribution Control Centres

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***Abstract*—Established network operator control systems continue to evolve, but are neither homogenous nor necessarily designed to scale with the pace of change required to meet decarbonisation aims. Intrinsic to 'smart' and 'autonomic' power system concepts is a need for adaptive and accordingly more flexible control philosophies, grounded in reflexive systems able to balance local optima with global conditions. To bridge technological differences between these aspirations and foundational infrastructure in place today, principles and techniques in solution architecture are explored. A solution architecture concept design is presented in this paper, primarily intended as a basis for more detailed design iterations toward vendor- and operator-agnostic control systems, and in support of control system scalability and flexibility. Operator aspirations are ambitious, such that systems risk growing in complexity. This risk and associated mitigations are highlighted and incorporated within the proposed design.**

***Index Terms*—Electrical distribution, Control, System design**

I. INTRODUCTION

Electrical distribution networks play a central role in a transition to 'net zero', facilitating a step change in volume and diversity of connected low carbon technologies (LCTs). New dynamic energy products and services are emerging that are specifically targeted at LCT owners, bringing new actors and variables to the energy sector; such as flexibility services and commercial market platforms. These products and services will combine to change the established behaviour of the system and will require network visibility and control significantly beyond current levels. In future, new sensors, forecasts, and critical datasets will inform control room decision making at a scale, and a complexity level, well in excess of existing electrical system (technical *and* commercial) operation.

Whole system solutions, where distributed energy resources (DERs) will deliver a range of services to support both bulk system needs and resolve local issues, will add further complexity. An increasingly complex system will lead to new risks and a high volume of real time critical decision making involving technologies such as artificial intelligence and decision support tools. It is necessary to understand how these systems behave in normal and extreme events, and their interaction with human operators and decision makers alongside the behaviours of customers and markets.

Peak risks in control room activity occur during storms or other disruptive events. It is anticipated that the "storms" of the future are not only going to be triggered by weather conditions but will also arise due to the complex interactions required between distribution network operators (DNOs), distribution system operators (DSOs) [1], different industries (e.g. gas networks and transport), customers, and other actors, to achieve net zero and a decarbonised grid. These peak risks will escalate as the rate of change of control room complexity accelerates; especially with the increasing need for control room interactions with other industries to achieve net zero.

Studies of the 2019 Boeing 737 Max failures [2] revealed that complex systems introduced on an old architecture caused new failure modes; particularly the co-ordination and handover between automated interventions and human-led interventions. These challenges are not industry specific and the potential exists for similar issues in the DNO/DSO control centres of the future. Without a new approach, the control room itself could become a constraint which could compromise network resilience and security of supply, operational safety, restrict the connection and performance of local energy systems (LES), LCTs, DERs, and hinder the development of the DSO.

This paper considers the changing context of modern control centres in Section II. The method is outlined in Section III, which in turn introduces three contributions: early requirements capture, in Section IV; a need for structured approaches and the use of frameworks, in Section V; and a concept architecture is then presented in Section VI. Discussion is offered in Section VII before Section VIII concludes this work.

II. BACKGROUND

Presently, control systems are not homogenous: systems from distinct license areas do not interact; are often '*locked-in*' to an oligopoly of monolithic suppliers; and comprise various distinct and proprietary components, requiring piecemeal upgrade projects. Control philosophies are centralised. Data are collected and relayed to a central location where decisions are taken, for the most part by human operators in collaboration with maintenance teams, an energy system operator, forecasting, and planning teams. Naturally, latencies in decision making result from communication, human oversight, and collaboration. Visibility of a network (and particularly 'last mile' assets) is limited, such that end-users are often those to first alert a control centre of a supply interruption. Security is a foremost concern, in terms of both information and systems of work, and further contributes to necessary delays in information retrieval and processing and threatens to constrain the scalability of existing solutions.

A distribution system designed for net zero carbon impact is expected to include bidirectional power flows, DERs, and consequently less predictable, more flexible network operation. Evolving electrical systems from conventional topologies and approaches toward greater numbers of connected renewables and the improved system flexibility required to accompany them, incentivises a change in control philosophy (p1433, [3]).

When an analogous problem (the challenge of overcoming physical limits – a 'power wall') faced computer architectures, parallelism was the solution (p55, [4]). Should the number and speed of decisions increase with network flexibility, a possible solution is to scale decision-making through parallelism and concurrency: a decentralised or distributed control philosophy is prerequisite to unlocking the flexibility and dynamism anticipated for a scaled transition toward decarbonised energy.

III. METHODOLOGY AND APPROACH

To this end, collaboration with industry colleagues helped to precipitate a set of requirements for future control systems as a requirements elicitation (Section IV), principles of solutions architecture and high-level system design have been adopted (Section V), to then inform a concept architecture (Section VI).

In this work, a set of 4 principles shape the approach taken:

1) leveraging existing expertise and established approaches;
2) taking an iterative and incremental approach to a solutions design by broadly aligning with layers of the SGAM [5];
3) given the scale of envisioned change, an open-minded, 'blank canvas' approach is intended to avoid requirements being too closely shaped by existing systems; and
4) to design for uncertainty wherever practicable, in the knowledge that further change is uncertain and inevitable.

IV. INDUSTRIAL COLLABORATION

A. Format and Planning

A series of meetings organised with industrial colleagues have offered an opportunity to gauge opinion, seek insight, and build consensus for future research directions. Their format included two events per network operator, each of which had two or three breakout rooms, and involved the use of digital whiteboard tools to facilitate discussion. Questions were open ended, with the primary motivation to capture aspirations for the future, beyond immediate challenges. Open discussions were also held with other parties with interests in the subject area, including those who contribute to generator connections.

These meetings have been transcribed and, line by line, notes labelled with one or more aspirational themes until a set of non-functional system requirements could be precipitated through a methodical process of iterative textual analysis.

B. Non-functional Requirements

These general aspirations for future control capabilities are comprehensively detailed in project documentation [6], and are entitled: 1) improved communication; 2) balancing automation and human-centred control; 3) secure, resilient, safety-critical national infrastructure; 4) market facilitation; 5) forecasting and long-term planning supported by data; 6) customer relationships and new market participants; 7) power system modelling; 8) realistically scalable, responsive, and extensible; 9) monitor assets, fault response, isolation and servicing (FRIS) & outage anticipation, and blackstart; 10) usability, ergonomics, culture change, knowledge elicitation (KE) & mobility; 11) whole systems, open data, & vendor interoperability; 12) system voltage, inertia, and constraint flexibility; and 13) LV monitoring, modelling, control, & data processing.

C. Discussion and Reflection

Open formats were effective in allowing areas to be covered which facilitators had not anticipated. Digital meetings are second to being co-located with contributors, or to actually view and understand the processes described, but this format was necessary under public health restrictions in place at the time of this activity. These workshops and interviews primarily aimed to encourage a common ownership of the research problem; to gather views and understand challenges faced by control centre engineers; and to collect design requirements.

Notes taken during these exercises were documented as text, from which themes were generated, and used as a basis to collate relevant notes, before these notes were expanded and synthesised into narrative prose. Inevitably, this process is limited by facilitators' understanding, and is the outcome of inherent subjectivity (in recognising themes from across a set of distinct conversations), but adhering to a methodical process has been intended to maintain reasonable objectivity.

V. SOLUTIONS ARCHITECTURE

An aspiration for this project is to adopt existing disciplines and approaches, hence solutions architecture is used to help form and articulate industrial colleagues' design requirements.

A. Why Use Solutions Architecture?

Solutions architecture offers proactive design co-ordination. In general, errors identified early in a project or development lifecycle incur significantly less cost to remedy than those found late, particularly where multiple parts of an interdependent system must change to resolve each one. Solutions architecture and systems design leverage prior experience to guide creation of new systems, and crucially, with the dual intention of reducing barriers to communication across disciplines while offering a structure to promote early dialogue – ultimately to avoid or resolve errors and their overall costs.

B. Principles and Frameworks

Moreover, architectural principles learned through experience help maintain best-practise and prior learning to each new project, during which the principles themselves can be tried and tested in order to be reinforced or refined over time.

Architectural frameworks are a natural outcome of this process, which offer designers 1) a point of reference and guidelines to inform more detailed designs; 2) the benefit of learnings made during the design of previous projects; and

3) a common vocabulary with which to navigate and referring to components within disparate systems and subject areas.

PCBMER is the architectural framework chosen for this project. It proposes a set of hierarchical layers (which abbreviate to 'PCBMER') with a set of associated design principles.

Principles advocated by the PCBMER framework [7] include e.g. a 'downward dependency principle' requiring information to pass upward through its layered architecture, such that this unidirectional control flow can be used to form a distribution control system as a single control loop.

C. Functional Requirements

The smart grid architecture model (SGAM) [5] is also a layered framework, which attempts to contextualise designs in unified modelling language (UML). Functional requirements for future control systems can be incrementally refined by specifying use cases on the most abstract 'business' layer of the SGAM, and subsequently refining each one with greater detail on those closer to physical network assets under control.

UML is suited to software and technical projects, and offers a common vocabulary to information system designs; just as for solutions architecture frameworks, this helps to lower communication barriers around contractual specifications [7], while also offering a common vocabulary understood within the software community to convey a technical meaning. It can therefore be useful for all parties involved with specifying and designing infrastructure to build familiarity with UML, particularly where infrastructure is scalable, or otherwise sufficiently critical as to merit a thorough organisational understanding.

In this project, StarUML has been used to prepare functional designs. An important benefit to structured representations is to provoke early thoughts and discussion around a proposal: structured representations encourage a designer to question a design as it is prepared ('is the relationship 1-to-1, or 1-to-many?', 'is aggregation or composition most appropriate?').

VI. A CONCEPT DESIGN

Figure 1 shows an initial concept architecture outlined as a series of component blocks organised into a layered hierarchy.

The hierarchical nature of this design separates a model of the present network state from control functions, where an:

1) *information* layer collates and attempts to rationalise *data* received from the network (alongside other networks and energy vectors associated with whole-system operation), with the presently-understood *simulation* state (an internal network model, as in [2]); before passing to a
2) *decision-making* layer, enabling *control* collaboration, in which human-in-the-loop decisions are augmented by decision-support or automation; that together inform an
3) *actuation* layer, designed to achieve desired *actions* whether by co-ordinating conventional interventions, employing remote telemetry, or via market-based incentives.

Together with primary network assets, component blocks form a control loop, thus keeping human operators within the control loop but allowing for an appropriate balance between the control burden placed on operators and on automation.

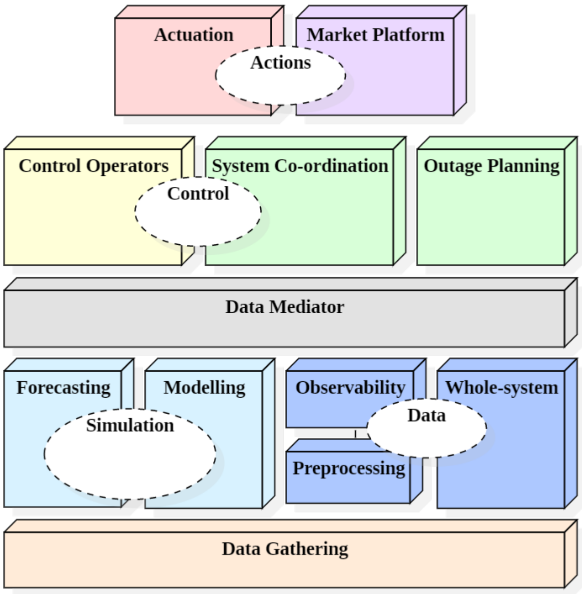

Fig. 1. Concept Solutions Architecture

A principle for architecture is to offer long-term control over a solution which will continue to grow and evolve over time. As such, this concept design allows for collaboration between central components: 1) data is processed between a combination of preprocessing and observability functions, which are likely to evolve over time as a greater number of network sensors are deployed and observability functions correspondingly become more sophisticated; 2) where forecasting is initially limited, modelling and forecasting will operate in tandem to identify the conditions necessary to provoke control decisions, but will facilitate a gradual balance between forecasting and modelling to be struck as both functions grow; 3) as human operators remain an integral part to control systems, but risk being inundated by increasing alarm volumes with an increase in monitoring and changes in network operation, automated functions could gradually handle an increasing amount of the more straightforward control decisions to relieve human operators to focus on critical tasks; and 4) while actuation can be achieved using telecommunications or co-ordination with personnel on site, market-based mechanisms are likely to play a greater role in future networks and could help achieve widespread behaviour changes in supply and demand which could mitigate a need for an operator to intervene directly.

Figure 2 shows UML of a second design iteration to expand on the original design by exploring individual components associated with each block, an example of which is shown in Figure 3, as well as the connecting interfaces required for data to pass between subsystems. Each block of the overall concept design is further expanded in project documentation, both in terms of a functional overview through an exploration of initial *use cases*, and non-functionally in terms of a possible underlying structure through *component diagrams* (Figure 3).

In a third design iteration, the proposed design was brought

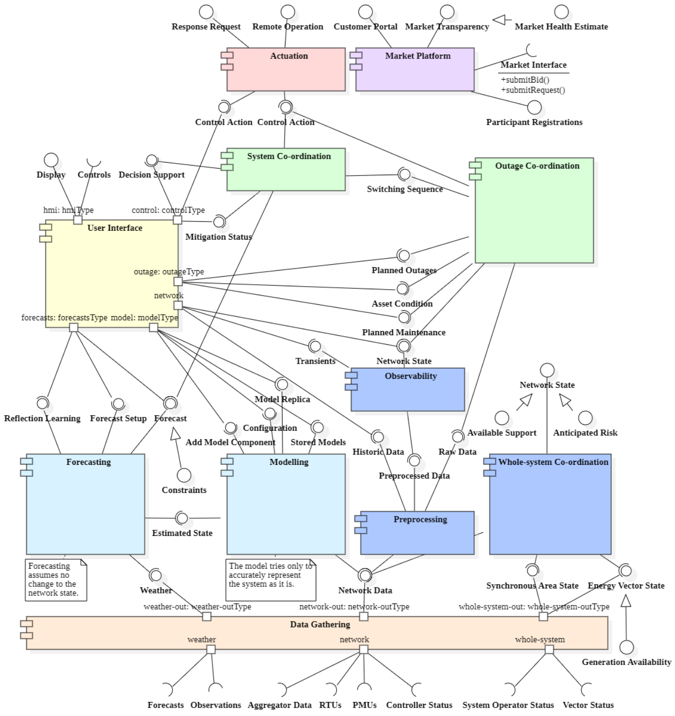

Fig. 2. Second Iteration Component Overview

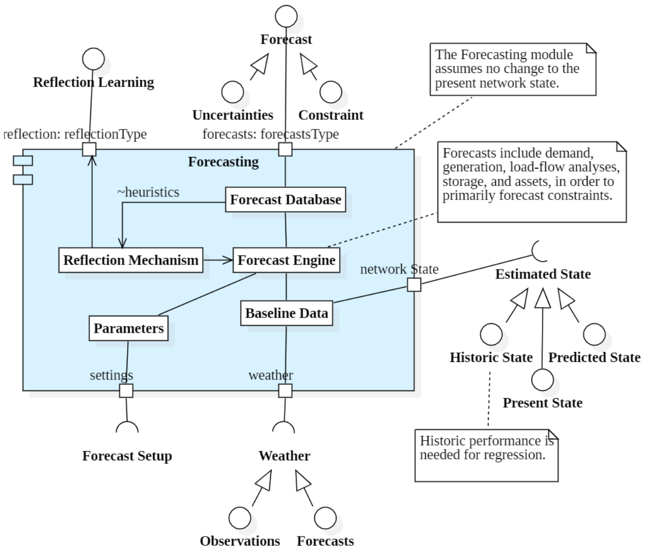

Fig. 3. Forecasting Component Diagram

into alignment with the structure and principles associated with the PCBMER design framework, where subsystems have been allocated to each layer of this framework as in Figure 4[1]. Dependencies are limited between layers of this framework, in support of a cohesive and accordingly loosely-coupled system design[2]: a review of the design was necessary at this stage, to ensure the framework structure is followed by redesigning dependencies in the proposed concept design found to be incongruent with the framework, but also to ensure the principles behind the adopted framework are respected.

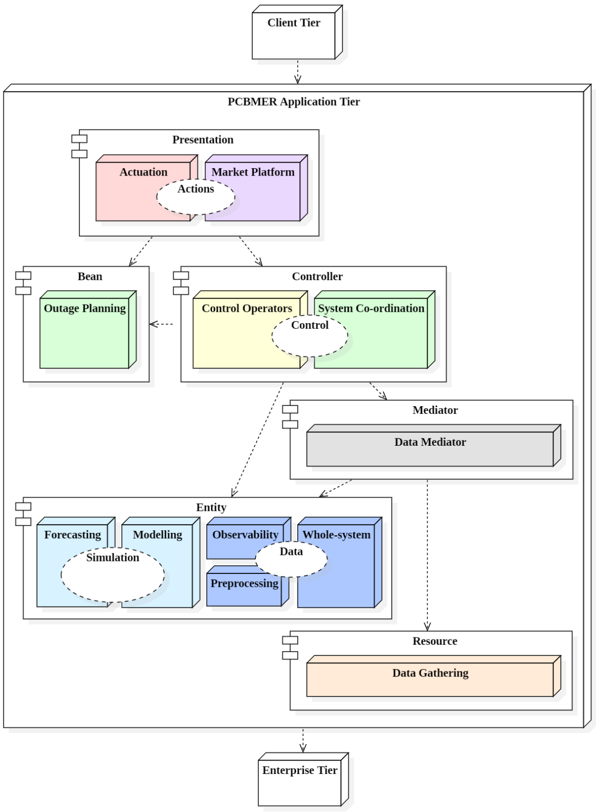

Fig. 4. Aligning the Concept Design to the PCBMER Framework

VII. DISCUSSION

The purpose of proposing detailed architectures is to bring forward discussion and promote a coherent understanding of a system early in the development lifecycle. This not only cultivates shared understanding but when done well can even serve to eliminate errors prior to the costs associated with development, and therefore saving on the significantly increased costs of retrospectively resolving errors or misunderstandings.

A. Complexity

In Figure 2, the 11 proposed subsystems result in over 40 distinct data interfaces. Even for this low number of individual subcomponents this hints at a complexity likely to mimic combinatoric expansion, and serves to illustrate the need for reduced coupling which frameworks are designed to promote. Growing system complexity is a foreseeable problem which solutions architecture and early systems design can mitigate ahead of time, to limit development, test, and integration costs.

B. Interoperability

The GridWise architecture council (GWAC)'s interoperability framework [8] aims to improve intrinsic compatibility and

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[1] Figures 1, 2, 3, and 4 are similarly colour coded for ease of reference.

[2] Loose coupling promotes robustness, security, maintainability, and extensibility by reducing the burden of work associated with subsequent changes.

thus supply chain interoperability, to reduce efforts needed for integration (termed the ‘distance to integrate’). This paradigm would improve system extensibility and adaptiveness, and could even enable ‘plug and play’ capabilities. Furthermore, subsystems designed to be interoperable are necessary to avoid vendor ‘*lock-in*’ (Section II), by enabling subcomponents to directly identify one another and dynamically interact.

Non-functional requirements 3, 8, and 11 could in part be met by subsystem interoperability, where each component would offer an interface allowing it to: subscribe to a common registry; collaborate dynamically; and to use shared semantics.

C. The Case for Open Source

Sustained growth in some information technology industries (such as for mobile phones) must be caveated with an understanding of relevant business models and culture: open source software ecosystems result from a *collaborative* (rather than a competitive) ethos. Should a similarly collaborative culture be accommodated within the supply chain for distribution control technologies, open-source development could offer a number of advantages [9]: 1) collaboration fostered between organisations in a supply chain allows for scalability, 2) an opportunity for subject experts to contribute directly to a common solution, 3) improved trust as a consequence of security assertions being verifiable, and 4) the potential for reduced long-term costs to consumers as a result of licensing arrangements. An open source culture is the key to the rate of development in other industries, and given the pace of change required to decarbonise electrical systems, could offer the scalability, stability, and rate of development necessary to achieve global sustainability development goals at pace [10].

D. Validation

While it is necessary to consider high-level architectures in order to guide more detailed development effort and provide structure to a system expected to adapt over the long term, there remains a clear need to explore the applicability and appropriateness of a concept architecture which appears plausible but remains little more than an abstract design.

The proposed solutions architecture and the principles associated with it, will be taken forward as a basis for further work in specifying demonstrators as a future project.

The transition to DSO will take a lot of work among many parties and possibly where there are competing interests. It is therefore essential to this process to ground the dialogue in a common, if abstract, architecture in order that a division of labour can be achieved while nevertheless facilitating common cause and the adherence to common principles which suit the whole system, but are written into individual components.

E. Opportunities for Further Work

As a system comprising safety-critical control functions, some components are envisaged to be more time-critical than others, but the presented concept design remains to be explored and characterised in these terms. An extension of this work might choose to consider this aspect of a design, and possibly within the wider context of a system’s *shearing layers*: the rate of change of a system’s environment influences the level of adaptiveness its architectural design should accommodate.

One part of this operating environment is the *enterprise architecture* any system is designed for. While this work considers an information system’s technical nature, and is accordingly limited in scope to *solutions* architecture, any successful solution must necessarily be sympathetic with the enterprise architecture it forms part of. This important design aspect remains a possible direction for further work.

Finally, design coherence risks a cognitive illusion of validity (p209 [11]), ultimately to be best tested by implementation.

VIII. CONCLUSIONS

Engagement with industry partners has been a basis for requirements gathering, offering a platform for functional and non-functional requirements to be articulated and a concept design for future control systems formed. While there remains scope for further work, a solutions architecture outlined in this paper underscores the scale of ambition of network operators to accommodate decarbonisation aims. This need to decarbonise will increase system complexities as new control capabilities are integrated to meet emerging requirements.

Given expected increases in data throughput, greater parallelism for future control systems can be unlocked by a degree of automation. Control system roles are expected to evolve to include an element of supervision of otherwise autonomous systems, to free operators to focus on edge cases and prevent overburdening critical personnel. The proposed architecture has been incrementally refined by adopting solutions architecture principles, and aligned with a design framework in anticipation of system complexity expected to grow in time.

As further ambitions emerge among DNO/DSOs, design discussions require a common point of reference among cross-industry parties. To this end, this paper presents a concept solution architecture for electrical distribution control centres.

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