Advantages of Integrated System Model-Based Control for Electrical Distribution System Automation

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Abstract—Integrated system models based upon the generic programming paradigm and which include all fundamental problem domain objects are applied to electrical distribution system automation and control. The control architecture resulting from this approach is reviewed. Flexibility of design, topology independence, fail-safe operation, and robustness of algorithms are considered.

I. INTRODUCTION

The automation and modernization of the electrical distribution system (EDS) is a popular topic among utilities, vendors, developers, researchers, policy makers, and regulatory bodies. While utilities and vendors have been steadily improving the capabilities of the EDS for decades, recently grid modernization and automation has been brought to the forefront. One area of grid modernization that promises to yield great benefits for many different stakeholders is advanced EDS control.

While modernizing the grid is undoubtedly necessary, utilities cannot sacrifice quality of power or reliability of service in the process. With this in mind, a successful EDS control strategy must have the following properties:

- **Fail safe:** There are many advantages to adding advanced communication and control capabilities to EDS devices. The added complexity, however, can lead to more opportunities for failure, misoperation, or sabotage. When a communication or control failure does occur, the system must maintain a state that does not violate circuit constraints, threaten personnel and public safety, or risk damaging utility and customer equipment.

- **Integrate legacy and modern equipment:** The trend in power system modernization is to focus on devices with advanced capabilities. In reality, legacy equipment will continue to be used on the EDS for the foreseeable future, and the operation of these legacy control devices will impact the performance of the automated devices.

- **Flexible:** The EDS topology is designed to be reconfigured. The topology can change frequently, either from planned reconfigurations or from unscheduled reconfigurations due to protective device action. These topology changes can have a dramatic impact on control strategy and the performance of EDS control devices.

- **Extensible:** After decades of relative consistency, the landscape of the modern EDS is rapidly changing. New devices are being used, and traditional devices are being used in new ways. A control scheme should be able to integrate new devices as well as new applications.

- **Robust:** The control system must be able to provide a solution for any circuit condition.

This work will discuss how a model-based approach to EDS automation and control can provide all of the above. In addition to the fundamental criteria above, model-based EDS control can have the following advantages:

- **Decreased monitoring costs:** Model-based control schemes can reduce monitoring costs by estimating electrical parameters using measurements at strategic locations on the circuit.

- **Incremental modernization:** By allowing modern and legacy equipment to coexist, a utility may replace infrastructure as it is convenient.

- **Increased awareness:** Monitoring is becoming more common on the EDS; however, it is unlikely that a utility will be able to monitor all loads on the circuit in real time. Model-based control can estimate quantities at all loads in the circuit to ensure performance criteria are not being violated.

- **Error detection:** Model-based control can be used to detect errors in model state or measurement by comparing SCADA values against calculated results.

II. EDS ANALYSIS AND CONTROL

Due to the constantly changing nature of the EDS, one of the major challenges of model-based control is maintaining a model that accurately reflects the state of the system. This challenge is further complicated by the traditional utility approach to modeling and simulation. Shortcomings in modeling software used for EDS analysis have made it necessary for individual groups within a utility to construct separate models to perform analysis. For example, protection engineers may create and maintain a model of the EDS, planning engineers have another model, while operation staff may create and maintain a different model. This fragmented approach to modeling leads to inconsistencies and errors. A collaborative environment exits when everyone shares the same model and the accuracy of the model and the analysis results obtained from the model is improved. This is the approach proposed here.
The controller design described in this work uses an integrated system model (ISM) to mitigate these issues. The ISM concept as it pertains to EDS analysis and control is described below.

**Integrated System Model**

An ISM is built on the concept that all data necessary to solve problems within the problem domain are related within the same model. In the realm of EDS analysis and control, an ISM is defined as a single model that contains all data needed to perform any EDS planning, operation, and control study. By including all of the necessary data into a single model, the need to produce and maintain multiple representations of the same system (in this case, the EDS) is eliminated. The ISM promotes a cohesive analysis environment within a utility and reduces the time needed to construct and validate the EDS model.

A static view of the ISM used here consists of a hierarchal set of relational database tables [1]. These database tables fully describe all electrical systems, circuits, components, and their functions. Furthermore, the database tables describe the topological, spatial, and temporal relationships of each element. A dynamic view of the ISM is created when the model is loaded into the memory.

ISM models have been successfully used for EDS control [2, 3]. Additionally, the accuracy of ISM predicted values has been validated against field measurements [4]. Fig. 1 shows an example of an ISM where all components of an EDS are modeled together.

**III. HIERARCHICAL, MODEL-BASED CONTROL**

To demonstrate some of the advantages of ISM-based control, a hierarchical, model-based control scheme based on the ISM is considered here. This work will focus on how to leverage an ISM for EDS control, paying special consideration to the criteria listed above. Reference [4] describes the controller in more detail.

**A. Controller Overview**

The controller described here is a model-based control scheme designed to coordinate all active control devices on the EDS, including capacitors, voltage regulating transformers, and distributed energy resources (DER). The controller is designed to find improved, steady-state operating points using all available control devices. If an improved operating point is discovered, the central controller provides the new operating point to the local controllers. The local controllers are then responsible for implementing the control set-point as well as dynamic or transient operation. The controller uses graph trace analysis [6] to automatically discover control devices connected to the circuit and to determine device usability. The control algorithm is illustrated in Fig. 2.

Using properties of the EDS to limit the solutions space, the controller uses iterative calls to a power flow algorithm and a local exhaustive search to find an improved operating point. The search algorithm is a prioritized, nested routine.

**D. Fail Safe Operation**

By utilizing a hierarchical architecture, the burden of implementing the control is distributed. Thus, when the eventual communication or controller failure occurs, the EDS is left in a manageable state. Furthermore, the local controllers may have overrides based on local feedback that prevent the devices from exceeding operational limits.

**E. Integrate Modern and Legacy Equipment**

Before the controller can utilize a control device, the device must have communication and control capabilities and must be in a mode suitable for remote control. Despite ongoing efforts to modernize the EDS, controllable and non-controllable devices will coexist on the EDS for some time. Since these legacy control devices often act autonomously on local information, interaction will occur between controllable and non-controllable devices.

The ISM models the non-controllable devices along with the controllable devices, including controller set-points, operating modes, and device behavior. Thus, the results of the search algorithm will contain the impacts of legacy device operation. For example, if by manipulating a voltage regulating transformer the controller causes a legacy switched shunt capacitor to change states, the model will reflect this operation.

Traditional control methods that aren’t based on models can have difficulty detecting these interactions. When these interactions occur, they can lead to device cycling and operational criteria violations. In practice, devices are often detuned to prevent these interactions.
B. Flexible

A controller must be flexible enough to handle changes in circuit topology. Scheduled and unscheduled topology changes can occur often on the EDS. Each change in topology has the potential to alter the way a control device impacts a circuit and therefore the effectiveness of control strategies.

The ISM-based control algorithm discussed here is topology independent. The algorithm performs a search over a number of power flow solutions. Each power flow solution represents a unique combination of control device states. As long the model accurately represents the physical system, the current topology of the system does not affect the controller’s ability to provide an improved solution.

C. Extensible

The EDS is undergoing a period of unprecedented innovation. Devices such as photovoltaics are being connected to the circuit in growing numbers, and traditional devices are being used in new ways. Additionally, devices such as plug-in electric vehicles and community energy storage systems are on the horizon. The arrival of these devices promises to greatly impact the behavior of the EDS as well as the effectiveness of control devices and strategies. To avoid becoming instantly obsolete, control schemes must be able to account for these devices as well as other that may not be commonly interconnected today.

A model-based control scheme such as the one described here can integrate these new devices and operation modes into the control scheme as long as an accurate representation exists in the model. Because utilities will likely require models for devices prior to interconnection to the EDS, such modes will likely be readily available. Furthermore, steady-state models are generally easier to obtain from manufacturers because the need to disclose proprietary information is relatively small.

The extensibility of the ISM-based approach comes from two major factors. First, a search algorithm is used to find an improved solution rather than explicitly calculating a solution. Second, the controller is agnostic to the operational specifics of the control device.

Similar to the discussion with regard to controller flexibility, the extensibility of the controller greatly benefits from using a search algorithm to determine improved operating points. Because the search algorithm can be used as long as power flow successfully converges, the controller needs to know very little about the specifics of the control devices.

Additionally, the algorithm the controller uses to manipulate the control devices is generic. All that the controller requires to incorporate a new device into the control scheme is the nature of the control variable (discreet or continuous) and the acceptable range of values. In other words, the controller does not need to know if the control device changes taps, varies reactive power, performs demand response, or curtails real power. The circuit response to changes in the control parameter is captured by the power flow solution.

F. Robust

An EDS controller must provide a solution under a wide variety of operating conditions. The loading on EDS circuits can vary greatly throughout the year. The central controller ensures a solution is always available to the local controllers by treating the current operating point as the base case. If the controller fails to find an improved solution, the circuit is left in the current operating condition.

Furthermore, the search algorithm based on power flow solutions provides a solution more reliably than explicitly calculated optimal solutions. The limiting factor for producing a solution using this approach is the convergence of power flow. The convergence of power flow on radial EDS systems (the vast majority of systems in the United States) for modern simulation packages is very reliable [7].

IV. CONCLUSION

This paper describes fundamental criteria for a modern electrical distribution control scheme as well as a model-based control scheme and the methods used to meet the fundamental criteria. The controller provides a number of advantages over conventional control methods, including extensibility, integration of modern and legacy control equipment, and topology independence.

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REFERENCES


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