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Distributed Rules-Based Deconfliction of ADMS Applications

Part 2: Conceptual Implementation

March 2023

Alexander Anderson
Subramanian (Mani) Vadari
Todd Wall
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U.S. DEPARTMENT OF ENERGY

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Summary

This work introduces a conceptual framework and preliminary methodology for resolving conflicting device control commands issued by advanced power applications. The methodology is designed to serve as one of multiple possible alternative implementations for the numerical component of the Deconfliction Pipeline introduced in [1]. The Deconfliction Pipeline is a framework for deconflicting multiple applications that intercepts control commands issued by advanced applications to (sometimes the same) field equipment, identifies possible conflicts, and generates new controls and/or setpoints. It is anticipated that future operational implementations of the Deconfliction Pipeline will use a combination of the rules-based methodology (introduced in this work), application cooperation, and global optimization.

The rules-based deconfliction methodology focuses on using a combination of technical, economic, environmental, and social rules to guide selection of a suitable set of equipment controls and/or setpoints that are acceptable to the distribution system operator and do not violate real-time operational constraints. The methodology can be implemented as constraints on a global optimization problem or as a decision criteria as part of a multi-criteria decision-making framework. The second approach is well-suited for use with distributed applications and distributed computing, and thus, will be the focus of two complementary reports, *Distributed Rules Based Deconfliction, Part 1 and Part 2*.

The previous document, *Rules Based Deconfliction: Part 1* applied a Grid Architecture approach to characterize the domain problem and introduces the context, requirements, and methods for handling the deconfliction problem. Key concepts of the Laminar Coordination Framework and Variable Grid Structures were applied to define a conceptual framework for formulating the deconfliction problem. The deconfliction problem was then decomposed into a distributed optimization problem based on the concept of quasi-static grid segments, which form independent distributed areas for control and coordination.

This document, *Distributed Rules Based Deconfliction, Part 2* details the various criteria, rules, and processes by which setpoints are analyzed, ranked, and ultimately selected. It introduces an initial set of technical, economic, and environmental criteria for generating a deconfliction solution that meets the requirements of the distribution system operator. It also introduces specific qualitative rules that are used as part of the deconfliction methodology to eliminate non-viable setpoint alternatives. This work also details how the deconfliction optimization problem is converted into a ranking of individual discrete setpoints, scored by specific decision criteria. Several multi-criteria decision-making frameworks are examined with the simple multi-attribute rating technique exploiting ranks (SMARTER) recommended as a simple implementation alternative that aligns with the steps of the rules-based deconfliction methodology.

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Acronyms and Abbreviations

ADMS	Advanced Distribution Management System
AGC	Automatic Generation Control
AMI	Advanced Metering Infrastructure
AOR	Area of Responsibility
AVR	Automatic Voltage Regulation
CIM	Common Information Model
CVR	Conservation Voltage Reduction
DER	Distributed Energy Resource
DMS	Distribution Management System
DR	Demand Response
ESB	Enterprise Service Bus
FLISR	Fault Location Isolation and Restoration
HV	High Voltage
IEC	International Electrotechnical Commission
IT	Information Technology
LTC	on-Load Tap Changer
MADM	Multi-Attribute Decision Making
MAUT	Multi-Attribute Utility Theory
MCDM	Multi-Criteria Decision Making
MODM	Multi-Objective Decision Making
OMS	Outage Management System
OT	Operations Technology
PCC	Point of Common Coupling
SCADA	Supervisory Control and Data Acquisition
SMART	Simple Multi-Attribute Rating Technique
SMARTER	Simple Multi-Attribute Rating Technique Exploiting Ranks
VVO	Volt-Var Optimization

Contents

1.0 Introduction

Ongoing decarbonization and grid modernization efforts are rapidly transforming electric distribution networks, with significant increases in penetration levels of distributed energy resources (DERs), including distributed generation, battery storage, electric vehicles, and controllable customer-owned resources. Additionally, numerous new data streams are becoming available advanced metering infrastructure (AMI) systems and grid-edge devices, internet of things (IoT) devices, smart inverter controllers, intelligent reclosers, and micro-phasor measurement units. To leverage these new devices and data streams, distribution utilities are investing in new advanced power applications as part of advanced distribution management systems (ADMS) and distributed energy resource management systems (DERMS).

Within this new paradigm, the historically challenging data integration problem is complicated further by the emergence of application conflict. Each new advanced power application pursues its own set of objectives and may send control commands to change the setpoints of these devices. Unless these applications have been carefully integrated and tested as part of a single vendor suite, it is likely that different applications may issue competing setpoints to the same device. Without a robust deconfliction process, multiple mis-operation scenarios are possible, including 1) devices responding to setpoints arbitrarily, 2) oscillating system behavior as conflicting setpoints arrive asynchronously, and 3) applications completely failing to achieve their individual objectives.

This work provides a conceptual structure for a rules-based deconfliction methodology as one of three possible numerical methods that can be implemented in the Deconfliction Pipeline proposed by [1]. The concepts and tools of Grid Architecture are leveraged extensively, along with a set of design principles that recognize that power systems are not simply an electric circuit. Instead, the electric grid comprises a network of structures involving control, coordination, communications, sensing, and data management. This network of structures is used to define substructure specific to the application deconfliction problem and sequential steps used to derive a locally optimal set of deconflicted device setpoints.

This is the second document in a two-part work and defines a conceptual implementation of a rules-based deconfliction methodology satisfying the requirements and architecture of the first document. Specifically, this work defines an initial set of technical, economic, and environmental criteria, as well as thirty specific qualitative rules that underpin the deconfliction methodology in order to eliminate non-viable setpoint alternatives. This approach works by converting the deconfliction optimization problem into a ranking of individual discrete setpoints, which are scored by the extent to which they satisfy specific decision criteria. The ranking is determined through the concepts of deconfliction exclusivity, priority, and preference. Several multi-criteria decision-making frameworks are examined with the simple multi-attribute rating technique exploiting ranks (SMARTER) [2] recommended as a simple implementation alternative that aligns with the steps of the rules-based deconfliction methodology.

2.0 Identification of Deconfliction Rules and Criteria

A core design principle of the rules-based deconfliction methodology is the use of a set of heuristic decision criteria and direct rules to eliminate non-viable deconfliction alternatives. The overall sequential process for applying the rules and numerical decision-making within the deconfliction methodology is illustrated in Figure 1. These rules are derived from a combination of real-time operational considerations, interviews of subject matter experts, and prior literature reviews [3], [4]. From these sources, it is possible to create four categories of rules and decision criteria:

- Technical criteria, which focus on physics-based constraints on distribution grid and physical assets
- Economic criteria, which focus on cost considerations for business processes and market mechanisms
- Environmental criteria, which focus on decarbonization and environmental impacts
- Social criteria, which incorporate energy equity and energy justice considerations

Formulations of these criteria are summarized in Figure 2, sorted by their popularity within optimization studies surveyed by [3].

The rules-based deconfliction methodology also enables the distribution system operator to select a sub-set of deconfliction criteria to create a near-optimal combination of device setpoints for their operations. The deconfliction criteria are ranked from most important to least important, with criteria weights determined by both the ranking, and values for priority and preference (introduced in Section 4.5). Depending on real-time grid conditions, the ranking of criteria importance can be adjusted based on pre-defined rules or operator preferences.

This section will provide a generic summary of key considerations and constraints that can be used for creating specific deconfliction rules and decisions criteria. However, selection of individual criteria and numeric formulations will be addressed in future work.

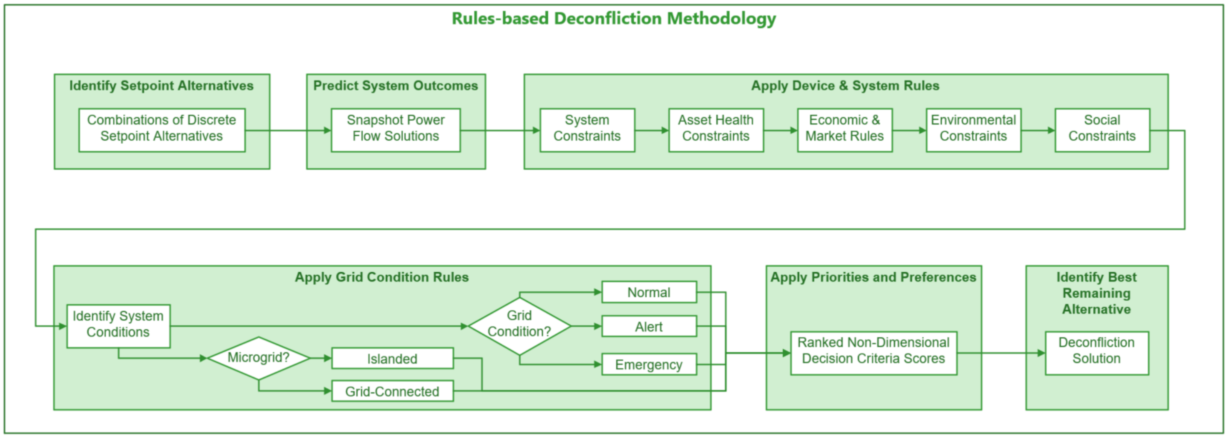
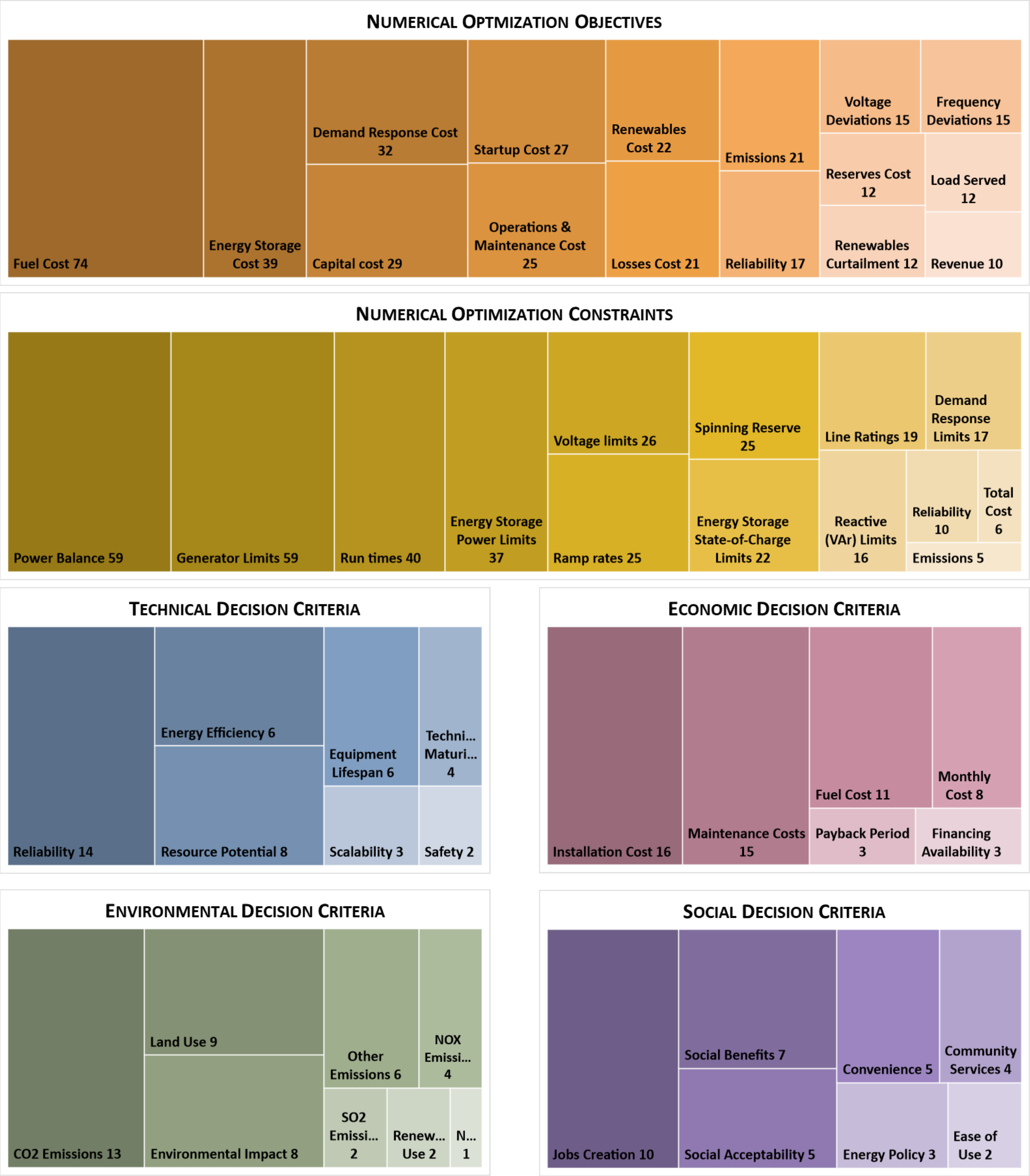


Figure 1: Structure of the rules-based deconfliction methodology and usage of specific rules to eliminate non-viable setpoint alternatives and rank decision criteria based on system conditions



Numerical Optmization Objectives

Numerical Optimization Constraints

Technical Decision Criteria

Economic Decision Criteria

Environmental Decision Criteria

Social Decision Criteria

Figure 2: Graphical summary of common criteria used for microgrid optimization and decision-making. Size of each box corresponds to popularity within the literature

2.1 Technical Criteria

Physics-based technical constraints are the first set of criteria used for eliminating non-viable combinations of discrete setpoint alternatives. These constraints can be grouped into two categories: 1) network constraints imposed by power flow dynamics and 2) asset health constraints imposed by the operational characteristics of individual devices.

2.1.1 Network Constraints

The first set of deconfliction rules used to eliminate setpoint are derived from classic power flow constraints commonly found in optimal power flow and similar optimization problems. These focus on physical constraints on the electrical network and power flow. These constraints can be expressed as qualitative rules that will be quantified at a future stage.

1) **Maximum Voltage Limits:** The voltage at all nodes in the distribution network must not exceed a chosen threshold (typically 1.10 pu) to avoid damage to utility and customer-owned equipment.

2) **Minimum Voltage Limits:** The voltage at all nodes must not fall below a chosen threshold (typically 0.90 pu) to avoid malfunctions of customer-owned equipment.

3) **Thermal Limits:** The power flow through any device must not exceed its rated thermal limit for longer than the specified time allowable for that limit.

4) **Ramp Rates:** Redispatch of inverter-based resources must not result in conventional generators, “peaker” plants, or synchronous DERs exceeding their maximum ramp rates.

5) **Run Times:** Fossil-fueled generation and DERs cannot be requested to start up or shut down sooner than the minimum required times for the unit to be online or offline.

Additionally, there exist some operational considerations specified to distribution system operations that must be respected by the deconfliction solution:

6) **Grid Congestion:** Downstream optimization cannot cause upstream network congestion.

7) **Transmission Backfeeding:** If required by the transmission system operator (TSO), reverse power flows from distribution-connected DERs into the bulk transmission system cannot exceed the specified threshold.

8) **Planned Outages:** If a set of physical assets lie within a section of grid that is scheduled for a planned outages, the associated control setpoints should be removed from the solution.

9) **Transmission Voltage Support:** If the TSO is already using substation reactive control devices for support of the transmission system, the TSO should be assigned exclusivity for the specific devices. All application setpoint alternatives for these devices are removed.

2.1.2 Asset Health & Lifespan Constraints

The second set of technical considerations focus on preservation of asset health and lifespan constraints, which stem from the fact at all devices have a total number of cycles or control changes in their overall lifespan. Increasing DER penetrations are causing significant increases in the number of daily control changes and much shorter equipment lifespans due to fluctuating and reverse power flows in the distribution grid [5]. As a result, it is critical for the deconfliction solution to consider the lifespan of the devices in terms of the total number of control changes / device cycles, as well as some rules specific to individual device types.

The rules-based deconfliction methodology adopts a concept of a controls budget, similar to the daily/weekly/monthly reservoir drainage budgets used for over fifty years in dispatch of hydroelectric power plants [6], [REF]. Hydro budgets specify the cumulative amount of water (typically measured in acre-feet) that can be discharged over a period of time, which forms a hard constraint on the amount of electric power that be generated by the plant for each unit commitment / economic dispatch iteration. The rules-based deconfliction methodology extends this concept to set a total number of cycles or control changes for each asset. This budget is specified by the distribution system operator and can consider numerous asset management parameters, including the age of the device, its current health, the total number of control cycles remaining in its life. The deconfliction solution is then required to follow this daily budget of control changes and (depending on grid conditions) deny any setpoint requests that exceed the controls budget.

These constraints can be expressed as a set of qualitative rules that will be formulated numerically at a future stage.

10) **Controls Budget:** Under normal operating conditions[1], the deconfliction solution must not exceed the total number of cycles or setpoint changes specified for each individual device.

11) **Tap Changes**: Changes to the tap position of the voltage regulators and LTC transformers must not exceed the total number of tap positions. A single setpoint change across multiple tap positions should be counted as sum of the total number of positions traversed (i.e. a setpoint request to move the tap from position #3 to position #7 deducts 4 tap changes from the regulator's control budget for that time period).

12) **Capacitor Banks**: The total amount of time that the capacitor bank is exposed to over-voltage conditions must be kept within the specified controls budget for each capacitor.

13) **Battery Storage Cycles**: The total number of ESS charge-discharge cycles cannot exceed the controls budget for each battery. The controls budget should be formulated using for the depth-of-discharge vs lifespan curve for its specific battery chemistry. Each reversal of power flow from charging to discharging and vice-versa deducts one cycle from the controls budget of that device.

14) **Battery Voltage-Temperature-Time Triangle**: Most ESS manufacturers specify very strict minimum and maximum temperature limits and an operations triangle that specifies that if any two parameters are high, the third must be brought low as quickly as possible.

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[1] This rule may be relaxed during "alert" and "emergency" conditions, as described in Section 2.6

The time aspect should be quantified as controls budget similar to that of capacitor banks. The voltage aspect is represented by a firm rule that rejects any ESS charging setpoints requested when the cell temperature is high.

15) **Transformer Winding MVA**: All setpoint combinations that would result in a transformer exceeding 80% of its emergency MVA rating should be rejected

16) **Daytime Transformer Winding Temperature**: If the real-time winding temperature exceeds a specified threshold, any setpoint combinations that further increase transformer loading should be rejected. Strong preference should be assigned to setpoints that decrease transformer loading.

17) **Nighttime Transformer Winding Temperature**: A daily controls budget should be assigned for winding temperature with a nighttime cooldown period for transformers. Setpoint requests that raise winding temperature during the night (e.g. for EV charging) deduct from the from the cooldown budget.

18) **Timeseries Trends**: In addition to the controls budget, timeseries trends in setpoint changes should be considered in eliminating setpoint alternatives that deviate significantly from prior setpoint requests and deconfliction outcomes (e.g. if last three tap setpoint requests were for positions of #5, #6, and then #7, a new setpoint request of #2 should be eliminated or given low priority).

2.2 Economic Criteria

In addition to physics-based technical constraints, it is important for the rules-based deconfliction methodology to respect key utility business processes, economic rules, and market mechanisms. The economics of distribution system operations have changed significantly within the last several years due to market deregulation and separation into separate distribution service providers, consumer-choice retailers, and community aggregators. With the introduction of Federal Energy Regulatory Commission (FERC) Rule 2222 [7], distribution-connected DERs will be able to participate into wholesale markets, energy imbalance markets, and other auctions previously restricted to entities in the bulk electric system. The impacts and implementation paths of FERC Rule 2222 are still not fully understood by the electricity industry but will likely play a significant role in operational implementations of the proposed rule-based deconfliction methodology.

A minimum set of economic rules which need to be considered by the deconfliction methodology include

19) **Exceedance of System Peak**: Most distribution utilities have power purchase agreement a maximum peak load set by the TSO, with real-time exceedance of this peak resulting in energy costs an order of magnitude (or more) higher than the base rate. Any setpoint alternatives that result in the distribution utility and/or feeder exceeding the specified peak load should be eliminated.

20) **Excessive DER Curtailment**: Most developers of large-scale distribution-connected renewables sign a power purchase agreement with the distribution utility that output of

solar farm (or other DER) can only be curtailed for a specified number of hours per year. A controls budget should be established for curtailment of such DERs, with any setpoint alternatives that exceed the controls budget eliminated. Additionally, preference should be given to curtailing DERs not restricted by such power purchase agreements.

21) **Market Participation of DER**: If a DER has a bilateral agreement or an accepted energy auction bid to supply a particular amount of power to the bulk electric market, any setpoints that would curtail, outage, or otherwise affect that DER should be eliminated.

2.3 Environmental Criteria

Although any carbon trading schemes or emissions limit have not been established nationally for utilities in the United States, it is likely such restrictions may soon be imposed at state regulatory level. Additionally, many utilities are seeking to decarbonize their operations through internal initiatives. As a result, environmental criteria form another import component of the rules-based deconfliction process.

Rules for environmental criteria are still poorly defined due to lack of standardized metrics similar to those for reliability, such as system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI). Some metrics exist for measuring environmental impact (illustrated previously in Figure 2), including CO_2 emissions, NO_X emissions, and noise. However, the initial conceptual definition of the rules-based deconfliction methodology will be limited to some simple heuristics:

22) **Renewables Curtailment**: Any setpoints that result in unnecessary curtailment of renewable resources instead of ramping down fossil-fueled generation should be eliminated (unless curtailment is necessary to avoid violating other network or health asset rule).

23) **ESS Charging**: Any setpoints that result in curtailment of renewables instead of charging of energy storage should be eliminated (unless charging the ESS would result in violation of a network or asset health rule).

2.4 Social Criteria

Likewise, energy equity and energy justice are increasingly becoming concerns among utility decision-makers, but no standardized metrics exist yet. As social metrics are formulated, they should also be included as criteria within the rules-based deconfliction methodology. Some general considerations that can be specified:

24) **Load Criticality**: Any setpoint combinations that result in outages or poor service quality to critical loads (such as those providing community services) should be eliminated.

25) **Neighborhood Income**: Any setpoint combinations that result in outages, load shedding, or curtailment of low-income customer neighborhoods prior to high-income customers should be eliminated.

26) **Fairness**: Any setpoint combinations that result in curtailment or demand response-based load reduction of a particular set of customers preferentially over others should be eliminated (unless required to avoid violation of network or asset rules).

27) **Repeated Outages / Curtailment**: A controls budget should be established for load shedding, demand response, and curtailment of customers and DERs. Setpoint combinations that result in repeated impacts to a group of customers should be eliminated. Setpoint combinations that result in exceedance of the controls budget of a group of customers should be eliminated.

2.5 Specification of Exclusivity, Priority, and Preference

The concepts of exclusivity, priority, and preference for application deconfliction were first introduced in [1]. These concepts are expanded and refined further for the rules-based deconfliction methodology and will be used to determine the swing weights of ranked decision criteria in Section 3. The values of exclusivity, priority, and preference can be tabulated in matrix form with the rows comprising the available setpoints of each device to be deconflicted and the columns corresponding to each application.

2.5.1 Exclusivity

The concept of exclusivity enables bypassing of the deconfliction decision-making process by particular setpoints by granting exclusive control to a particular user or application. The one-app-to-many-devices exclusivity of [1] is expanded with the following specific definitions:

- **Setpoint Exclusivity**: An application is granted exclusive control of a single setpoint of a particular device (e.g. real power output). Other applications may still control other setpoints of the same device (e.g. reactive power output).

- **Device Exclusivity**: An application is granted exclusive control of all control setpoints of one or more specific devices (e.g. capacitors). Other applications are still able to control other devices within the same feeder or distributed control area (e.g. smart inverters).

- **Distributed Area Exclusivity**: An application is granted exclusive control of all control setpoints of all devices within a distributed control area. This may be recommended for islanded microgrid controllers that need to perform high-speed control of devices for primary frequency response.

- **Application Exclusivity**: An application is granted exclusive control of all setpoints of all devices in a feeder. Setpoints from any other applications are rejected.

- **User Exclusivity**: The device may only be controlled by the system operator. Any application setpoint requests are rejected. This may be recommended for storm situations, abnormal grid conditions, hot-line work, or other operating conditions when application-based control is not desired.

2.5.2 Priority

The second set of deconfliction concepts are centered around priority, which is expanded beyond the definition in [1] and its use in the MESA-DER protocol [8], where it is currently used to deconflict multiple control mode specifications. As shown in Figure 3 below, it is possible to specify a priority for each control mode schedule using the MESA-ESS specification. The highest priority control mode is then used for the relevant time period.

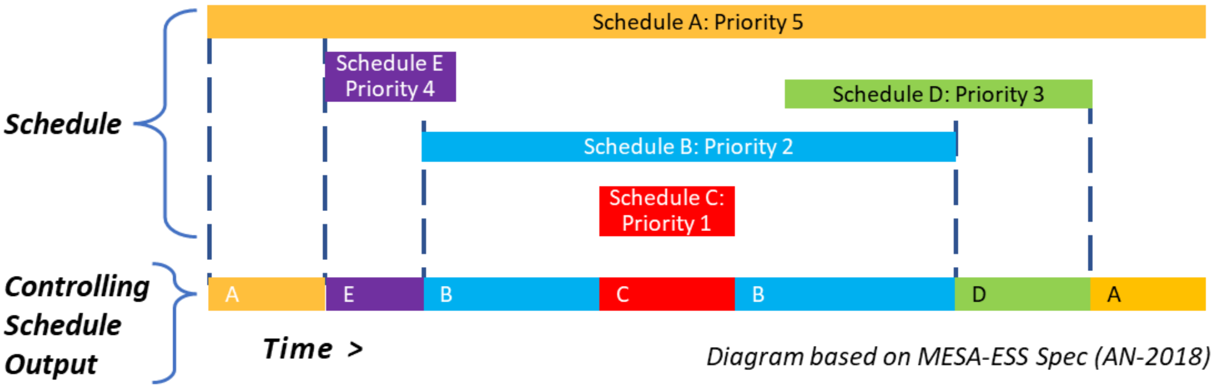

Figure 3: Use of priorities in the MESA-DER protocol for resolving multiple conflicting control modes scheduled for the same device (courtesy Bora Akyol).

This concept of priority is expanded to cover setpoints, applications, and deconfliction criteria, as defined below. The priority can be specified either qualitatively (e.g. low, medium, high, critical) or quantitatively using a numeric scale.

- **Setpoint Priority**: An application can specify the priority of a setpoint request, depending on the goal of the setpoint. For example, a CVR application could specify high priority for setpoints to bring load down below system peak and low priority for setpoints to correct local voltage issues.

- **Device Priority**: A specific device can be prioritized for control by one application over others (e.g. prioritized control of a regulator tap is granted to VVO over FLISR).

- **Application Priority**: An application be assigned priority by the system operator such that all setpoints from that application have higher or lower priority than conflicting setpoints from other applications.

- **Criterion Priority**: The final deconfliction solution is chosen by the rules-based deconfliction methodology based on non-dimensional performances scores on selected technical, economic, environmental, and social decision criteria. Applications that do not wish to share their objective function can specify a priority for each decision criterion.

2.5.3 Preference

The third core concept is that of preference, which is introduced in [1] to describe an abstract function of setpoints requested by apps and a weight assigned to each application's preference. In the context of the rules-based deconfliction methodology, it is refined to specify the *relative* importance of an entity or attribute when compared with others. The concept of preference will correspond directly with rank ordering of swing weights in Section 3.2.8. Specifically, it is possible to define

- **Setpoint Preference**: An application can specify which setpoints are relatively more important to its objective than others. For example, a VVO application can specify that it has a higher preference (more important) for being granted the requested tap position and a lower preference (less important) for control of inverter output.

- **Criterion Preference**: Selection of the final deconflicted setpoint combination is based on the system operator's preference ranking of decision criteria from most important (e.g. profit) to least important (e.g. noise). Determination of these preference can be performed using the rank ordering interview process of Section 3.2.7.

2.6 Adjustment based on Grid Conditions

2.6.1 Normal / Alert / Emergency Operations

The final set of considerations in formulating the rules-based deconfliction methodology is that changing operational conditions will change the set of rules, criteria, available devices, and priorities/preferences used. The core set of rules specified in Sections 2.1 through 2.4 are for "normal" or "blue-sky" operations. In this condition, all control resources (including devices, measurements, and communications) are available, providing the maximum ability to perform application-level optimization and find locally optimal deconfliction solutions.

However, as the distributed grid transitions into "alert" or "grey-sky" operations, additional constraints begin to emerge. Common "grey-sky" limitations include:

- Regulator taps reach their maximum/minimum limits

- Lines are overloaded or have limited availability to carry additional power

- Renewable DERs drop to zero output and cannot be dispatched

Additionally, criterion priorities and criterion preferences will likely change significantly. For example, under "normal" operations, the operator may have previously preferred "profit", but under "alert" operations, they may prefer "reliability" as the most important decision criterion. Limitations in control availability and changing priorities/preferences can be reflected numerically be removing or modifying the corresponding values in the priority and preference matrices.

With further degradation from "alert" to "emergency" or "black-sky" conditions, even fewer options are available for grid control. Large portions of the distribution feeder may be outaged, measurement data may be unavailable, and communications to devices may be impacted. This may result in failure of the rules-based deconfliction methodology due to inability to find a single setpoint alternative that do not result in violations of any previously specified technical, economic, environmental, and social rules. In “emergency” operations, some (or many) of the rules may need to be relaxed, such allowing the deconfliction solution to exceed controls budgets for the duration of the emergency.

2.6.2 Islanded Microgrids

If the distribution grid contains microgrids that can transition from grid-connected to islanded mode, additional technical rules should be applied to eliminate non-viable alternatives during islanded operations:

28) **Frequency Deviations**: During islanded operations, the bulk electric system is unavailable, and electrical frequency must be regulated by local droop controllers (and other primary frequency control schemes). Any setpoints combinations that would result in violation of island frequency limits should be eliminated.

29) **Spinning Reserve**: The microgrid may choose to maintain a percentage of generation capacity as spinning reserve to absorb changes in load and operational contingencies. Any setpoint combinations that would result in violation of the minimum spinning reserve threshold should be eliminated.

30) **Fuel Reserve**: The microgrid may choose to set a controls budget for generator fuel and battery storage state-of-charge to ensure that critical loads are served for the maximum time during severe storm situations. Any setpoint combinations that would exceed the fuel usage budget for the given time period should be eliminated.

3.0 Conceptual Implementation

Key prerequisites to implementation of the rules-based deconfliction methodology listed are a numerical framework for applying the decision criteria listed in the previous section and a computational architecture for hosting the distributed deconfliction agents. Many suitable numerical methods and computational architectures are suitable for the deconfliction methodology, but the discussion here will be limited to a single decision-making framework and implementation of distributed deconfliction agents supported by CIM-based messages buses coordinated by a Field Bus Manager and Context Manager [9], [10].

3.1 Selection of an Optimization and Decision-Making Framework

There exist two approaches to resolving conflicts between multiple optimization objectives, either within a single application or between multiple conflicting applications [11]: multi-objective optimization (MOO) and multi-criteria decision-making (MCDM).

3.1.1 Multi-Objective Optimization

MOO is based on the concept of the pareto-front, with each objective function kept intact. The solution space is examined from the concept of pareto-dominance, which states that a particular alternative (formed from a vector of decision variables) dominates another alternative solution if and only if all of the objective function values are better for the first solution and at least one objective is strictly better [12]. If a solution is not dominated by any other solution, then it is said to be pareto-optimal, such that no one objective can be improved without deterioration of the others. Pareto-front MOO is widely used in optimization of microgrids [13] – [20] and distribution systems [21] – [26]. Due to several challenges of formulating a global optimization function discussed in Section 1.3, MOO techniques are poorly suited for the rules-based deconfliction methodology introduced in this report.

3.1.2 Multi-Criteria Decision-Making

In contrast, multi-criteria decision-making techniques are a branch of operations research models designed for resolving conflicting objectives and criteria under high uncertainty [27]. Unlike MOO methods, MCDM techniques focus on combining conflicting goals into a single weighted objective that is evaluate across either discrete or alternatives forming the solution space. Multi-objective decision making (MODM) techniques search for an optimal solution within a set of continuous alternatives constrained by limits placed on decision variables and related system parameters. MODM techniques range in complexity from simple weighted sum methods (which is effective for one-dimensional optimization) to sophisticated techniques, such as the technique for order of preference by similarity of ideal solution (TOPSIS). However, all MODM methods still require well-defined numerical objective functions, which will be unknown or have high uncertainty due to the reluctance of application developers to share ADMS application "trade secrets."

Multi-attribute decision making (MADM) methods focus on choices between a small number of discrete alternatives, typically evaluated against a set of attributes that are difficult to quantify. These techniques differ significantly from MOO and MODM in that objective functions and constraints are replaced with qualitative and quantitative decision criteria. Likewise, the solutions space against which a traditional optimization solver would run is replaced with a set of discrete alternatives. Alternatives and decision criteria can be considered holistically or compared in a pairwise manner, with the analytical hierarchy process (AHP) [28] – [30] comparing pairs of criteria and the preference ranking organization method for enrichment evaluation (PROMETHEE) [31], [32] comparing pairs of individual alternatives. Selection of a particular discrete MADM technique is largely determined by the number of alternatives and criteria that need to be considered. For example, elimination et choices expressing reality (ELECTRE) is designed to compare a large number of alternatives using a few criteria, whereas PROMETHEE is best suited for comparing a small number of alternatives against many criteria.

MADM are better suited for the rules-based deconfliction methodology due to elimination of the need for a specific objective function and numerical optimization solver. There exist many numerical methods and decision-making frameworks that can be applied. However, this section will focus on the simple multi-attribute rating technique exploiting ranks (SMARTER), which is selected for several reasons, including novelty within the power system domain, simplicity of formulation, ability to consider both qualitative and quantitative criteria, and support for optimal rules-based decision-making without the formulation of a multi-objective optimization problem or numerical objective functions.

Implementation of SMARTER (or other suitable MCDM framework) conceptually resides one layer below the rules-based deconfliction methodology, as shown in Figure 4 below. The choice MCDM framework does not affect the overall steps within the methodology. Rather, SMARTER merely provides a set of sequential sub-steps to formulate each deconfliction step numerically.

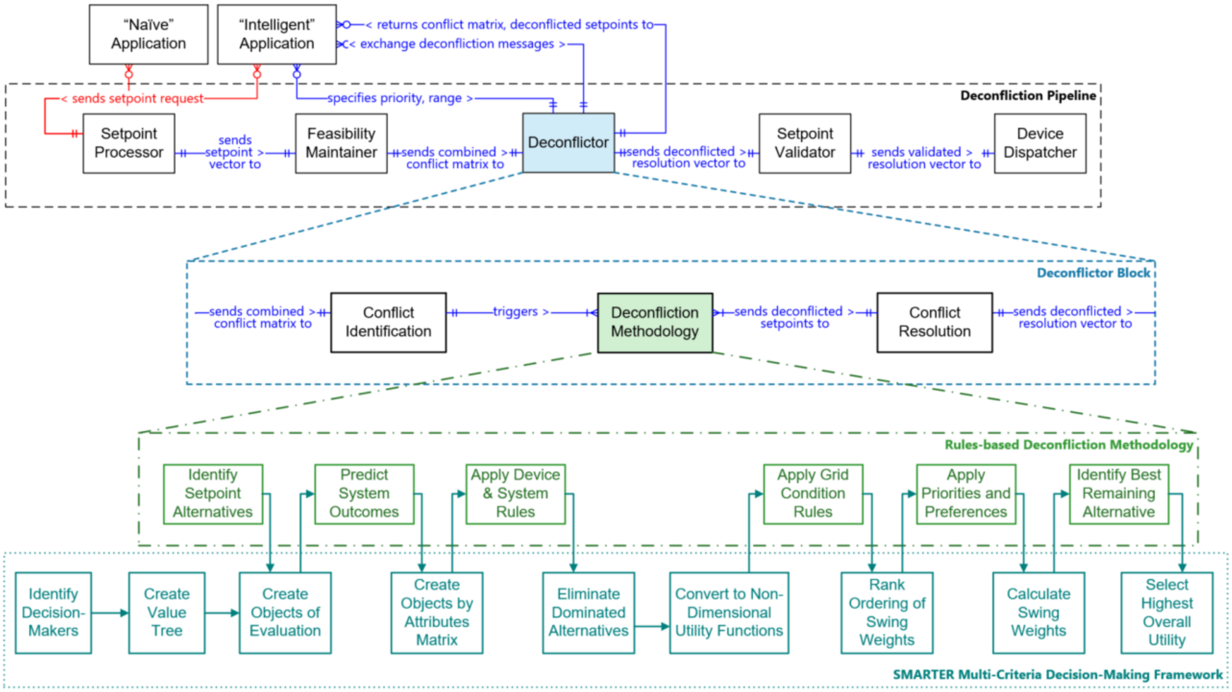

Figure 4: Implementation of the SMARTER MCDM framework as one of the numerical methods that can be used for the rules-based deconfliction methodology.

3.2 SMARTER MCDM Framework

SMARTER is one of several MCDM techniques based on utility theory, which describes the set of relationships between the costs and the “utility” of a particular decision, as judged by a human decision-maker(s). Multi-attribute utility theory (MAUT) considers multiple utility functions, which are used to perform a preference-based ranking of alternatives, with the optimal decision corresponding to the alternative with the highest overall combined utility. MAUT methods are able to consider uncertain factors in the decision analysis in a consistent manner [33]. Uncertainties can be classified as external (which can affect the decision outcome) and internal (relating to the decision-maker’s preferences). Common uncertainties in the power systems domain include physical conditions (such as technology assets and consumer demand), economic variables (fuel prices and installation costs), and regulatory policy.

Utility functions are non-dimensional expressions with values ranging from either zero to one or zero to 100, reflecting the extent to which the alternative satisfies the decision-maker’s preference for the corresponding decision criterion [34]. The utility function is also able to indicate the decision-maker’s tolerance of risk. Concave functions indicate an aversion to risk; linear utility functions indicate neutral risk; convex functions indicate a preference for risk. However, MAUT is rarely used as originally formulated due to the complexity of formulating utility functions and computing scaling constants. Instead, most formulations use simplified versions of utility theory methods, such as SMARTER and the, which can easily handle as many as twenty conflicting qualitative and quantitative power system objectives simultaneously [35].

The original simple multi-attribute rating technique (SMART) was developed in the 1970s to address the formulation difficulties of MAUT and uses linear approximations of utility functions and an additive aggregation model to calculate the overall utility of each alternative as the weighted sum of utility values [36], [37]. Shortly afterwards, the concept of swing weights was introduced to correct a conceptual error in the original SMART framework, which failed to recognize the impact of the range of values on the meaningfulness of the utility function [2]. Subsequently, justifiable rank weights were developed to yield the SMARTER process, which removed the burden of determining weighting factors from the decision maker. Despite its ease of use, SMARTER has only been applied to a handful of microgrid planning cases [4], [38] – [41], demand response studies [42], [43], and an electric utility wildfire risk assessment [44].

SMARTER uses a nine-step process for rules-based decision-making including two planning level steps to identify the set of decision criteria (discussed in the previous section) followed by a sequential process to identify an optimal alternative based on predictive estimates of discrete outcomes. The nine steps are illustrated graphically in Figure 4 above.

3.2.1 Identification Decision-Makers and Goals

The first step is identification of the purpose of the decision-making process (*value elicitation*) and key stakeholders (*elicitees*) involved in the decision process. An explicit and exhaustive list of elicitees is essential for generating a satisfactory list of decision criteria. Key stakeholders within the deconfliction process include the system operator, system dispatcher, field crew, power marketer, community aggregator, retail provider, asset owner, and utility customer.

3.2.2 Creation of a Value Tree

The second step is to ask the elicitees to create a list of attributes (criteria) that are relevant to them in the decision-making process. A common structure and set of labels must be agreed upon by all elicitees participating in the value elicitation process. The technical, economic, environmental, and social consideration described in Section 4 are a first approximation at the full list of criteria considered in the rules-based deconfliction methodology. The criteria submitted by all the elicitees must then be combined into a single list with all duplicates eliminated and overlapping labels merged. It is recommended by [2] that the total number of decision criteria used in a SMARTER framework be limited to 12 by combining related attributes, redefining attributes that are too specific, and omitting unimportant attributes. After all attributes are categorized, they are combined into a value tree that depicts all the elicited attributes in a simple graphical format.

3.2.3 Identification of Objects of Evaluation

The third step of the process is identification of the "objects of evaluation," which comprise the set of discrete alternatives for device setpoints and control modes. For devices with discrete setpoints (such as regulator taps), the alternatives comprise the highest and lowest conflicting setpoints, as well as all intermediate setpoint values bounded therein. For controllable devices with continuously variable setpoints (such as kW output of an ESS), the solution space is defined as range of values between the highest and lowest conflicting setpoints. The solution space is then discretized into equal increments, with the resolution selected by the user of the deconfliction methodology based on a tradeoff between computational speed and solution optimality. For controllable devices with control mode setpoints (such as those specified by the MESA DER protocol), the alternatives are simply the set of control modes requested. If applications specify a range of acceptable setpoints, then the minimum and maximum values of the ranges are used as the upper and lower bound for selecting the set of discrete setpoint alternatives.

Within the Deconfliction Pipeline introduced in [1], this is the first step of the Deconflictor Block that is triggered when the Setpoint Processor and Feasibility Maintainer detect a direct setpoint collision or physics-based collision. The objects of evaluation are then formed as the set of all combinations[1] of individual discrete alternatives for each controllable device. The total number of objects of evaluation grows multiplicatively with the number of controllable devices in a quasi-static grid segment, and so it is important to perform a tradeoff analysis of the number of problem decompositions, as described in Section 3.4.

3.2.4 Creates of Objects-by-Attributes Matrix

The fourth step in SMARTER tabulates the individual setpoints alternatives as the rows and decision criteria values as columns of the objects-by-attributes matrix. The value of each decision criterion is obtained by running a snapshot power flow solution for each individual combination of discrete setpoint alternatives and then calculating values of each decision criterion. The use of discrete power flow snapshots enables inclusion of abstract control mode settings commonly used for DER (such as "active power smoothing") that would be extremely difficult to formulate as part of a numerical objective function.

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[1] Ordering of alternatives does not matter, so the objects of evaluation are formed from a combination of alternatives rather than a permutation.

3.2.5 Elimination of Dominated Alternatives

Dominated alternatives can often be eliminated by visual inspection. This step is optional since dominated options will be eliminated in course of the subsequent analysis. However, this step is useful if elimination of dominated alternatives reduces the range of one or more evaluation criteria. If the difference between the maximum and minimum values of a single criterion is reduced to a small range, then that attribute should be eliminated as well.

Within this step, the rules-based deconfliction methodology extends the original SMARTER formulation by applying the first comprehensive set of “rules” within the rules-based deconfliction methodology, as shown in Figure 5. Any setpoint combinations that violate any of the technical, economic, environment, and social rules identified in Section 4 are directly eliminated as non-viable solution alternatives. The particular set of rules implemented can be adjusted based on current system conditions and the preferences of the decision-maker. Through the rules-based elimination process, all remaining setpoint combinations are guaranteed to satisfy the core requirements for safe, secure, economic, and equitable operation of the distribution system.

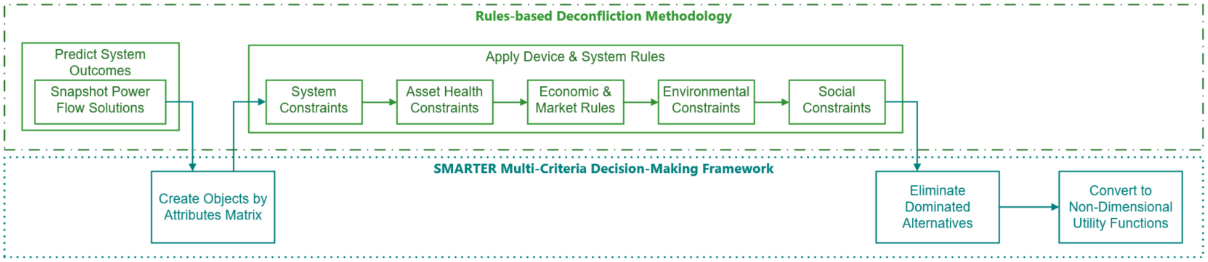

Figure 5: Application of technical, economic, environmental, and social rules to eliminate setpoint combinations that violate operational constraints based on snapshot power flow solutions

3.2.6 Conversion to Non-Dimensional Utilities

The sixth step within the SMARTER MCDM framework is conversion of the values in the objects-by-attributes matrix to non-dimensional utilities in a manner not unlike conversion of power systems parameters to a per-unit basis. The use of non-dimensional utilities allows the formulation of a weighted sum of qualitative and quantitative decision metrics incorporating technical, economic, environmental, and social considerations. In other words, the values in the objects-by-attributes table may have units of kWh, amperes, dollars, and tons of CO_2. It is impossible to add these parameters, but conversion of each criterion to a non-dimensional utility function enables the deconfliction methodology to sum them directly.

The conversion process is performed by (for each criterion independently) identifying the single worst value (e.g. highest kW losses) and single best value (e.g. lowest kW losses), which are assigned utility function values of zero and one. One of the core simplifications offered by SMARTER compared to general MAUT methods is introduction of the assumption that utility functions are linearly increasing or decreasing, such that a change in a particular metric corresponds to a change in perceived benefit in a linear manner.

3.2.7 Rank Ordering of Swing Weights

The next key concept within SMARTER is the ranking of decision criteria from most important to least important using the concept of swing weights. The ranking is performed by asking the decision-maker to consider a worst-case scenario where they are forced to choose the worst alternative that has utility scores of zero for all decision criteria. Subsequently, the decision-maker is asked to pick a single criterion that will be allowed to "swing" from the worst possible value to the best possible value. The decision maker is then asked for their second choice, third choice, etc. until all the decision criteria have been ranked.

The rules-based deconfliction methodology expands this logic by recognizing that the ranking of criteria is likely to change based on real-time operating conditions of the distribution grid. For example, profit and decarbonization may be the two most important criteria in normal operations, but load-served and outage times could be the first and second choice during emergency operations. Thus, an additional set of rules are applied to specify the set of rankings that should be used for a given iteration of the deconfliction pipeline. The most basic set of rules are illustrated in Figure 6 and categorize the system state as islanded, grid-connected, normal, alert, or emergency. Each state will specify a different set of importance rankings that will be applied to calculate the swing weights in the next step.

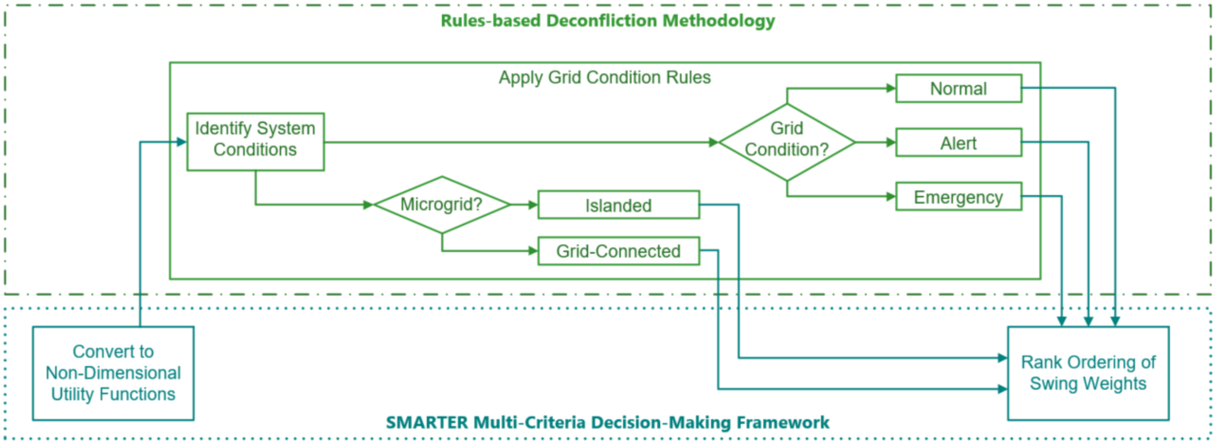

Figure 6: Application of grid condition rules to change the rank ordering of swing weights

3.2.8 Rank Order Centroid Weighting

If neither the distribution system operator nor any of the applications have specified their priority or preference for setpoints and/or decision criteria, SMARTER offers a method for calculating swing weights using the concept of the rank order centroid. Within all MCDM frameworks, there exists a general convention that the sum all of weights (as applied in any weighted sum formulation) must equal one. The simplest possible method is to assign all the decision criteria equal weights. Consequently, the point representing equal weighting is the centroid of the hyperspace simplex of all weighting variables possible.

The SMARTER framework modifies this concept by adding a ranking of importance among the decision criteria. When the geometric coordinate points of the simplex are specified with knowledge of ranking, it is possible to determine the resulting centroid. The resulting weights have a rather convenient computational form. For the series of weights where w_1 corresponds to the highest priority criterion and w_n to the lowest priority criterion as determined in the previous step, the weighting values are

$$w_1 = \left(1 + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{n}\right)\left(\frac{1}{n}\right)$$

$$w_2 = \left(\frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{n}\right)\left(\frac{1}{n}\right)$$

$$w_3 = \left(\frac{1}{3} + \cdots + \frac{1}{n}\right)\left(\frac{1}{n}\right)$$

$$w_n = \frac{1}{n^2}$$

The rules-based deconfliction methodology will expand on the concept of the rank order centroid to include the priority and preference factors specified by users and applications. However, development of specific numerical formulation will be examined as part of future work.

3.2.9 Selection of Highest Multi-Attribute Utility

The final step in the decision-making process is performing a matrix multiplication of the objects-by-attributes matrix with the vector of swing weights. The resulting vector represents the total multi-attribute utility score for all remaining alternatives of device setpoint combinations. A direct search of the vector is performed for the highest score, which corresponds to the final deconfliction solution.

3.3 Standards-based Platform Implementation

The term “platform” is commonly used by many stakeholders with slightly different meanings. In the context of constructing the rule-based deconfliction methodology, the term will be used in the sense of software platform. The platform provides 1) an environment within which applications can be developed, tested, and executed and 2) well-defined application programming interfaces (API) that enable key functionalities, interoperability, testing, and user interaction.

The discussion will focus on a CIM-based data integration platform introduced in [45], [46] that is structured around an Enterprise Service Bus (ESB) defined by IEC standard 61968-1:2020 [47] and messaging paradigms of IEC standard 61968-100:2022 [48]. A conceptual representation of such a CIM-based platform is depicted in Figure 7. Data from multiple disparate sources (such as SCADA measurements, weather info, and smart meter data) are to be aggregated and published to a CIM-based message bus. These data streams are mapped to the terminals of associated power system equipment through a set of unique measurement mRIDs defined for each measurement ingested by the platform. The ingested measurements, power system network model, and associations are contained in a set of databases structured around the unique mRIDs and directional relationships between the set of CIM classes and attributes used.

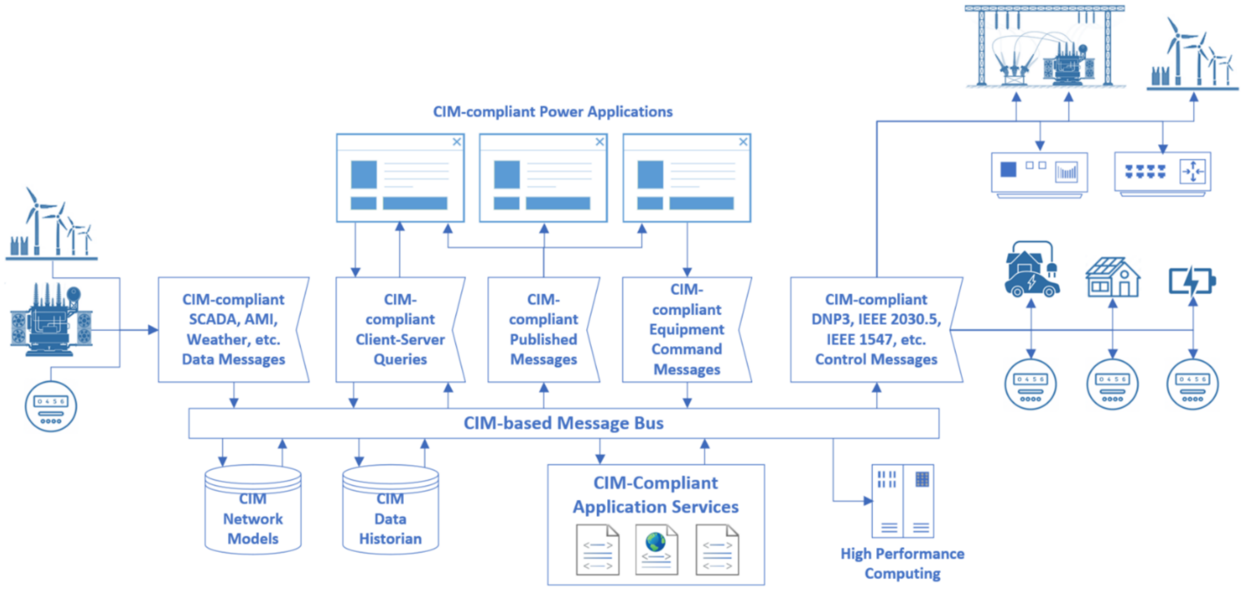

Figure 7: Conceptual representation of a CIM-based platform for data and application integration [45]

All applications communicate across a shared enterprise message bus to query for power system model data, receive real time measurements, and publish equipment commands. All device setpoint requests and control mode commands are formatted as CIM difference messages, which are then converted to the correct device protocol format. Within this conceptual platform, the deconfliction pipeline is implemented as another shared service that intercepts the publishes setpoints, solves the deconfliction problem, and then issues deconflicted control settings to the correct device protocol translation service.

3.4 Distributed Architecture Implementation

The concepts of separating the IT Data Bus from OT Control Bus in a distributed manner are applied to the distributed architecture implementation of the deconfliction process. Communications and control of the distribution grid are separated into two sets of interfaces for centralized and distributed applications, as shown in Figure 8. Centralized applications still communicate across the centralized enterprise message bus to pass database queries and publish device setpoints. However, distributed applications are a configured to run on a set of distributed field message OT Control Buses, which provide communications only to the devices within that application's area of responsibility.

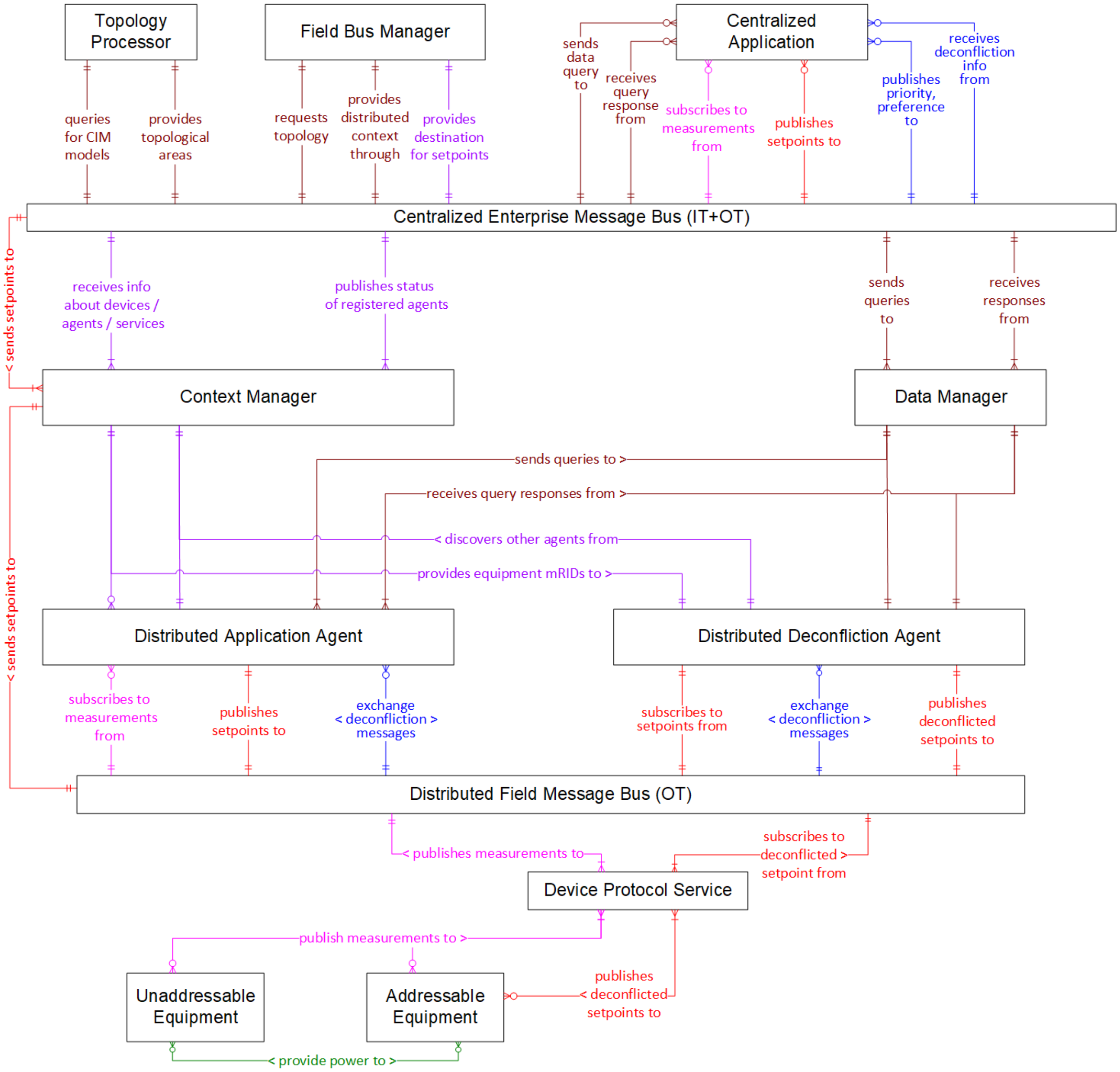

Figure 8: Structure for hosting distributed applications and deconfliction agents with separation of IT and OT functionalities between the centralized and distributed message buses

4.0 Conclusions and Future Work

This work introduced a rules-based deconfliction methodology in terms of a specific requirements, context, and methods for decomposing the deconfliction problem created by competing setpoint requests issued by different advanced power applications. The deconfliction problem was decomposed into a distributed optimization problem based on the concept of quasi-static grid segments, which form independent distributed areas for control and coordination. It was recommended that selection of the optimal number of decompositions of the deconfliction problem be made based on a tradeoff analysis between computational speed and global optimality.

The methodology itself uses a six-step process of discretizing the solution domain, creating predictive estimates of system outcomes, and applying technical, economic, and environmental criteria to determine a locally optimal deconflicted setpoint. To help contextualize the rules of the methodology, thirty specific qualitative rules were defined to eliminate non-viable setpoint alternatives. Multiple MCDM techniques were examined, with SMARTER recommended as an intuitive numerical method that can be adapted to include the concepts of deconfliction exclusivity, priority, and preference. Key features of the rules-based deconfliction methodology included

- Decomposition of the global deconfliction problem into distributed subproblems
- Discretization of solution space of conflicting setpoints into individual alternatives
- Ability to create alternatives formed of control mode settings and numerical setpoints
- Predictive estimation of system outcomes for each discrete alternative setpoint combination
- Direct elimination of setpoint alternatives that violate technical, economic, environmental, and social rules
- Ability for users and applications to specify objectives, priority, and preference for setpoints and control modes
- Ability to adjust ranking of deconfliction priorities and rules in response to grid conditions
- Support for both qualitative and quantitative criteria in selection of deconfliction result
- Selection of a deconfliction solution without solving a formal optimization problem
- Support for both centralized and distributed applications
- Support for both centralized, distributed, and decentralized computational architectures

The rules-based deconfliction methodology introduced in this work is limited to deconfliction of real-time applications operating within a single utility and communicating across a well-defined set of IT / OT message buses. It can handle both centralized and distributed applications using the layered decomposition method described.

However, it cannot deconflict interaction between centralized/distributed applications and fully decentralized / local device controllers using direct feedback loop control with no external communications. Existing local device controllers, often contained within a control box on the same pole as the voltage regulator or capacitor bank, would need to be disabled or reconfigured to pass their control setpoint as a message onto the local field OT bus to which the appropriate deconfliction agent is subscribed.

It is conceptually possible to extend the rules-based methodology to deconfliction of operations planning and market applications in the hour-ahead or day-ahead timeframe. It may also be possible to deconflict transactive applications and incentive signals using discrete predictive estimates of system outcomes in a similar manner that the rules-based framework estimates outcomes from alternative device setpoints.

Future work will focus on 1) definition of a numerical framework to calculate swing weights based on the multiple levels of exclusivity, priority, and preference introduced, 2) examination of the independence of switch-delimited topological areas and definition of sensitivity metrics (similar to power transfer distribution factors (PTDF) used in transmission grid analysis) to simplify coordination of distributed deconfliction agents, and 3) demonstration of the rules-based deconfliction methodology with a set of simple ADMS applications.

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**Pacific Northwest
National Laboratory**

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

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