Real-time System of Operative Management of Demand for Electricity on the Consumer's Side

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Relevance of the Research

Physical Properties of Electricity

The unique characteristics of electricity as a commodity necessitate continuous balance between production and consumption. Electricity markets are designed to incentivise participants to maintain this delicate balance.

Demand Response Definition

Demand Response refers to changes in electricity consumption by end consumers relative to their normal load profile in response to changes in electricity prices over time or in response to incentive payments designed to reduce consumption during periods of grid overload threat.

Primary Goal

The main objective of demand management is to reduce peak loads in the power system, which can lower wholesale electricity prices and subsequently retail prices.

Demand management has gained widespread recognition as a means of ensuring reliability of energy supply, integrating renewable energy sources, increasing competition in the electricity market, and expanding consumer capabilities.

The development of automatic high-dynamic real-time electricity demand management systems will significantly increase the reliability of the energy supply system.

Current Contradictions in Demand Management

In practice, most energy markets across different countries face various administrative, regulatory, technical, and technological barriers to consumer participation in demand management.

However, there are markets with widespread consumer resource participation.

Examples of Advanced Markets

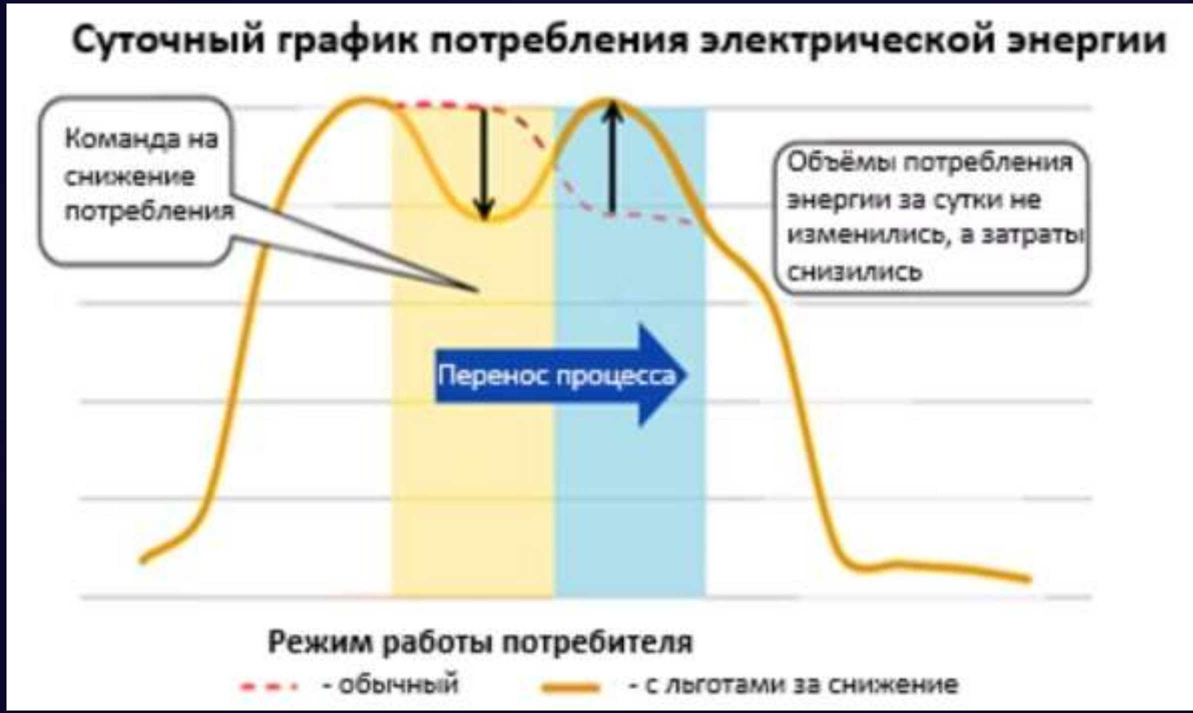
- In the USA (PJM, MISO, and CAISO markets), consumers participate in electricity, capacity, and system service markets
- In the UK, within National Grid's operational zone, consumers can participate in the system services market and the recently launched capacity market

The Achilles' Heel

The primary weakness of current systems is their **response speed**. This limitation prevents the full utilisation of Demand Response as a tool for preventing emergency modes. In most cases, this technology is used only

Proposed Solution

Development and improvement of tools and methods for operational management of electricity demand on the consumer side in real-time through the development of a hardware and software complex using a multi-agent approach to the organisation of hardware and software architecture for monitoring and control in energy systems.



The multi-agent approach enables rapid request-result cycles, dramatically improving system responsiveness.

Project Objectives

Global Analysis

Analyse global experience in developing and implementing electricity demand management systems on the consumer side, research the advantages and disadvantages of existing systems, and formulate requirements for developing improved solutions.

Architecture Development

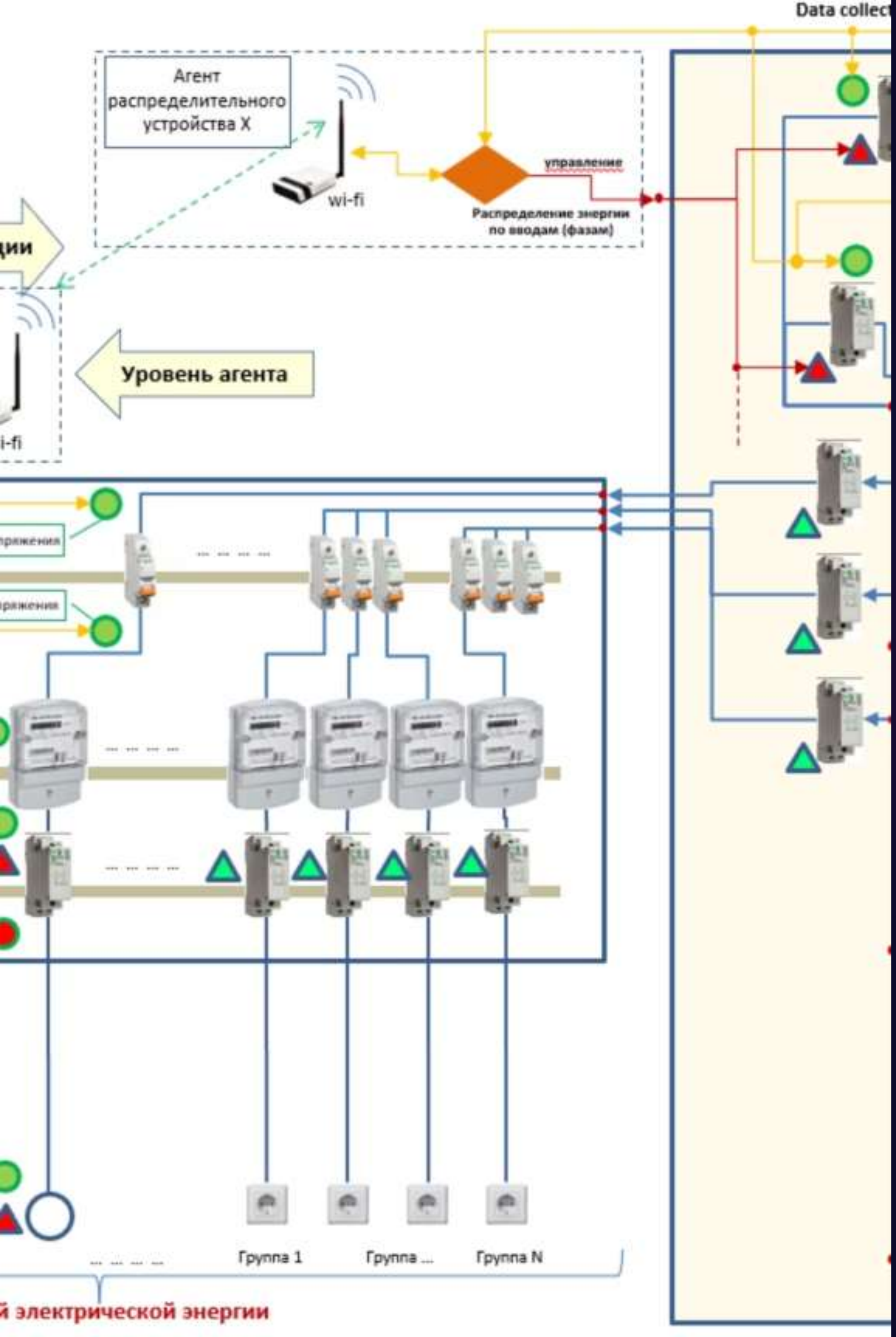
Develop hardware and software architecture using a multi-agent approach that will address the shortcomings of existing analogues.

Algorithm Creation

Develop inter-agent interaction algorithms that ensure the implementation of the process of managing electricity demand on the consumer side in real-time.

Emergency Response

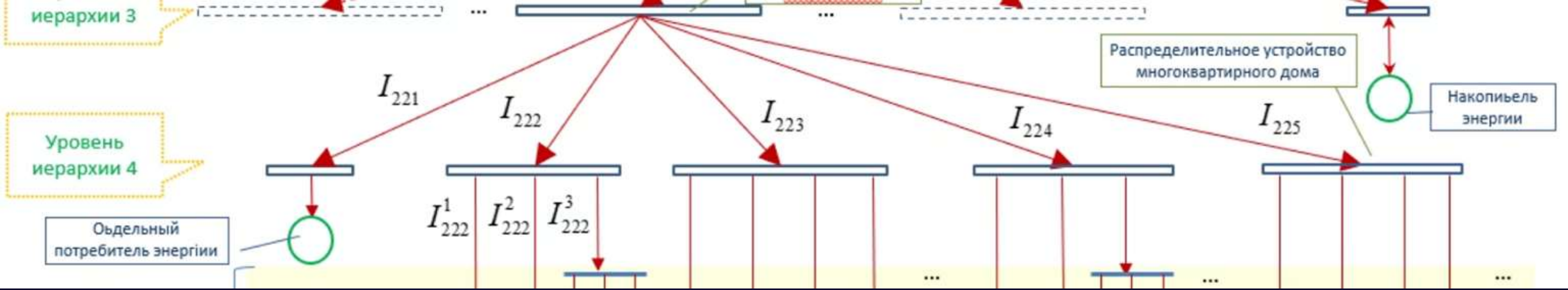
Develop inter-agent interaction algorithms that will ensure the reaction of the monitoring and control system in real-time to emergency situations to localise the accident, minimise financial damage, and reduce post-accident recovery time.



Multi-agent Architecture

The multi-agent architecture provides a distributed approach to managing electricity demand. Each agent operates autonomously but coordinates with others to achieve system-wide objectives. This architecture allows for rapid response to changing conditions and emergencies through decentralised decision-making processes.

Agents at different levels of the system hierarchy can communicate directly, eliminating bottlenecks in traditional centralised systems and reducing response times from minutes to seconds.



Hierarchy Levels of the Interaction Field

Top Level

System operators and market participants that oversee the entire power grid operation and set broad parameters for demand response.

Middle Level

Distribution points and regional controllers that manage local areas of the power grid and coordinate responses across multiple consumers.

Consumer Level

Individual end-users and their smart devices that can adjust electricity consumption based on signals from higher levels or local conditions.

This hierarchical structure enables both top-down control when needed and bottom-up autonomous responses for fastest reaction to local conditions.

Computational Model of Energy Flow Distribution

The computational model determines optimal energy distribution across the network by considering multiple factors including:

Network Topology

Physical connections and capacities between different nodes in the electricity distribution system

Consumer Characteristics

Demand profiles, flexibility potential, response time, and contractual agreements

System Constraints

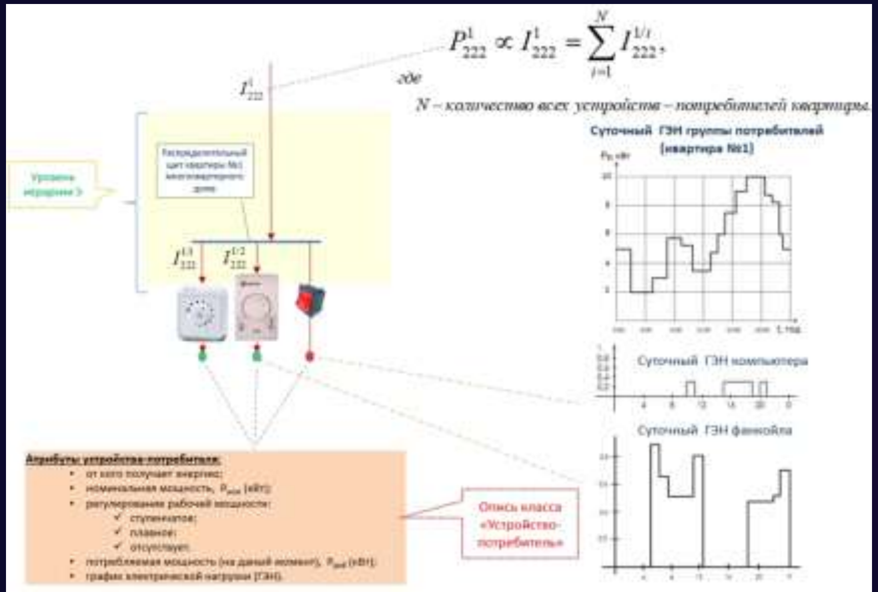
Voltage limits, thermal constraints, stability requirements, and operational security margins

Economic Factors

Electricity prices, incentive payments, and opportunity costs for different stakeholders

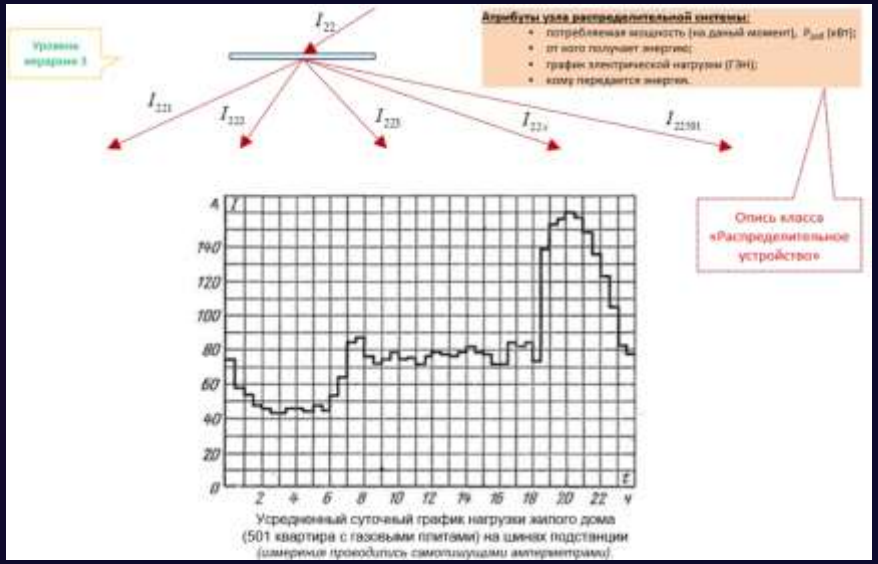
Consumer and Distribution Node Models

End Consumer Model Characteristics



- Consumption profile and patterns
- Load flexibility parameters
- Response capabilities and constraints
- Preference settings and priority loads

Distribution Node Model Characteristics



- Connected consumers and their aggregated capacity
- Current load and capacity constraints
- Distribution efficiency parameters
- Communication capabilities with adjacent nodes

Both models incorporate dynamic parameters that can be updated in real-time to reflect changing conditions in the power system. This enables accurate prediction of responses to control signals and optimisation of demand management strategies.

Main Entities (Actors) in the Interaction Field

System Operator

Responsible for overall grid stability and issuing high-level commands during critical situations. Provides system-wide coordination and emergency management.

Distribution Node

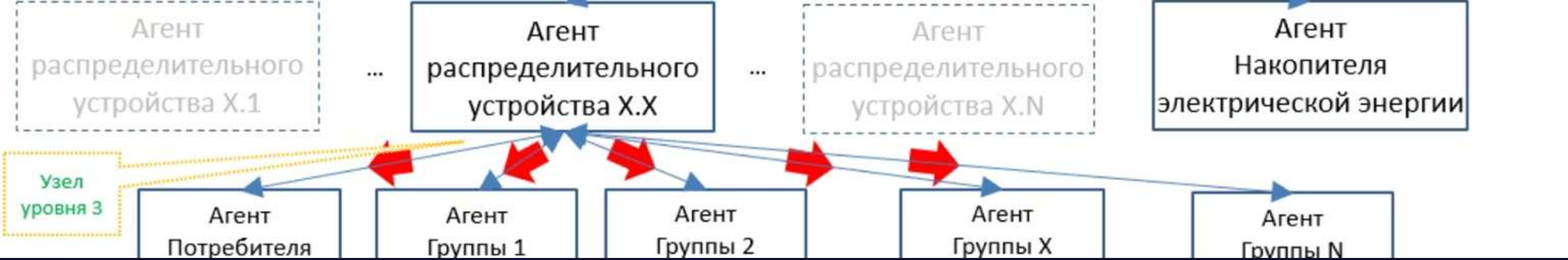
Manages local distribution networks, coordinates responses from connected consumers, and implements control strategies to maintain local stability.

Consumer

End-users with flexible loads that can respond to demand management signals. Includes residential, commercial, and industrial consumers with varying response capabilities.

Energy Storage

Systems that can store and release energy to help balance supply and demand. Includes batteries, thermal storage, and other technologies that provide flexibility.



Additional Entities in the Interaction Field

Market Operator

Facilitates electricity market operations, settlement processes, and pricing mechanisms that drive demand response actions. Provides economic signals that influence system behaviour.

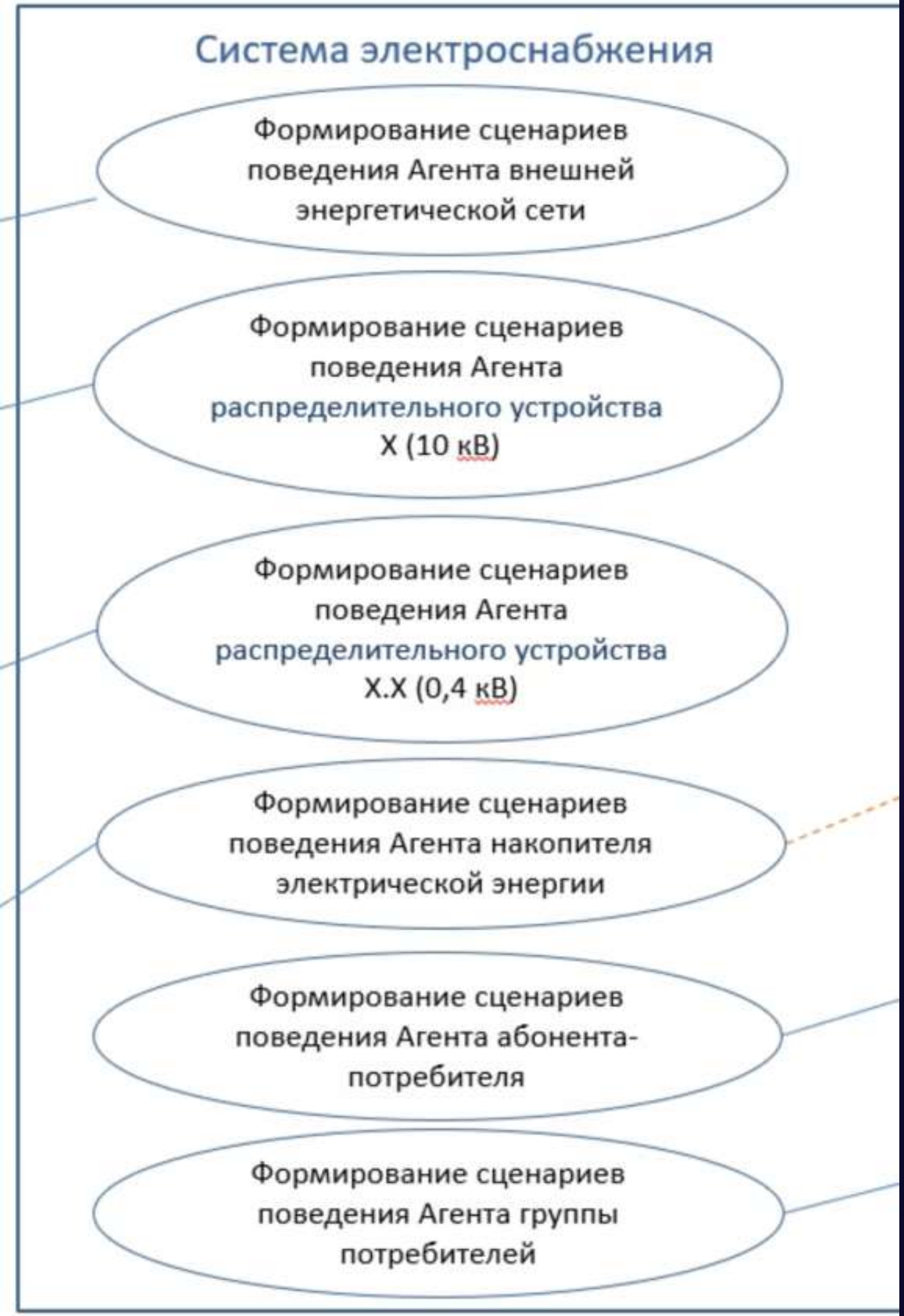
Aggregator

Combines multiple smaller consumer loads into a single virtual entity that can participate effectively in demand response programmes. Manages portfolios of flexible resources to maximise value.

Distributed Generator

Small-scale power generation facilities connected to the distribution network that can respond to local conditions. Includes renewable sources like solar and wind that add variability to the system.

These entities interact within a complex ecosystem where technical, economic, and regulatory factors influence their behaviour and decision-making processes. The multi-agent system coordinates these diverse actors to achieve optimal system-wide outcomes.



System Use Case Diagram

The use case diagram illustrates the main system functionalities and how different actors interact with them. Key use cases include:

Real-time Monitoring

Continuous observation of system parameters, load levels, and network conditions to detect anomalies or opportunities for demand management.

Demand Response Execution

Implementation of load reduction or shifting based on market signals or system needs during peak periods or emergencies.

Emergency Handling

Coordinated response to system disturbances or equipment failures to maintain stability and minimise service interruptions.

Load Forecasting

Prediction of future electricity demand patterns to prepare appropriate demand management strategies proactively.

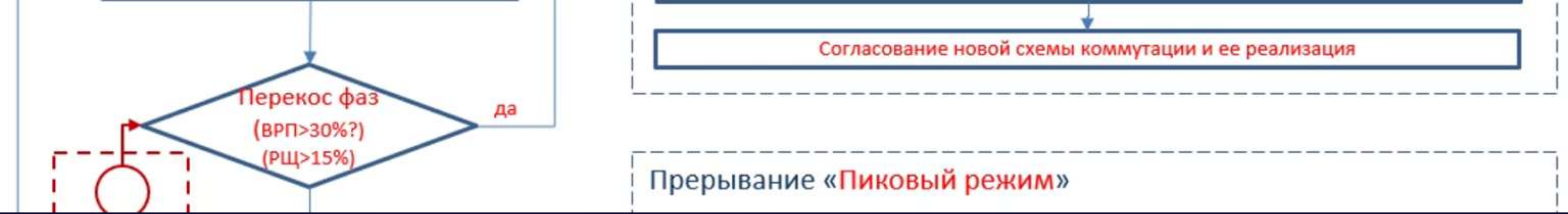
Practical Implementation: Inter-agent Interaction Algorithms

Agent communication flow diagram showing message exchange sequences during normal operation and event handling.

Decision-making process within individual agents showing internal logic flow from sensing to action.

The inter-agent interaction algorithms define how different entities in the system communicate and coordinate their actions. These algorithms are designed to:

- Minimise communication overhead while ensuring all necessary information is shared
- Prioritise critical messages during emergency situations
- Implement fallback mechanisms when communication channels are compromised
- Balance autonomy of individual agents with system-wide coordination needs
- Adapt to changing network conditions and communication constraints



General Algorithm for Intelligent Energy Flow Management Module

(Distribution Point Example)

Data Collection & Analysis

Continuous monitoring of power flows, voltage levels, and connected consumer states to establish situational awareness.

State Classification

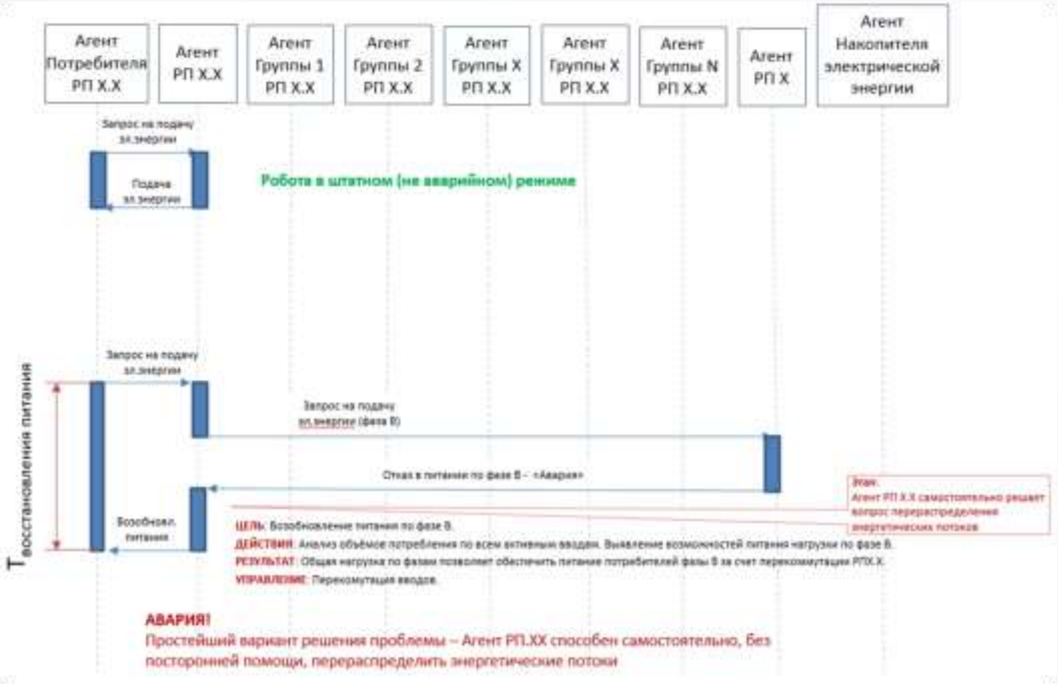
Determination of current operational mode (normal, minor emergency, medium emergency, severe emergency, or peak load) based on collected data.

Strategy Selection

Choosing appropriate response strategies based on the identified state, historical performance, and system constraints.

Command Execution

Implementation of selected strategies through coordination with connected agents and adjustment of controllable parameters.



Interaction Diagrams: Normal Operation and Minor Emergency

Normal Operation Mode

During normal operation, the system focuses on:

- Regular status reporting and health checks
- Continuous data collection and analysis
- Predictive maintenance scheduling
- Optimisation for economic efficiency
- Fine-tuning of response parameters

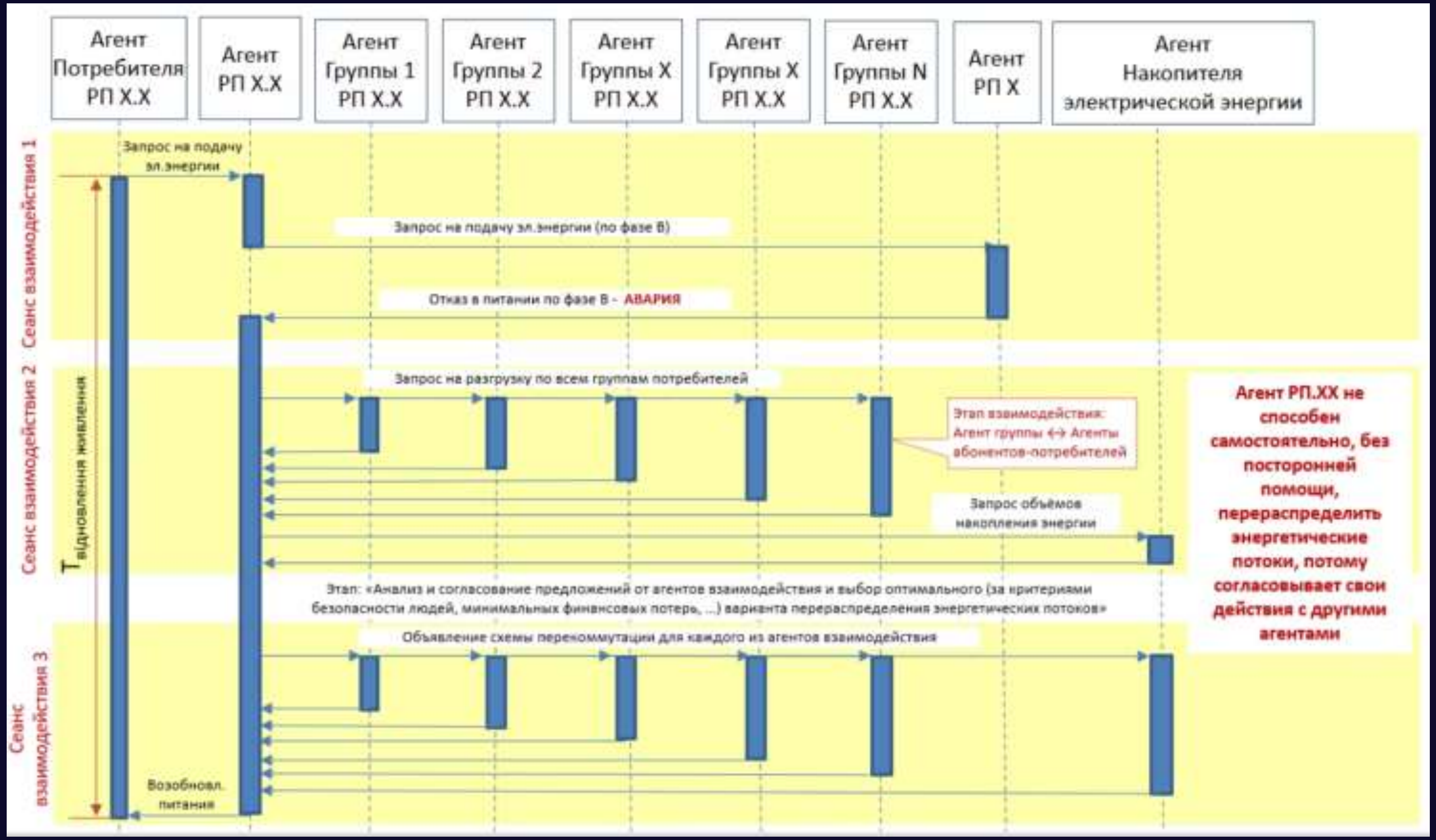
Minor Emergency Mode

When minor disturbances occur, the system:

- Increases monitoring frequency
- Activates local corrective measures
- Prepares contingency plans
- Issues early warnings to connected nodes
- Performs detailed diagnostics

In both modes, communication remains largely hierarchical with regular updates flowing between adjacent levels in the system hierarchy. Decision-making authority is primarily local with minimal intervention from higher levels.

Interaction Diagram: Medium-Level Emergency



01

Emergency Detection

System identifies abnormal conditions exceeding thresholds for minor emergencies but below critical failure levels.

02

Alert Propagation

Notifications sent to adjacent nodes and higher-level controllers with emergency classification and preliminary assessment.

03

Resource Coordination

Group agent aggregates available flexible resources and develops coordinated response strategy.

04

Load Management

Direct communication with consumer agents to implement required load reductions or redistributions.

05

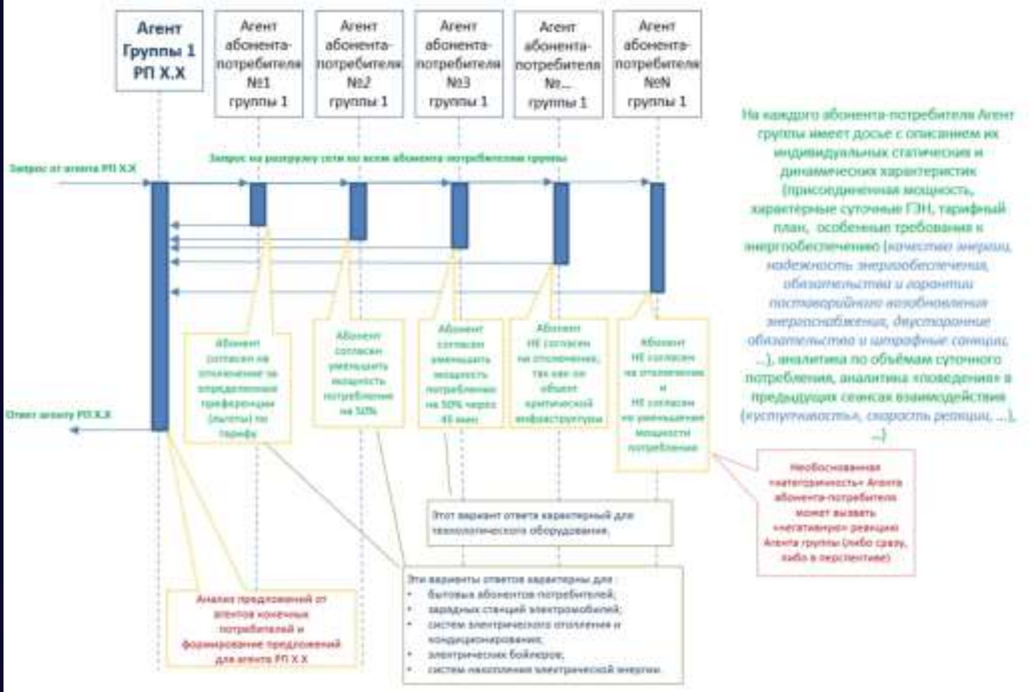
Stabilisation & Recovery

Continuous monitoring of system response and adjustment of control actions until normal operation is restored.

During medium-level emergencies, the communication patterns become more complex with direct interactions between non-adjacent levels to expedite response time.

Interaction Diagram: Medium-Level Emergency

Session 2 - Group Agent ↔ Consumer Agents



This diagram details the specific interactions between a group agent and multiple consumer agents during the response to a medium-level emergency:

1. **Request for Flexibility**

   Group agent broadcasts emergency notification and requests available flexibility from all connected consumer agents.

2. **Capacity Reporting**

   Consumer agents evaluate their current state and report available load reduction capacity, response time, and duration limitations.

3. **Optimisation**

   Group agent performs rapid optimisation to determine the most efficient distribution of load reduction requirements.

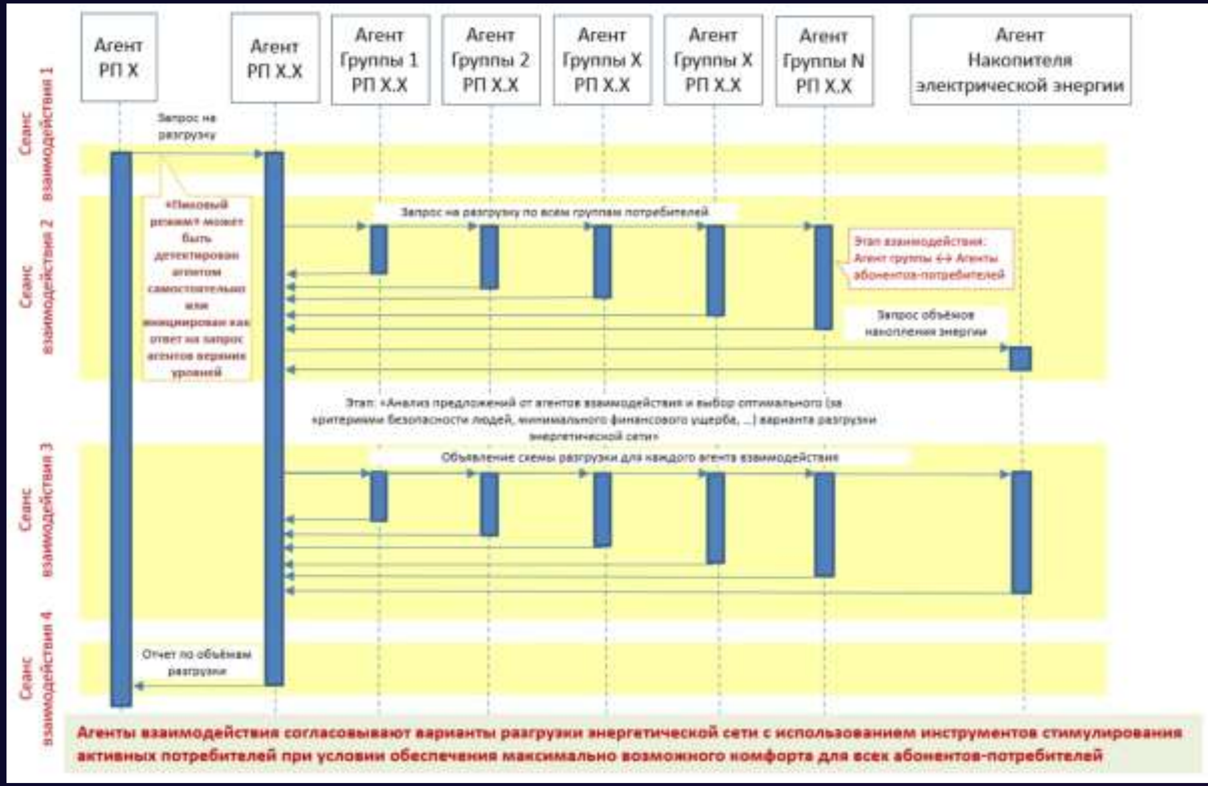
4. **Command Dispatch**

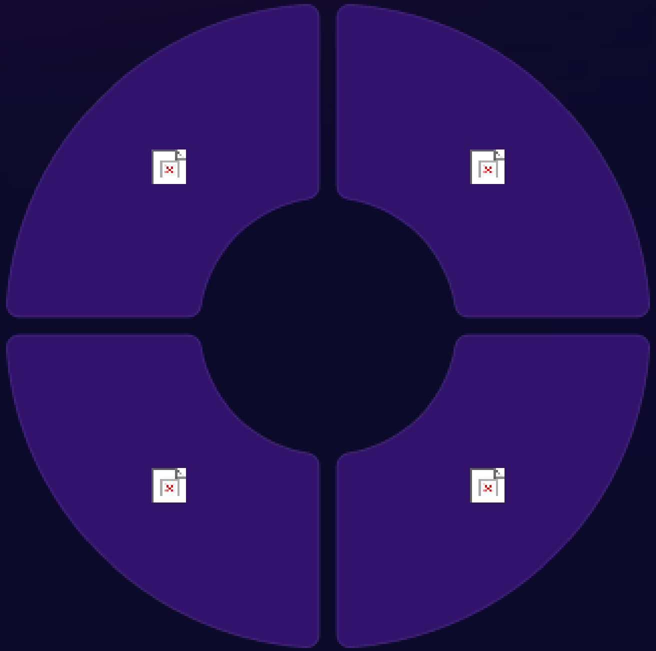
   Individualised load reduction commands sent to selected consumer agents based on optimisation results.

5. **Implementation Feedback**

   Consumer agents confirm command receipt, implement requested changes, and report actual response achieved.

Interaction Diagram: Peak Mode





Peak Prediction

System forecasts approaching peak demand period based on historical patterns, weather conditions, and current trends.

Economic Evaluation

Analysis of current market prices, incentive programme parameters, and cost-benefit of demand reduction.

Coordinated Execution

Staged implementation of load adjustments across multiple consumer groups to achieve desired peak reduction while minimising consumer impact.

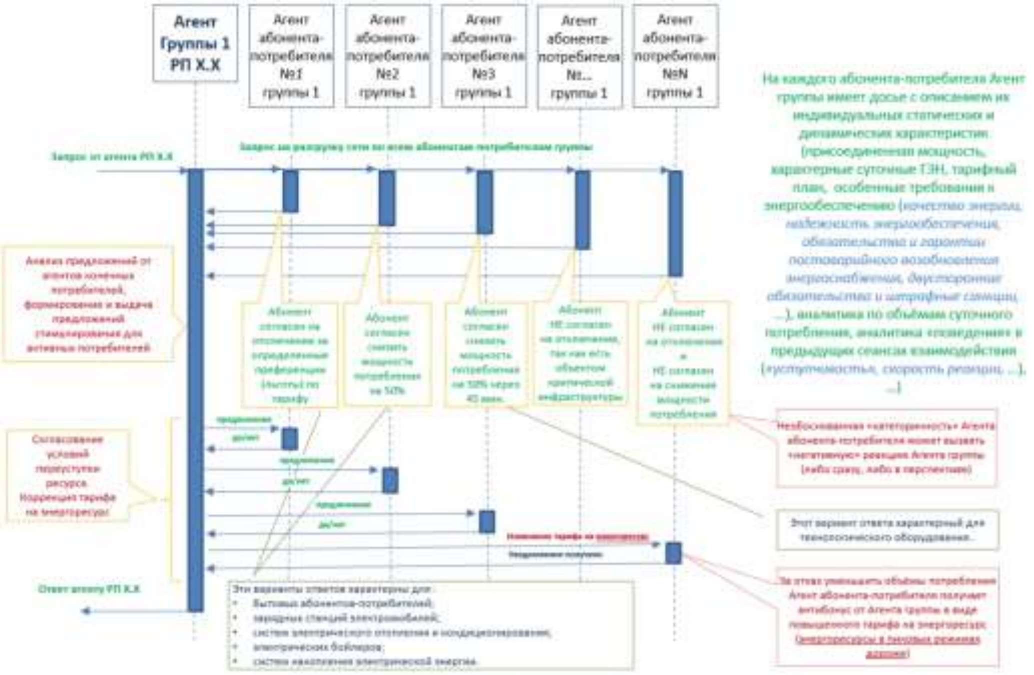
Strategy Development

Formulation of peak management approach considering duration, magnitude, and available flexibility resources.

Peak mode operation differs from emergency handling primarily in its predictive nature and economic focus, allowing for more gradual and planned responses that optimise for cost-effectiveness rather than just system security.

Interaction Diagram: Peak Mode

Session 2 - Group Agent ↔ Consumer Agents



During peak mode operations, the interaction between group agents and consumer agents follows a market-oriented approach:

Advance Notification

Group agent issues early warning about upcoming peak period with preliminary estimates of required reduction and potential incentive payments.

Bid Collection

Consumer agents evaluate their flexibility options and submit bids indicating capacity, duration, and price requirements for participation.

Bid Evaluation

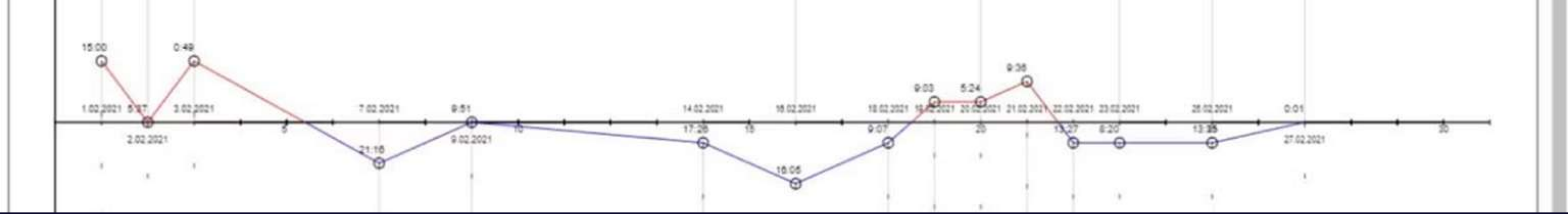
Group agent ranks received bids based on cost-effectiveness, reliability, and technical suitability for the specific peak event.

Bid Acceptance

Notifications sent to selected consumer agents confirming their participation with specific reduction targets and compensation terms.

Execution & Verification

Monitoring of actual load reductions achieved compared to commitments, with real-time adjustments if needed to meet overall targets.



Software Implementation Results

(Visualisation of System Behaviour in "Peak" Mode)

Key Findings

Computer modelling demonstrates the effectiveness of the proposed approach to developing real-time systems for operational management of electricity demand on the consumer side through the application of a multi-agent approach to the organisation of hardware and software architecture.

15-20%

Peak Reduction

Average peak load reduction achieved during simulation trials

<5s

Response Time

System reaction time from detection to implementation

99.7%

Reliability

System availability during extended operation tests

The multi-agent system demonstrates superior performance compared to traditional centralised approaches, particularly in response speed and adaptation to changing conditions. These improvements enable the use of demand response as a tool for real-time grid stabilisation and emergency prevention.