

A Finite State Machine Model for Business Flow in Active Distribution Networks Considering the Multi-flow Fusion Process

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Received 19 July 2023; revised 30 October 2023; accepted 12 March 2024

The continuous development of informatization and digitization in active distribution networks has endowed them with the characteristic of multi-flow convergence, incorporating energy flow, information flow, control flow, and business flow. The combination of multi-flow fusion and business flow modeling in active distribution networks are examined in this work, and a method for constructing business flow model that considers the process of multi-flow convergence is described. The viability of modeling business flow that incorporates the fusion process is examined by studying the interactive process of multi-flow fusion. The operating states of the network and the characteristics of business events are defined by using the finite state machine approach to create the business flow model of active distribution networks. The experimental findings show that the suggested strategy successfully captures the business flow process in active distribution networks and satisfies the requirements for practical use. This study serves as a reference for business flow modeling and the use of finite-state machine models, and it offers useful insights for optimizing and managing the functioning of active distribution networks.

Keywords: Business scheduling, Cyber-physical systems, Discrete state transition, Distribution network fault recovery, Event-level model

Introduction

Numerous distributed power sources, electric vehicle charging stations, energy storage systems, next-generation distribution automation and terminal devices, flexible interconnection devices, and flexible transformers are being integrated into the distribution grid as a result of the ongoing construction and renovation of the nation's distribution grid. The distribution grid's traditional "generation follows load" operation mode is being replaced by an active distribution network operation mode that is characterized by "multidimensional coordination and flexible interaction of source, grid, load, and storage".¹ Further, when contemporary communication technologies, like 5G and computer networks, are created and implemented, the interdependence between energy, information, control, and business is growing more complex.² The difficulty of business flow modeling is rising as active distribution networks' intelligence continues to develop.

The area of Cyber-Physical Systems (CPS), which involves the interplay between energy flow, information flow, and control flow, is where the

majority of research on multi-flow fusion is currently concentrated. It fuses energy, information, and control to a high degree by integrating communication and control technologies with physical power systems.^{3,4} Wang *et al.* in 2020 simultaneously describes the active distribution network and distributed control system using a CPS hybrid system model.⁵ By using a model prediction technique, they accomplish seamless energy and information flow. Using a model predictive method, energy flow and information flow are seamlessly combined in this work, although the remaining two flows are not specifically addressed. To accomplish accurate modeling under load fluctuations, Reddy *et al.* provided a CPS model that takes into account price and reward concerns by combining demand-side management tactics.⁶ To accurately simulate a power CPS while accounting for potential network assaults, Ayad *et al.* in 2020 considered the structure of CPS and employed branch current state estimate methods in addition to convex relaxation techniques.⁷

The aforementioned research, however, ignores the impact of business flows on CPS and instead concentrates on the fusion and interaction of energy, information, and control flow. The involvement of business flows frequently has a substantial impact on

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the power CPS that cannot be ignored in business scenarios like load forecasting.

The majority of recent business flow modeling research in active distribution networks is concentrated on certain business processes. Hu *et al.* in 2021 analyzed the application of block chain technology in demand response services and designed an automatic demand response solution for small and medium-sized power users based on this technology. The interaction between user physical layer equipment and information network is enabled, but it does not represent multi-flow convergence and interaction.⁸ Power CPS enjoys the convenience of information technology but runs the risk of being exposed to cyber-physical threats. Sinha *et al.* in 2021 suggested a novel network-physical defensive framework for attack prevention based on hierarchical Petri net theory and combining national standards with NIST standards.⁹ Attacks on active distribution networks are addressed by this architecture. Power restoration work must be done when power outages occur in the distribution networks. Snullah *et al.* in 2020 built the power restoration model using the minimum spanning tree method and took load priorities and minimal power losses into account.¹⁰ The model's accuracy is tested by introducing many distributed power sources at various nodes in an enhanced IEEE-69 distribution system.

As a result, current research on multi-flow fusion and business flow modeling in active distribution networks frequently concentrates on particular features without thoroughly examining how they interact. On the one hand, the energy-information-control components of CPS are the main focus of research on multi-stream fusion. While ignoring the interaction of business flow, it largely involves description of CPS modeling and interaction mechanisms. The focus of conventional business flow modeling in distribution networks, on the other hand, is frequently on modeling and characterizing particular business activities. However, there is a tendency to overlook the interconnections among different business flows. Furthermore, minimal consideration is given to how to coordinate the flow of energy, information, and control to facilitate the interconversion among diverse business flows. In the practical operation of active distribution networks, the flow of energy, information, control, and business is closely interrelated and mutually influential. Variations in energy flow can trigger the transmission of information and adjustments in control flow, while the demands and optimization of business flow, in turn, impact the configuration and operation of energy

flow, information flow, and control flow. The lack of consideration for multi-flow fusion in business flow scheduling may result in information transmission delays and the potential for control failures or delays. Consequently, it can impact the real-time perception and decision-making capabilities of business flow, ultimately manifesting as a less flexible response to changes in active distribution networks. By incorporating the process of multi-flow fusion into business process modeling, a more comprehensive understanding of system operations and business flow scheduling can be achieved. This work aims to provide theoretical support for intelligent scheduling and adaptive operation of active distribution networks in the context of multi-flow integration.

This paper establishes a finite state machine model for business flow in active distribution networks, taking into account the multi-flow convergence process. Initially, the concept of multiple flow and their interactive processes are explored. Subsequently, the operating states of active distribution networks are delineated, and an event-level model for business proposed to provide a unified description of various business processes. Finally, considering the process of multi-flow fusion, a finite state machine model for business flow is constructed. This model facilitates the scheduling of tasks within different business flow, and the accuracy of the model is validated through a case study involving fault recovery scenarios.

Methodology

Analysis of the Multi-flow Fusion Process

Multi-flow fusion has steadily turned into a key feature of these networks as information and communication technology has been incorporated more and more into active distribution networks. It offers a smart way to run power systems by fusing energy, data, control, and business flow. The construction of business flow models for active distribution networks that contain multi-flow fusion is investigated in this research using multi-flow fusion as a starting point and combining it with finite state machine theory. Before examining their interaction, we will first explain the fundamental ideas of multiple flows in distribution networks, including energy flows, information flows, control flows, and business flows.

Basic Concept of Multi-flow

An active distribution network's energy flow is the system's internal energy transmission and conversion. Electrical energy is the most common type of energy

transfer in power systems. Other types of energy include thermal energy, mechanical energy, and electrical energy. In the active distribution network, distributed energy resources, loads, transformers, cables, switches, and inverters are principally responsible for the energy flow. Depending on the condition of the power equipment and changes in the control signals, the flow of energy can alter in both direction and distribution.

The process of delivering information in a variety of contexts, including computing, control, and communication, is referred to as information flow. The information in the flow can be in the form of data, text, or images, among others. The active distribution network's ability to monitor, control, and schedule the operational state of the power grid makes information flow of utmost importance. It makes it easier to gather and disseminate vital information on electricity demand, grid health, and user needs. The network can increase its dependability, security, and cost-effectiveness by utilizing this information flow.

Control flow, which primarily transmits the control signals to regulate the running condition and operation of the power equipment, including the switching signals, adjustment signals, and protection signals of the equipment, can be thought of as a type of information flow. Control flow can be used to monitor and manage power equipment, which enables automation of the active distribution network. To provide a secure and reliable distribution network, control flow must be transmitted and addressed promptly.

The complete process of managing the distribution network is referred to as business flow following operating standards and business process requirements. The coordinated execution of one or more business tasks in a certain order and under particular circumstances comprises real-time monitoring, analysis, and scheduling processes. The active distribution network's business flow model, which is crucial for the realization of automatic control and ideal scheduling, is established by examining the operating condition, business requirements, and process rules of the active distribution network.

Process of Multi-flow Fusion

The interaction process between "energy flow, information flow, control flow, and business flow" is depicted in Fig. 1.

Energy moves across the distribution network, and before it can be transferred to the information flow,

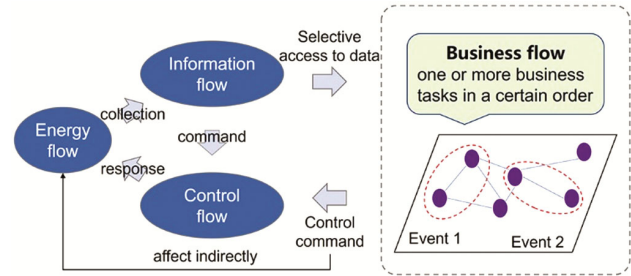


Fig. 1 — The process of multi-flow fusion

energy information must first be gathered. During the acquisition process, devices or instruments, often sensors, are frequently utilized to collect data. The energy information is sensed by these sensors, which subsequently transform it into electrical signals or other information that travels through the information flow. The information flow module receives the original data that was transmitted during the information flow as its input. Following information processing, the control station provides control orders to the control flow and makes corresponding control decisions. The terminals carry out the required operations, such as opening or closing switches and circuit breakers, after receiving the control information. The distribution and flow of energy in the energy flow are impacted by these actions. Based on the information in the information flow, the business flow chooses the type of business to be accessible when the status of the distribution network changes. It will be necessary to control the distribution network, which depends on control flow, by altering output power or the operational condition of inverters, for example. To increase the distribution network's operational effectiveness and dependability and support the long-term growth of active distribution networks, several flows can be coordinated and integrated.

Assuming the normal operation of distribution networks, various distribution terminals collect voltage, current, and power data from each node. This information is then transmitted to the distribution network master station system via communication channels such as optical fibers, enabling the monitoring of distribution network operations. This process involves both energy and information flows. In the event of a single-phase grounding fault or short circuit fault, distribution terminals process fault information, switch operation details, and temporary status records before transmitting the data to the master station. The master station, based on the

received information, makes decisions and sends instructions back to the terminals for execution. This process involves energy, information, and control flows. During this sequence, switch malfunctions may occur, introducing events such as packet loss and delays. The distribution master station must consider these events collectively and make comprehensive decisions. Subsequently, it remotely controls the relevant switches to restore power supply to non-faulty segments, completing an automated feeder process. Throughout this entire process, energy and information flows dictate the decisions made in the control flow. These decisions, in turn, affect energy and information flows. Simultaneously, the business flow acquires information from the information flow to understand the ongoing business or decide which business to engage with.

Business Flow Modeling in Active Distribution Networks

Principles of Finite State Machines

A mathematical model known as a Finite State Machine (FSM) is typically used to explain systems with discrete inputs and outputs. It divides complex logic into a finite number of states, where events are assessed at each state. FSM is generally defined as a five-tuple as follows:

$$FSM = (\Sigma, Q, \delta, q_0, Q_m) \dots (1)$$

where,

- (1) Σ is a set of events;
- (2) Q is a set of finite states;
- (3) δ is the state transition function, indicating how the system transitions from one state to another based on the received events;
- $\delta: Q \times \Sigma \rightarrow Q \dots (2)$
- (4) q_0 is the initial state of the system, $q_0 \in Q$;
- (5) Q_m is the set of system termination states, where the system returns to the initial state, $Q_m \in Q$.

FSM theory provides a structured and formalized approach to describing various states within a business flow, the transitions between states, and their relationships with input events. Business flow in active distribution networks is typically composed of a series of discrete events and is event-driven. Different events or decisions can lead to state changes within the system. There are often one or more states

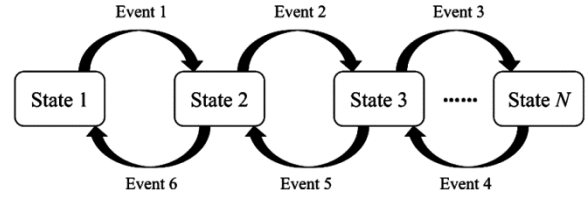


Fig. 2 — Transition diagram of a finite state machine

within the life cycle of a business flow. The state transition diagram is displayed in Fig. 2.

Operating State Division of Active Distribution Networks

In active distribution networks, the distinction of operational states is essential and crucial for the efficient management and operation of the distribution network. It is essential for maintaining the security and stability of the network.

There are typically different operating indicators for various business processes that correspond to various operating states. The following five categories of active distribution network operating states are used in this paper:

(1) Optimization state

At this point, the operating indicators of the distribution network comply with the optimization goals, and it is safe and stable to use.

(2) Normal state

The active distribution network satisfies the load restrictions and operational requirements in this state, operating faultlessly and without any anomalies. The functioning indications do have room for future improvement, though. This suggests that even while the network is operating within reasonable bounds, there are still ways to improve its efficacy in terms of efficiency, dependability, and cost.

(3) Abnormal state

The distribution system is getting close to the point where it can no longer maintain normal operation. The maximum voltage deviation, for instance, is greater than the permitted voltage range for normal operation.

(4) Fault state

The distribution network's operating indicators, such as overvoltage and overcurrent, are currently above the safe operating limit values.

(5) Restoration state

Even though the active distribution network is under control, there are still some places that lose

Table 1 — Collection of business events

Operating States	Business Events
Optimization state	Load forecasting, electricity market trading
Normal state	Automatic diagnosis and localization of distribution network faults
Abnormal state	Automatic power limiting or peak shaving for distribution network overload
Restoration state	Repairing power equipment failures and restoring the power supply
Fault state	Conducting emergency repairs at fault locations

power when a problem occurs in the system. The system exits the restoration state once the topology and power have both been fully restored.

Finite State Machine Model for Business Flow

Different operating phases during the active distribution network's operation correlate to various business needs and processing strategies. As a result, it's important to segment particular services based on the active distribution network's operational condition while modeling the business flow. The probable business events that could take place in the distributed network under the aforementioned operational states is displayed in Table 1.

Even though collective business events are described above for the operating state, it's crucial to remember that they don't just happen in one state. They take place as the power system switches between several operational states. Consequently, it is essential to have a consistent account of all business events.

Business events can be defined as follows:

$$T = (B, S, D, C) \quad \dots (3)$$

where,

(1) *B* represents the business needs. Business events serve the dual purposes of meeting user demands and ensuring system safety by optimizing the distribution of energy within a system through control and regulation of power electronic devices and smart grid controllers. Constraints can be used to describe business requirements uniformly:

$$B: \begin{cases} G(x) \leq 0 \\ H(x) = 0 \end{cases} \quad \dots (4)$$

Among them, *x* represents the optimization variable to be solved, *G(x)* and *H(x)* are inequality and equality constraints, respectively. Different objective functions and constraints can be designed to achieve various business event kinds.

(2) *S* represents the system state. The active distribution network may function in several states,

each of which may call for the execution of a distinct business event. This should be considered while defining business events.

(3) *D* represents the data requirements. The type of information gained from information flow must be considered in the definition of business events. These data types can be grouped and represented using a matrix to simplify representation and processing. The following relationship between business events and the appropriate data types is shown by the matrix:

$$D = \begin{bmatrix} D_{11} & \dots & D_{1n} \\ \vdots & \ddots & \vdots \\ D_{m1} & \dots & D_{mn} \end{bmatrix} \quad \dots (5)$$

Among them, $D_{ij} \in \{0,1\}$, where $D_{ij} = 1$ indicates that the business event *i* numbered needs data type *j*, while $D_{ij} = 0$ indicates that it does not require that particular data type.

(4) *C* represents the control information. The creation of control information, including its many forms and objects, must be considered while defining business events.

$$C = f(B, S, D) \quad \dots (6)$$

Among them, the function *f* represents the method of generating control information, which can be generated based on predefined rules, artificial intelligence algorithms, or other methods.

Define the state of the finite state machine as $Q = \{Q_0, Q_1, Q_2, Q_3, Q_4\}$, corresponding to the above five operating states of the active distribution network. Among them, Q_0 represents the optimization state, which is defined as the initial state; *D* is the information obtained from the information flow, which is used as an indicator to judge the operating state; *C* is the control signal transmitted from the business flow to the control flow; $T = \{T_1, T_2, T_3, T_4\}$ represents the business events currently occurring in the state. The state transition diagram while taking into account the integration of various flows is depicted in Fig. 3.

First, pertinent data is gathered from the information flow to evaluate the functioning state of

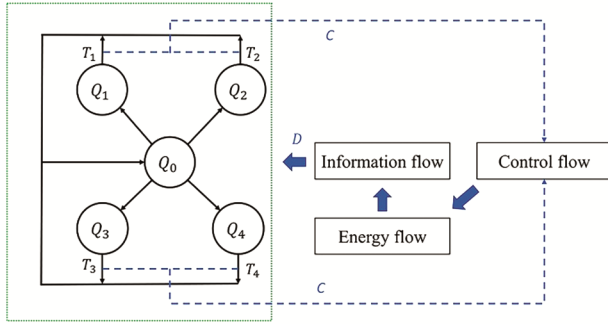


Fig. 3 — State transition diagram considering multi-flow fusion process

the active distribution network following the classification standard for that network. Based on the unique business requirements, the associated business is then accessed. As a result, the control information produced by the company is sent to the control flow, which then has an impact on the energy flow. The aforementioned actions will repeat until the active distribution network reaches its initial optimal operational state since information flow in real time. Changes in the operational state will have an impact on the definition of business events and the generation of control information during this process, leading to different control methods and outcomes.

Results & Discussion

The Stateflow component in Simulink is used for simulation in the calculation example in this study. The modeling of finite state machines is facilitated by Stateflow's user-friendly visual interface. Users can define transition conditions and actions between states, as well as sketch the states, transitions, and events of the state machine using the graphical tools supplied by Stateflow. This graphical modeling approach not only makes the state machine design process simpler but also makes the state machine easier to comprehend and maintain.

Using a system with a 5-terminal SOP connected to IEEE 33 and IEEE 69 nodes as an example, Lu *et al.* in 2022 established an ideal decision-making approach for fault recovery of interconnected power distribution systems with multi-terminal soft switches (SOP).¹¹ The example results from Lu *et al.*, 2022 will be utilized in this study to assess the fault recovery business process and confirm the accuracy of the finite state machine model for business flow.

The rate at which the electrical system returns to normal load when a fault or other abnormal circumstances occurs is referred to as the load

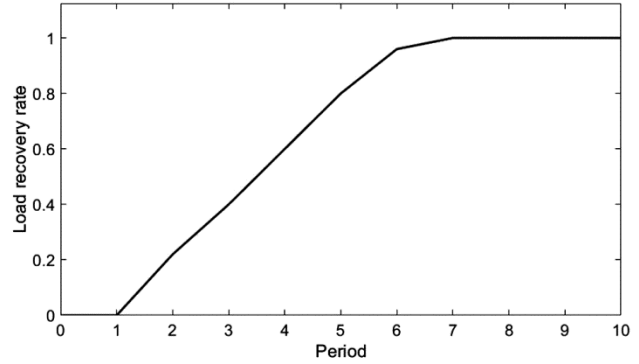


Fig. 4 — Changes in load recovery rate

recovery rate. Let L_0 represent the normal load level before the fault, and l represent the load level during the recovery process. Then the load recovery rate can be expressed as follows:

$$\sigma = \frac{l}{L_0} \times 100\% \quad \dots (7)$$

In this paper, only 10 fault periods are considered. With reference to Lu *et al.* (2022), the change in the system load recovery rate is shown in Fig. 4.

Business Event Definition

(1) Business requirements

In this instance, the interconnected active distribution network must recover from faults using a multi-terminal SOP in the event of a significant loss of power as a result of extreme events. Restoring the system to its default state, denoted by $\sigma = 1$, is the goal.

(2) System status

In this instance, the process of going from a fault condition to a normal state is taken into consideration, where business events could call for several choices.

(3) Data requirements

The load recovery rate is chosen in this instance as an operating indication to evaluate the active distribution network's operational status.

(4) Control information

The system includes multiple SOPs with VSC (Voltage Source Converter) ports located at nodes 91, 81, 54, 35, and 27. In the process of fault recovery, each VSC port has different control modes. In this case, five control commands e_1-e_5 are defined as shown in Fig. 5. Each control command determines the control mode of the VSC ports of these five nodes, and "1" indicates Vf control and "0" indicates PQ or $V_{dc}Q$ control for the respective node.

Control commands	Node number				
	27	35	54	81	91
e_1	1	1	0	1	1
e_2	1	1	0	0	1
e_3	1	0	0	0	1
e_4	0	0	0	0	1
e_5	0	0	0	0	0

1— V_f control
0— PQ control or $V_{dc}Q$ control

Fig. 5 — Control commands for voltage source converter

Table 2 — Classification of operating states according to load recovery rate

Serial number	Operating state	Load recovery rate
1	Fault state	0–0.2
2	Restoration state	0.2–0.8
3	Abnormal state	0.8–1
4	Normal state	1

Table 3 — Correspondence between business event, control signal, and load recovery rate

Load Recovery Rate	Business Event	Control Signal
0	T_1	e_1
0.2	T_2	e_2
0.4	T_3	e_3
0.6	T_4	e_4
0.8	T_5	e_5

Construction of Business Flow Finite State Machine Model

The operating state division of the distribution network will change depending on the many business process indicators, as was already mentioned. As shown in Table 2, the fault state, restoration state, abnormal state, and normal state phases of the active distribution network's operation in this case study are split according to the load recovery rate.

In the fault recovery process, the system may stay in the restoration state for a prolonged duration due to the wide range of indicators used to evaluate the restoration state. To mitigate this issue, it is advantageous to partition the restoration state into sub-states based on the load recovery rate. This subdivision enables the determination of the suitable business and output control information for each specific sub-state. The corresponding relationship is shown in Table 3.

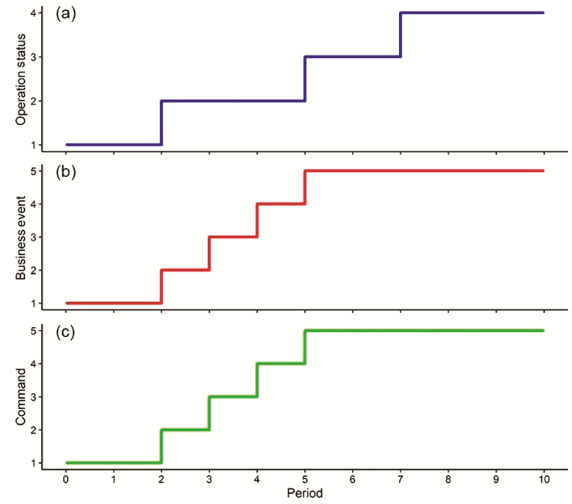


Fig. 6 — Output: (a) Operation state; (b) Business Event; and (c) Command

The outputs of the final state, business event and control command, which can be obtained by feeding the model with the change in load recovery rate, are illustrated in Fig. 6.

It is discovered that the state output results generated from the calculation example in this study are consistent with the current distribution network's real functioning state. Additionally, this paper's sequence of suggested control output and the actual control sequence of Lu *et al.* (2022) are both consistent. This serves as further evidence that the finite state machine model for business flow developed in this research is capable of accurately simulating the operational flow of active distribution networks. During fault recovery, the model reliably assesses the active distribution network's operational state and applies the appropriate control measures. A considerable number of VSC ports implement V_f control to support the island grid voltage and hasten the recovery of the grid during the 1-2 time period when the active distribution network is in a fault state with a low recovery rate. When the distribution network reaches the late recovery state or abnormal state, the isolated island grid that was created in the initial stage has been integrated into a relatively strong island grid, where internal voltage support is primarily provided by distributed generation, and the VSC ports are no longer necessary to provide voltage support. At this time, most of the VSC ports are in PQ or in $V_{dc}Q$ control state.

The finite state machine business flow model suggested in this research has the following benefits over conventional business flow modeling:

(1) This model is a broad model with significant flexibility that can adapt to various business processes and operating states.

(2) More states and events can be added to the distribution network as it grows in size and complexity to accommodate shifting business needs.

(3) The state changes of many processes will interact in the case of multi-flow fusion, which is frequently not adequately represented by conventional models. The accuracy and dependability of state switching are increased when models taking into account the multi-flow fusion process can capture transitions and switching situations more correctly.

Conclusions

This study seeks to build a business flow model of active distribution networks based on the interactive link between energy flow, information flow, control flow, and business flow. The conclusions are as follows:

(1) A finite state machine model for business flows is proposed in this study. This model can be used to determine a business process's operating status based on the flow of information, and then it can be used to execute the corresponding business process based on the data.

(2) The entire business process is the subject of the model and examples used in this study. However, there hasn't been much in-depth research on the precise worth of control information or how it influences the distribution network's operational condition. This has to change in future research.

(3) Future research can focus on further refining and optimizing the model of business flow to enhance its simulation accuracy and computational efficiency. Additionally, the application scope of the model can be broadened to encompass more complex business processes and scenarios.

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