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Distributed Fixed-Time Energy Management for Port Microgrid Considering Transmissive Efficiency

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Abstract: To enhance the efficiency of a port microgrid, this paper proposes an energy management method and a topology construction mechanism considering the convergence rate and information transmission distances, respectively. Firstly, a distributed fixed-time energy management method is proposed to solve an energy management problem in a known time and guarantee the efficiency of the port microgrid. Secondly, to address the challenge of heterogeneous devices with multiple communication protocols, information exchange between different devices is facilitated through a polymorphic network. To obtain a connected communication topology that can ensure the implementation of the distributed energy management method, a connected networking mechanism is proposed. This mechanism minimizes the total communication distance to reduce the effect of the information transmission distance on communication effectiveness. Finally, the effectiveness of both algorithms is demonstrated by simulation, and the advantages of the distributed fixed-time energy management method on the convergence rate are reflected through a comparison with other methods.

Keywords: port microgrid energy management; fixed-time control; distributed optimization; polymorphic network; connected networking mechanism

MSC: 68M14; 93A16; 68W15

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1. Introduction

As important places for marine activities and trade transportation, ports require a large number of generators to satisfy the demand for electricity for the operation of equipment and to berth ships [1–3]. Motivated by the objectives of energy conservation and emission reduction, the traditional microgrids, reliant solely on fossil fuel power generation, have been replaced. As part of this transition, the integration of renewable energy into port microgrids has progressively increased, reflecting an ongoing effort to enhance sustainability [4]. The development of port microgrids has been accompanied by many problems, among which energy management problems (EMPs) have been widely studied as the fundamental area of research [5–7].

The EMP of port microgrids studies how to allocate generation resources to make the total minimum generation cost while balancing the supply and demand of the port microgrid and the ranges of the output power of generators [8–10]. In the past few years, many energy management methods have been revealed to try to solve EMPs [11–17]. These methods are essentially divided into two types: centralized and distributed. Compared with centralized methods, distributed methods avoid the single point of failure [9], and have poor privacy [18] and a high maintenance cost. Moreover, because of the distributed-structure port microgrids, many distributed methods have demonstrated advantages in solving EMPs of the port microgrid. Based on a multi-agent system (MAS), an energy management method was proposed to solve a complex optimization problem for a large port considering plentiful decision variables and coupling constraints in [14]. A distributed energy management method was introduced and solved the EMP of a port microgrid with carbon cycling devices to reduce carbon emissions in [15]. Reference [16] extended a new distributed energy management strategy to solve the EMP of a port electrical system considering false data injection attacks and improved data stabilization. However, the convergence rate of the method was ignored in the above references. The EMP can obtain the optimal scheme in a short time to cope with emergencies affecting port flexibility and efficiency under the effect of the fast convergence method [19]. Therefore, it is essential to improve the convergence rate of the energy management method to improve the port microgrid's energy management efficiency.

Finite-time control is a significant theory in which the state of a system can converge in a bounded settling time under the controller [20–23]. In order to speed up the convergence rate, it is warranted to combine distributed optimization and finite-time control. A novel distributed fixed-time optimization was proposed to solve an optimization problem under the directed communication network for a smart grid with the upper bound for settling time in [24]. On this basis, a new distributed robust finite-time optimization algorithm was presented for the problem with a coupled local cost function and rejection of effective disturbances, and simulation results showed that the equilibrium point (optimization point) for an MAS could be reached in a finite time in [25]. Compared with [24,25], a distributed optimization algorithm was presented that was based on the optimal conditions and extended to solve an optimization problem with inequality and equality constraints in a finite time in [26]. Reference [27] proposed a distributed finite-time incremental cost consensus algorithm to solve an optimization problem considering the time-varying range of output variables. The above references are based on the consensus of an MAS, and completing the information exchange between agents is the foundation of them. With regard to heterogeneous devices in the port microgrid, the traditional single communication network cannot support them. Therefore, a more flexible communication network should be considered.

A polymorphic network is a versatile technology that realizes the coexistence of multiple protocols on the same platform [28,29]. It flexibly uses and operates various communication protocols on the supporting communication network in the form of polymorphic addressing, including Internet Protocol (IP), Geonetworking, and Identity and Content. The polymorphic network has gained increasing attention due to the diversification of heterogeneous devices, massive data updates and the complexity of multi-objective tasks [30–34]. Different to a traditional network, the polymorphic network has an excellent ability to carry heterogeneous devices and process tasks such that it has been used widely in vehicular networks [35], resource allocation [36] and cooperative communications [37]. Therefore, how to construct the distributed polymorphic energy management configuration is worth considering to improve the performance of a port microgrid. On the other hand, it is a challenge to determine an appropriate communication topology for implementing distributed energy management methods [38,39]. However, it has received limited attention in the existing references. Therefore, it is necessary to propose a topology construction mechanism that takes into consideration the enhancement of communication efficiency in a port microgrid.

To solve the EMP of a port microgrid rapidly and address the challenges of communication between agents, this paper aims to investigate a distributed fixed-time energy management method with a topology construction mechanism. The contributions of this paper are summarized as follows.

(1). This paper proposes a distributed fixed-time energy management method. An optimal power allocation strategy can be obtained in a settling time to improve the efficiency of the port microgrid. Different from [24–27], the initial state is arbitrary and does not require a transformation of the dual problem under the proposed method.
(2). A distributed polymorphic energy management configuration for the port microgrid is constructed. On the one hand, information exchange between heterogeneous devices

can be completed under this configuration. On the other hand, the polymorphic network provides a computing platform to solve the EMP of a port microgrid.

(3). A connected networking mechanism is designed based on information transmissive distances. The connected communication topology with the shortest total path significantly improves the transmissive efficiency of the port microgrid. Meanwhile, the effectiveness of the proposed method is not affected so it can solve the EMP of the port microgrid.

The composition is as follows: In Section 2, the EMP of the port microgrid, notation, preliminaries of graph theory and useful lemmas to discuss the accuracy of the method are introduced. In Section 3, a distributed fixed-time energy management method is proposed and the fixed-time convergence is proved by Lyapunov theory. In Section 4, a configuration for distributed polymorphic energy management is presented with a connected networking mechanism based on information transmission distance. In Section 5, a simulation confirms the validities of the proposed methods. Finally, Section 6 concludes this paper.

2. Problem Formulation and Preliminaries

This section introduces the EMP of a port microgrid, the notation, the preliminaries of graph theory and useful lemmas involved in this paper.

2.1. EMP of Port Microgrid

The port microgrid studied in this paper consists of distributed generators, including diesel generators (DGs), photovoltaic panels (PVs) and wind turbines (WTs), and loads, including plug-in electric vehicles, berthing ships, lightings and cranes. The cost functions of generating devices can be formulated as quadratic functions [5,40]. Under the premise of maintaining the load demand of the port microgrid and satisfying the normal operation of generators, this paper aims to optimize the EMP of the port microgrid, which is performed as:

$$\min C(P) = \sum_{i=1}^{n} C_i(p_i) = \sum_{i=1}^{n} \delta_{i,1} p_i^2 + \delta_{i,2} p_i + \epsilon_i \tag{1}$$

$$s.t. \quad \sum_{i=1}^{n} p_i = \sum_{i=1}^{n} l_i \tag{2}$$

$$p_i^{min} \leq p_i \leq p_i^{max} \rightarrow p_i \in \Omega_i, i \in N \tag{3}$$

where n is the entire quantity of generators (loads) in the port microgrid, and $\delta_{i,1}$, $\delta_{i,2}$ and ϵ_i are coefficients of the cost function of the generator i. Meanwhile, $\delta_{i,1} > 0$ guarantees its convex optimization property, the output power for generator i is shown as p_i, $p = [p_1, p_2, \ldots, p_n]^T$, $l = [l_1, l_2, \ldots, l_n]^T$,$l_i$ is the load power demand for i, p_i^{min} and p_i^{max} are THE minimum and maximum output power of p_i, respectively, and Ω_i is the local closed convex set deduced by $p_i^{min} \leq p_i \leq p_i^{max}$. Equations (1)–(3) show the EMP for the port microgrid in this paper.

Assumption 1. *The Cartesian product for local closed convex sets Ω_i is non-empty $\Omega = \cap_{i=1}^{N} \Omega_i \neq \emptyset$; therefore, unique optimal solutions exist for the above optimization problem [41].*

2.2. Notation

The following notations in this paper are shown: $\mathbb{R}$ and $\mathbb{R}^n$ denote the real number and N-dimensional real space, respectively. The signal function is described as $sig[u]$, and $sgn[u]^k = |u|^k \cdot sig[u]$, where $l > 0$ and $|u|$ is the absolute value for u. $||u||_k$ is k-norm, $||u||_k = (\sum_{i=1}^{n} |u_i|^k)^{\frac{1}{k}}$,and $||u||_k^k = (||u||_k)^k = \sum_{i=1}^{n} |u_i|^k$. The Dini derivative for continuous function $h(x)$ is $D^+h(t) = \lim_{s \to 0^+} sup \frac{h(x+s)-h(x)}{s}$. $\nabla h(x)$ and $\nabla^2 h(x)$ denote the gradient and the Hessian matrix of the function $h(x)$, respectively.

2.3. Graph Theory

A port microgrid with n generators is actually an MAS. The communication network topology for the port microgrid can be modified as a graph $G(N, E, A)$, which is an undirected graph. The finite sets $N = \{1, 2, \ldots, n\}$ and $E \subset N \times N$ are, respectively, the set of nodes and set of edges representing the communication links to exchange information with neighbors η_i, where η_i represents the neighbor node set for node i. $A = [a_{ij}] \in \mathbb{R}^{n \times n}$ denotes the N-dimensional adjacency matrix, where $a_{ii} = 0$, $a_{ij} = 1$ if $(i, j) \in E$, otherwise $a_{ij} = 0$. Meanwhile, the degrees matrix defined as $D = diag\{\sum_{j=1}^{n} a_{1j}, \sum_{j=1}^{n} a_{2j}, \ldots, \sum_{j=1}^{n} a_{nj}\}$ is a diagonal matrix. The Laplace matrix of A is $L = D - A$. The minimum nonzero eigenvalue for L is described as algebraic connectivity $\lambda_2(L)$ if G is connected.

Assumption 2. *The communication topology for port microgrid energy management is connected.*

2.4. Useful Lemmas

To prove that the EMP is solved in a known settling time under the proposed method in this paper, some useful lemmas are shown.

Lemma 1 ([42])**.** *The projection of u onto the closed convex set Ω is denoted by $\Xi_\Omega(u)$, and the projection operator defined by $\Xi_\Omega = \arg\min_{v \in \Omega} ||u - v||$. For $\forall u, v \in \mathbb{R}$, it satisfies:*

$$||\Xi_\Omega(u) - \Xi_\Omega(v)||_2^2 \leq (u - v)^T (\Xi_\Omega(u) - \Xi_\Omega(v)) \tag{4}$$

Lemma 2 ([43])**.** *There exist inequalities for $\zeta_i > 0, \forall i = 1, 2, ..., n$*

$$\sum_{i=1}^{n} \zeta_i^l \geq \left(\sum_{i=1}^{n} \zeta_i \right)^l \quad , 0 < l \leq 1 \tag{5a}$$

$$\sum_{i=1}^{n} \zeta_i^l \geq n^{1-l} \left(\sum_{i=1}^{n} \zeta_i \right)^l , 1 < l < \infty \tag{5b}$$

Lemma 3 ([44])**.** *Consider the non-linear system*

$$\dot{x} = f(t, x) \tag{6}$$

where $x \in \mathbb{R}^n$, and $f : \mathbb{R} \times \mathbb{R}^n \to \mathbb{R}^n$. Let there exist a continuous radially unbounded function $V(x) \geq 0$ with $V(x) = 0 \Leftrightarrow x = 0$. There are real numbers $c > 0$ and $0 < \alpha < 1$ such that $V(x) > 0$, and it satisfies:

$$\dot{V(x)} + cV^\alpha(x) \geq 0 \tag{7}$$

The origin of the system is locally finite-time stable, and the settling time $T \leq \frac{V^{1-\alpha}(x_0)}{c(1-\alpha)}$ depends on the initial state $x(0) = x_0$.

Lemma 4 ([45])**.** *Consider the non-linear system (6): if it exists, the following inequality is shown:*

$$D^+ V(x(t)) \leq -(\alpha V^\rho(x(t)) + \beta V^{\rho'}(x(t)))^k \tag{8}$$

where $D^+ V(t, x) = \max_{i \in N(t)} \dot{V}_i(t, x)$, $\alpha, \beta, \rho, \rho', k > 0 : \rho k < 1, \rho' k > 1$. The origin is globally fixed-time stable in equilibrium with the settling time:

$$T(x_0) \leq \frac{1}{\alpha^k (1 - \rho k)} + \frac{1}{\beta^k (\rho' k - 1)}, \forall x_0 \in \mathbb{R}^n \tag{9}$$

3. Distributed Fixed-Time Energy Management Method for Port Microgrid

In this section, to improve the efficiency of the port microgrid and solve the EMP rapidly, a distributed fixed-time energy management method is introduced. Firstly, the dual problem of the EMP without the consideration of the output power limitation is analyzed.

$$\max_{y} \sum_{i=1}^{n} inf_{p_i \in \Omega_i} C_i(p_i) - y_i^T p_i + y_i^T l_i \tag{10}$$

$$s.t. \qquad y_i = y_j \qquad \forall i \in N, j \in \eta_i \tag{11}$$

where y_i is the dual variable for i and $y = [y_1, y_2, \ldots, y_n]^T \in \mathbb{R}^n$.

Through the analysis of the primal-dual problem, the properties of the projection operators and the application of fixed-time control, a distributed fixed-time energy management method is proposed:

$$\dot{p_i} = \alpha_i \Theta_{i,1}[-\nabla C_i(p_i) + y_i] + \beta_i \Theta_{i,2}[\Xi_{\Omega_i}(p_i) - p_i] \tag{12a}$$

$$\dot{y_i} = \gamma_i \Theta_{i,3}[l_i - p_i] + \omega_i \sum_{j \in N_i} \Theta_{i,4}[y_j - y_i] \tag{12b}$$

$$\Theta[u]_{i,\tau} = [sig(u), sgn(u)^{\mu_{i,\tau}}, sgn(u)^{\nu_{i,\tau}}]^T \tag{12c}$$

where $\alpha_i = [\alpha_{i,0}, \alpha_{i,1}, \alpha_{i,2}]$, $\beta_i = [\beta_{i,0}, \beta_{i,1}, \beta_{i,2}]$, $\gamma_i = [\gamma_{i,0}, \gamma_{i,1}, \gamma_{i,2}]$ and $\omega_i = [\omega_{i,0}, \omega_{i,1}, \omega_{i,2}]$ are tuning parameters, and $\alpha_{i,z}$, $\beta_{i,z}$, $\gamma_{i,z}$ and $\omega_{i,z}$ are positive for $\forall i \in N, z = 0, 1, 2$. $\Xi_{\Omega_i}(x_i)$ is the projection operator. $\Theta[u]_{i,\tau}$ is the fixed-time controller and $\tau = 1, 2, 3, 4$ expresses the number of terms for the algorithm. $\mu_{i,\tau}$ and $\nu_{i,\tau}$ are positive parameters and satisfy $0 < \mu_{i,\tau} < 1$ and $\nu_{i,\tau} > 1$ for $\forall i \in N$, $\tau = 1, 2, 3, 4$.

The property of the proposed method (12a)–(12c) that can solve the EMP in a fixed time is characterized in the following theorem.

Theorem 1. *If the EMP of a port microgrid with n generators satisfies Assumption 1 and the communication topology satisfies Assumption 2, then there exists a settling time $T > 0$ such that the optimal output power and incremental cost for each of the generators $p_i = p_i^*, y_i = y_i^*, \forall i \in N$ can be obtained when $t \geq T$ under the proposed method (12a)–(12c). T is:*

$$T = T_1 + T_2 + T_3 = \frac{1}{\beta_1(1-\mu_2)} + \frac{1}{\beta_2(\nu_2-1)} + \frac{2}{W_1(1-\mu_4)} + \frac{2}{W_2(1-\nu_4)}$$

$$+ \frac{2m}{(\alpha_1 m \nabla^2 C(p) - \gamma_1)(1-\mu_1)} + \frac{2m}{n^{\frac{1-\nu_2}{2}}(\alpha_2 m \nabla^2 C(p) - \gamma_2)(1-\nu_1)}$$

where $\alpha_{i,z} = \alpha_z, \beta_{i,z} = \beta_z, \gamma_{i,z} = \gamma_z, \omega_{i,z} = \omega_z$ $W_1 = -\frac{\omega_1}{2} \cdot \lambda_2(L)^{\frac{1+\mu_4}{2}} \cdot 2^{\frac{1+\mu_4}{2}}$, $W_2 = \frac{\omega_2}{2} n^{\frac{1+\nu_4}{2}} \cdot \lambda_2(L)^{\frac{1+\nu_4}{2}} \cdot 2^{\frac{1+\nu_4}{2}}$ for $\forall i \in N, z = 1, 2$.

Proof of Theorem 1. The proof comprises three steps. Step 1 shows that output power $p_i, \forall i \in N$ can satisfy the output power limitation in a fixed time T_1. After that, Step 2 shows that the dual variables $y_i, \forall i \in N$ match in a fixed time $T_1 + T_2$. On the basis of Step 1 and Step 2, Step 3 shows that the EMP is solved in a fixed time $T_1 + T_2 + T_3$.

Step1: Consider the following Lyapunov function:

$$V_1 = \max_{i \in N} V_{1,i} = \max_{i \in N} \left\| p_i - \Xi_{\Omega_i}(p_i) \right\|_2^2 \quad D^+ V_1 = \max_{i \in N_i} \dot{V}_{1,i}$$

According to the proof for [46], it is easy to obtain $\beta_{i,0} = |\alpha_i \Theta_{i1}[-\nabla C_i(p_i) + y_i]|$, and the parameters $\mu_{i,2}$, $\nu_{i,2}$, $\beta_{i,1}$ and $\beta_{i,2}$ are the same values as μ_2, ν_2, β_1 and β_2, respectively, for $\forall i \in N$. The derivative of $V_{1,i}$ leads to: $\dot{V_{1,i}} = 2\big(p_i - \Xi_{\Omega_i}(p_i)\big)\dot{p}_i \leq -2\beta_1 \sum_{k=1}^{m} |p_i - \Xi_{\Omega_i}(p_i)|^{1+\mu_2} - 2\beta_2 \sum_{k=1}^{m} |p_i - \Xi_{\Omega_i}(p_i)|^{1+\nu_2}$.

From Lemmas 1, 2 and 4. The derivative of $\dot{V_1}$ leads to:

$$D^{+}V_1 \leq -2\beta_1 (V_1)^{\frac{1+\mu_2}{2}} - 2\beta_2 k_m^{1-\frac{1+\nu_2}{2}} (V_1)^{\frac{1+\mu_2}{2}}$$

where $k_m = 1$ in this paper. Thus, $V_1(p(t))$ converges to the origin in T_1 and $T_1 \leq \frac{1}{\beta_1(1-\mu_2)} + \frac{1}{\beta_2(\nu_2-1)}$. This leads to $p_i = \Xi_{\Omega_i}(p_i)$ for $t > T_1$.

Step2: Another Lyapunov function is designed and is defined as:

$$V_2 = \frac{1}{2}\sum_{i=1}^{n} ||y_i - \frac{1}{n}\sum_{k=1}^{n} y_k||_2^2$$

Let $v_{i,1} = \gamma_i \Theta_{i,3}[\tau_i - x_i]$. Then the derivative of V_2 based on the proof for [27] is:

$$\dot{V}_2 = \sum_{i=1}^{n}\left(y_i - \frac{1}{n}\sum_{k=1}^{n} y_k\right)^T \left(\dot{y}_i - \frac{1}{n}\sum_{k=1}^{n}\dot{y}_k\right) = \sum_{i=1}^{n}\left(y_i - \frac{1}{n}\sum_{k=1}^{n} y_k\right)\cdot \dot{y}_i$$

$$\sum_{i=1}^{n}\left(y_i - \frac{1}{n}\sum_{k=1}^{n} y_k\right)\cdot\left(\gamma_i\Theta_{i,3}[\tau_i - x_i] + \omega_{i,0}\sum_{j\in N_i}\mathrm{sig}\left[y_j - y_i\right]\right) \leq \sum_{i=1}^{n}\left(|\gamma_i\Theta_{i3}[\tau_i - x_i]| - \omega_{i,0}\sqrt{2\lambda_2}(L)\right)\left|y_i - \frac{1}{n}\sum_{k=1}^{n} y_k\right|$$

Let $\omega_{i,0} \geq \frac{|v_{i,1}|}{\sqrt{2\lambda_2(L)}}$ and $\psi = [\psi_1, \psi_2, \ldots, \psi_n]$ where $\psi_i = y_i - \frac{1}{n}\sum_{k=1}^{n} y_k$, $\mu_{i,4}$, $\nu_{i,4}$, $\omega_{i,1}$ and $\omega_{i,2}$ are the same value μ_4, ν_4, ω_1 and ω_2, respectively, for $\forall i \in N$.

$$\begin{aligned}
\dot{V}_2 &\leq -\frac{\omega_1}{2}\sum_{i=1}^{n}\sum_{j\in N_i}(\psi_j - \psi_i)\,\mathrm{sgn}[\psi_j - \psi_i]^{\mu_4} - \frac{\omega_2}{2}\sum_{i=1}^{n}\sum_{j\in N_i}(\psi_j - \psi_i)\,\mathrm{sgn}[\psi_j - \psi_i]^{\nu_4} \\
&\leq -\frac{\omega_1}{2}\left[\sum_{i=1}^{n}\sum_{j\in N_i}||\psi_j - \psi_i||_2^2\right]^{\frac{1+\mu_4}{2}} - \frac{\omega_2}{2}\cdot n^{\frac{1+\nu_4}{2}}\left[\sum_{i=1}^{n}\sum_{j\in N_i}||\psi_j - \psi_i||_2^2\right]^{\frac{1+\nu_4}{2}} \\
&\leq -\frac{\omega_1}{2}\cdot\lambda_2(L)^{\frac{1+\mu_4}{2}}\cdot 2^{\frac{1+\mu_4}{2}}\cdot V_2^{\frac{1+\mu_4}{2}} - \frac{\omega_2}{2}n^{\frac{1+\nu_4}{2}}\cdot\lambda_2(L)^{\frac{1+\nu_4}{2}}\cdot 2^{\frac{1+\nu_4}{2}}\cdot V_2^{\frac{1+\nu_4}{2}}
\end{aligned}$$

Thus, we can obtain $T_2 \leq \frac{2}{W_1(1-\mu_4)} + \frac{2}{W_2(1-\nu_4)}$ with $W_1 = -\frac{\omega_1}{2}\cdot\lambda_2(L)^{\frac{1+\mu_4}{2}}\cdot 2^{\frac{1+\mu_4}{2}}$ $W_2 = \frac{\omega_2}{2}n^{\frac{1+\nu_4}{2}}\cdot\lambda_2(L)^{\frac{1+\nu_4}{2}}\cdot 2^{\frac{1+\nu_4}{2}}$ based on Lemma 4.

Step3: When $t > T_1 + T_2$, the proposed method is expressed as: $\dot{p}_i = \alpha_i\Theta_{i,1}[-\nabla C_i(p_i) + y_i]$, $\dot{y}_i = \gamma_i\Theta_{i,3}[l_i - p_i]$.

Consider the following Lyapunov function candidate:

$$V_3 = \frac{1}{2}\sum_{i=n}^{n}||\nabla C_i(p_i) - y_i||_2^2$$

Under Karush–Kuhn–Tucker (KKT) conditions, the characterizations of m_i-convex functions $C_i(p_i)$ and m-convex functions $C(p)$, and the derivative of V_3 along with (12a) and (12b) lead to

$$\dot{V}_3 = \sum_{i=1}^{n}(\nabla C_i(p_i) - y_i)(\nabla^2 C_i(p_i)\cdot\dot{p}_i - \dot{y}_i)$$

Let $\nabla C_i(p_i) - y_i = \nabla_{p_i}\mathscr{L}(p_i, y_i)$ where $\mathscr{L}(p_i, y_i)$ is a Lagrangian function. At the same time, $\alpha_{i,z} = \alpha_z$, $\gamma_{i,z} = \gamma_z$, $\mu_{i,1} = \mu_{i,3} = \mu_1$, $\nu_{i,1} = \nu_{i,3} = \nu_1$, $\forall i \in N$, $z = 0, 1, 2$.

$$\begin{aligned}
\dot{V}_3 \leq &-\nabla^2 C(p)\sum_{i=1}^{n}(\alpha_0|\nabla_{p_i}\mathscr{L}(p_i, y_i)| + \alpha_1||\nabla_{p_i}\mathscr{L}(p_i, y_i)||_{1+\mu_1}^{1+\mu_1} + \alpha_2||\nabla_{p_i}\mathscr{L}(p_i, y_i)||_{1+\nu_1}^{1+\nu_1}) \\
&+\frac{1}{m}\sum_{i=1}^{n}(\gamma_0|\nabla_{p_i}\mathscr{L}(p_i, y_i)| + \gamma_1||\nabla_{p_i}\mathscr{L}(p_i, y_i)||_{1+\mu_3}^{1+\mu_3} + \gamma_2||\nabla_{p_i}\mathscr{L}(p_i, y_i)||_{1+\nu_3}^{1+\nu_3})
\end{aligned}$$

$$\dot{V}_3 \leq -\kappa_1\left(\sum_{i=n}^{n}||\nabla C_i(p_i) - y_i||_2^2\right)^{\frac{1+\mu_1}{2}} - \kappa_2 n^{1-\frac{1+\nu_2}{2}}\left(\sum_{i=n}^{n}||\nabla C_i(p_i) - y_i||_2^2\right)^{\frac{1+\nu_1}{2}}$$

where $\kappa_1 = \alpha_1\nabla^2 C(p) - \frac{\gamma_1}{m}$, $\kappa_2 = \alpha_2\nabla^2 C(p) - \frac{\gamma_2}{m}$ and $\kappa_1, \kappa_2 > 0$. From Lemma 4, V_3 converges in the fixed-time T_3: $T_3 \leq \frac{2m}{(\alpha_1 m\nabla^2 C(p)-\gamma_1)(1-\mu_1)} + \frac{2m}{n^{\frac{1-\nu_2}{2}}(\alpha_2 m\nabla^2 C(p)-\gamma_2)(1-\nu_1)}$

Thus, the optimal solution $p_i^*, y_i^*, \forall i \in N$ for the EMP can be obtained in a fixed time T. It satisfies $t \leq T_1 + T_2 + T_3$. □

4. Polymorphic Network and Topology Construction for Port Microgrid

To ensure the information exchange between heterogeneous devices and the implementation of the proposed method, a configuration for distributed polymorphic energy management and a connected networking mechanism are proposed in this section.

4.1. Configuration for Distributed Polymorphic Energy Management

On account of the differences in the factory settings of renewable energy devices and traditional energy devices from different manufacturers, there may be multiple communication protocols. However, a single IP network cannot support multiple protocols at the same time. Therefore, it is vital to integrate the polymorphic network with the port microgrid. The configuration for distributed polymorphic energy management is shown in Figure 1. Heterogeneous devices in the port microgrid are mixed into the polymorphic network through heterogeneous network interfaces.

This configuration consists of a data layer, a control layer and a service layer on the network for the port microgrid. The main function of the data layer is receiving the information from devices in the port microgrid and updating the data according to the port period corresponding level as the foundation for the polymorphic network. It provides accurate data support for the distributed fixed-time energy management method. The control layer completes the information exchange between different devices based on polymorphic addressing and routing to accomplish port microgrid energy management. It is a specific representation so that heterogeneous devices can coexist and communicate in the same network. The service layer establishes the model of the port microgrid EMP based on the information from the data layer and determines the communication topology for the distributed energy management method. As a fitting computing platform for business requirements to service policies, the service layer has powerful processing and computing capabilities. To summarize, the effective energy management of port microgrids can be successfully achieved by leveraging the cooperative synergy among these layers. Nevertheless, the identification and implementation of an optimal communication topology in the control layer remain a crucial challenge that warrants thorough exploration. By addressing this issue, it significantly enhances the performance and effectiveness of port microgrids, ensuring efficient energy management.

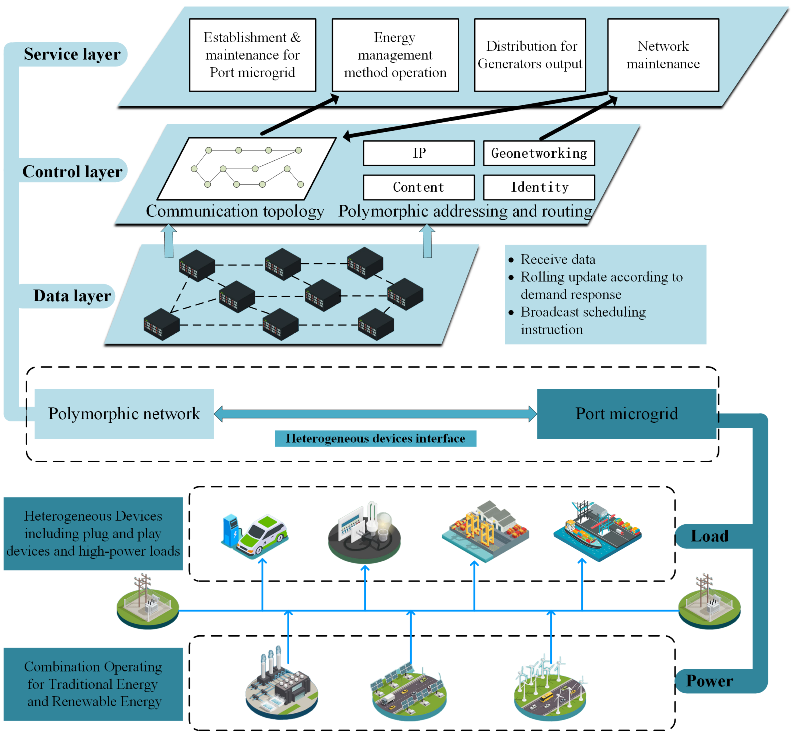

Figure 1. Polymorphic network for port microgrid energy management.

4.2. Connected Networking Mechanism

The configuration for distributed polymorphic energy management provides a computing platform for the port microgrid. To support information transmission with neighbors to complete energy management, a networking mechanism referring to the magnetic field intensity attenuation formula and Ampere theorem is proposed to improve the construction of the communication topology in the control layer. Based on the principle of a magnetic field, when multiple magnets that are the same exist at the same time, each magnet produces a magnetic field; meanwhile, the intensity of the magnetic field gradually decreases with remote distance. The magnetic field interaction between magnets with a closer distance is stronger and preferentially attracted. Therefore, this method can better estimate the interaction effect between objects characterized by distance.

Considering the communication efficiency between devices and the topological conditions of Assumption 2, a connected networking mechanism is designed based on information transmission distance e_{ij}, where this is distance between i and j. The main steps for the connected networking mechanism are shown in Algorithm 1. Firstly, multiple devices are pregrouped, and the devices with strong interaction are divided into the same group. This per-grouping strategy ensures that devices with close distances and strong interdependencies are aggregated within the same group, denoted as G_q. Next, in order to maintain the overall connectivity of the communication topology, the communication connection between groups is established based on the transmission distance in Step 2. To further minimize unnecessary communication connections and reduce transmission costs, the adding of any additional joining edges is refrained from between devices within the same group, namely G_q, G and $\mathscr{G}'$. This connected networking mechanism is effective in that it not only promotes strong intergroup interactions but also optimizes the overall transmission efficiency to enhance the performance of the port microgrid.

Algorithm 1 Connected Networking Mechanism based on Information Transmission Distance

Input:
The geographical location set of generators: $e = \{e_1, e_2, \ldots, e_n\}$, node distance set: $d = [e_{ij}], \forall i, j \in \mathcal{N}$, $\mathcal{N} = \{1 : n\}$, $G = \emptyset$, $\mathscr{G} = \emptyset$, $A = zeros(n)$, $q = 0, w = 0$.
Output: the adjacency matrix $A = [a_{ij}]$
STEP 1:
while $\mathcal{N}! = \emptyset$ **do**
  Search minimum distance e_{ij}, $i, j \in N$;
  if $i \notin G \& j \notin G$ **then**
    $q = q + 1$; create $G_q = \{i, j\}$; $a_{ji} = a_{ij} = 1$; $\mathcal{N} = \mathcal{N} / \{i, j\}$;
  end if
  $G = \{G, G_q\}$;
  if $i \in G || j \in G$ **then**
    Search $i || j \in G_{q'}$ where $q' \leq q$ and $G_{q'} \subseteq G$; update $G_{q'} = G_{q'} \cup \{i, j\}$; $a_{ji} = a_{ij} = 1$; $\mathcal{N} = \mathcal{N} / \{i, j\}$;
  end if
end while
return $A = [a_{ij}]$; $G = \{G_1, G_2, \ldots, G_q\}$;
STEP 2:
while $\mathscr{G}! = 1 : n$ **do**
  Search minimum distance e_{g_a, g_b}, where $g_a \in G_a$, $g_b \in G_b$ and $G_a, G_b \subseteq G$;
  if $\mathscr{G} = \emptyset$ **then**
    $\mathscr{G} = G_a \cup G_b$; $a_{g_a, g_b} = a_{g_b, g_a} = 1$; $G = G / \{G_a, G_b\}$;
  end if
  if $G_i || G_j \in \mathscr{G}$ **then**
    $\mathscr{G} = \mathscr{G} \cup G_a \cup G_b$; $a_{g_a, g_b} = a_{g_b, g_a} = 1$; $G = G / \{G_a, G_b\}$;
  end if
  if $G_a \& G_b \notin \mathscr{G}$ **then**
    $w = w + 1$; Create $\mathscr{G}_w = G_a \cup G_b$; $a_{g_a, g_b} = a_{g_b, g_a} = 1$;
  end if
end while
return $A = [a_{ij}]$;

5. Simulation

In this section, the availabilities of the distributed fixed-time energy management method (12a)–(12c) and the connected networking mechanism proposed in Section 4 are verified, respectively. We consider a port microgrid with 15 generators including DG, WT and PV in the square area of 12,000*12,000(m^2). The location information of the port microgrid is shown in Figure 2a. The parameters for each generator are shown in Table 1 subject to the demand generation constraint $l_i = 120, \forall i \in N$.

Table 1. The parameters of EMP for port microgrid.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\delta_{i,1}$	0.040	0.035	0.030	0.040	0.030	0.035	0.040	0.040	0.030	0.030	0.030	0.040	0.040	0.030	0.030
$\delta_{i,2}$	2.0	3.0	4.0	3.0	3.0	2.0	1.5	2.0	1.5	4.0	4.0	2.5	3.0	4.0	4.0
ϵ_i	261.27	206.35	301.32	264.36	284.82	346.21	362.15	412.30	283.46	362.12	196.25	254.60	175.85	265.21	213.25
P_{min}	0	0	0	0	0	20	0	0	0	20	0	0	15	0	0
P_{max}	150	150	200	160	200	200	150	140	200	150	200	200	200	130	200

5.1. CASE1: Communication Topology with 15 Nodes by Connected Networking Mechanism

In order for each node to exchange its information with the fewest nodes and so that the distances between them are the shortest, firstly, 15 nodes should be grouped. The result of the grouping is shown in Figure 2b, $G_1 = [1, 2, 6, 15]$, $G_2 = [7, 14]$, $G_3 = [8, 10]$, $G_4 = [3, 4, 5, 12]$ and $G_5 = [9, 11, 13]$. Next, the connectivity of the topology is determined by establishing communication between $[G_2, G_3]$, $[G_1, G_5]$, $[G_1, G_2 \cup G_3]$ and $[G_4, G_5]$, as is shown in Figure 2c. Finally, by analyzing a part of nodes (4, 6, 10, 11), it is determined that Node 3 should use Geonetworking and Nodes 2, 4, 10, 13 should use Geonetworking and IP. The others only use IP. This is shown in Figure 2d, and the total path is 26,740.31 m.

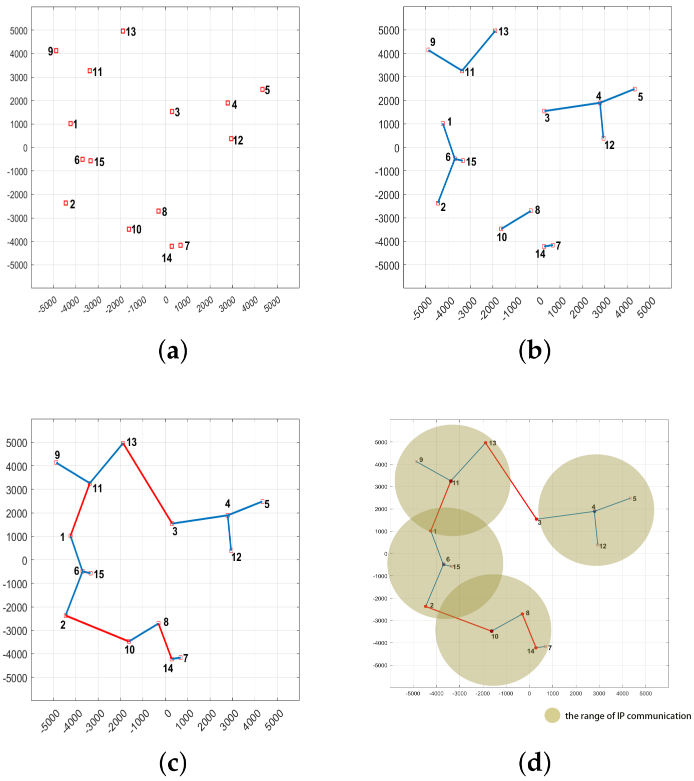

Figure 2. Confirmation of communication topology and communication protocol. (**a**) The location information of 15 nodes. (**b**) The grouping result of 15 nodes. (**c**) The communication topology of 15 nodes. (**d**) The communication range of Nodes 4, 6, 10, 11 used IP.

To verify that the connected topology with the shortest total path can be found by the connected networking mechanism, 40,000 connected topologies are randomly generated according to the node information of Figure 2c. By deleting the same case, the remaining 24,808 results are shown in Figure 3. In the non-repeated results, there is no connected topology lower than 26,740.31; therefore, the effectiveness of the mechanism can be proved.

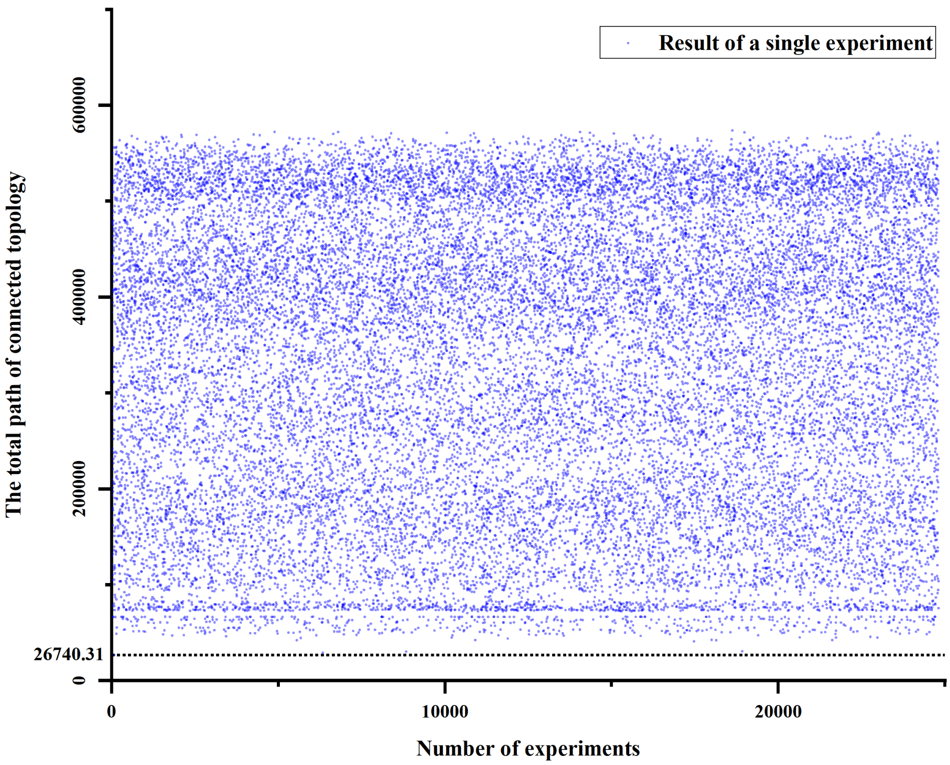

Figure 3. The total path for randomly generated connected topologies.

5.2. CASE2: Energy Management with 15 Nodes Based on Connected Networking Mechanism and Distributed Fixed-Time Energy Management Method

In this case, the effectiveness of the elucidated method is certified by considering the topology shown in Figure 2c. Firstly, the solution for the EMP is $p^* = [114.35, 116.40, 119.13, 101.85, 135.80, 130.69, 120.60, 114.35, 160.80, 119.13, 119.14, 108.10, 101.85, 119.13, 119.14]MW$, and the total cost for generation is USD 16,806.11 using the MATLAB fmincon function.

With $\alpha_i = [10, 10, 10]$, $\beta_i = [|\alpha\Theta_{i1}[-\nabla C_i(x_i) + y_i]|, 10, 10]$, $\gamma_i = [0.055, 0.055, 0.055]$, $\omega_i = [4 \cdot |\gamma\Theta_{i3}[\tau_i - x_i]|, 10, 10], \forall i \in N$ and $\mu_\tau = 0.5, \nu_\tau = 2, \tau = 1, 2, 3, 4$, the output power and incremental cost curves using algorithm (12a) and (12b) are shown in Figure 4a,e. At the second 3.5, the incremental costs for all generators converge to $y^* = 11.19$ and the optimal solutions for output power $p^* = [114.45, 116.60, 119.35, 102.07, 136.06, 130.88, 120.79, 114.54, 160.80, 116.61, 119.27, 108.34, 101.97, 119.38, 119.36]MW$, respectively. The total cost for generation is USD 16,806.32. Compared to the centralized algorithm, the total cost difference is USD 0.2094.

If the effect of the fixed-time control is not considered, then the formulation for (12c) is changed into $\Theta_{i,\tau}[u] = ku$. Moreover, p_i and y_i converge at non-finite time. The output power and incremental cost curves are shown in Figure 4b,f. The incremental costs approximately converge at 97 s, and at the same time, the optimal solution for the output powers is obtained.

If $\alpha_i = [10, 10, 0]$, $\beta_i = [|\alpha\Theta_{i1}[-\nabla C_i(x_i) + y_i]|, 10, 0]$, $\gamma_i = [0.055, 0.055, 0]$ and $\omega_i = [4 \cdot |\gamma\Theta_{i3}[\tau_i - x_i]|, 10, 0]$, then from Lemma 2, x_i and y_i converge at a finite time and the settling times are reflected in $V_i(x_0, y_0)$. In other words, the initial state for the system affects the settling time T. The output power and incremental cost curves are shown in Figure 4c,g. The incremental costs and output powers stabilize at about 25 s.

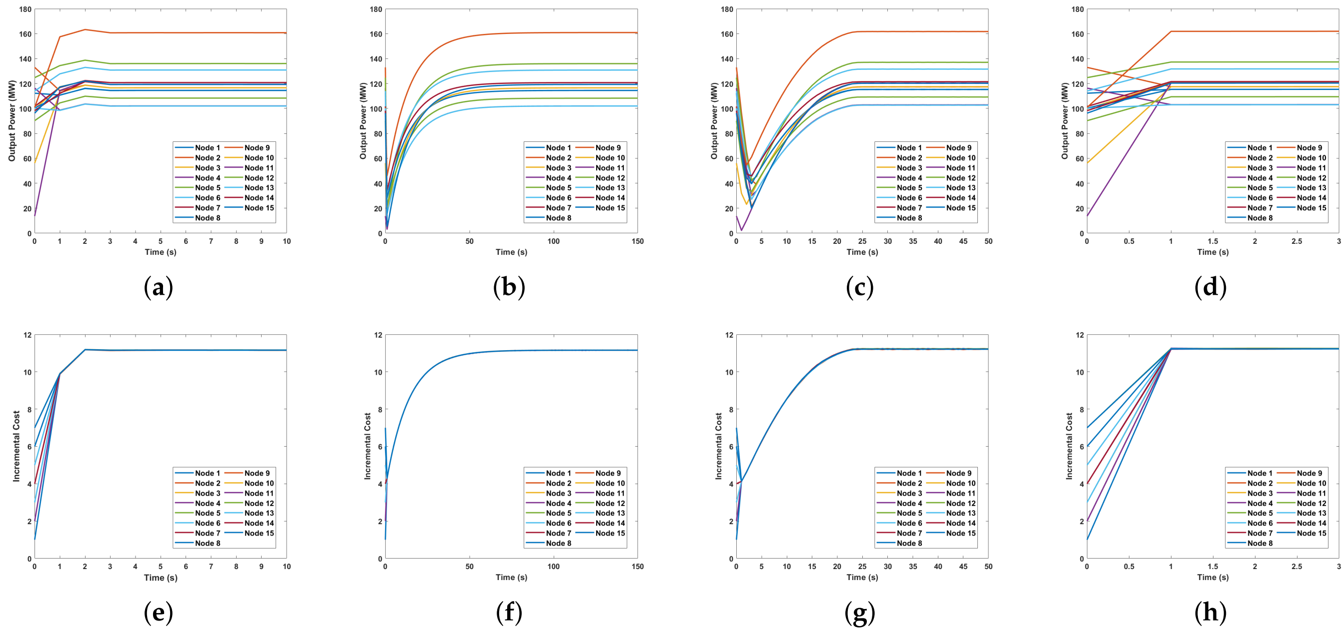

Figure 4. Output power and incremental cost curves of different methods. (**a**) Output power curves of fixed-time method. (**b**) Output power curves of non-finite-time method. (**c**) Output power curves of finite-time method. (**d**) Output power curves of prescribed-time method. (**e**) Incremental cost curves of fixed-time method. (**f**) Incremental cost curves of non-finite-time method. (**g**) Incremental cost curves of finite-time method. (**h**) Incremental cost curves of prescribed-time method.

If the fixed-time controller is replaced by a prescribed time controller, this is defined as $\Phi_{i,\tau}[u] = \left(f + h\frac{\dot{\Lambda}(t)}{\Lambda(t)}\right) \cdot (u) + \chi(v)$. $\Lambda(t)$ is the gain function and $\chi(v)$ is the steady component according to [46]. The settling time is defined as $T = 1$ for $\Lambda(t)$, and the variables x_i and y_i converge at 1 s. The output power and incremental cost curves are shown in Figure 4d,h. The time-varying gain of the controller converges towards infinity $\frac{\dot{\Lambda}(t)}{\Lambda(t)} \to \infty$ if t approaches the threshold for prescribed time $t \to t_0 + T$. To ensure that the control input is bounded, a positive number should be determined $0 < \iota \ll 1$. When $t \in [t_0, t_0 + T - \iota)$, $\Lambda(t) = \frac{T^p}{(T+t_0-t)^p}$, and $\Lambda(t) = 1$, then $t \in [t_0 + T - \iota, \infty)$. Moreover, variables p_i and y_i converge to a neighborhood of the optimal solution p_i^* and y_i^* within a prescribed time.

6. Conclusions

This paper extends a distributed fixed-time energy management method to solve the port microgrid EMP with a fast convergence rate. In order to realize the information exchange between devices, this paper constructs a distributed polymorphic energy management configuration for a port microgrid. In addition, a connected networking mechanism based on communication transmission distance is proposed to improve the transmissive efficiency. Simulation results demonstrate the effectiveness of the proposed algorithms. Compared to non-finite-time and finite-time methods, the convergence rate can be improved by 96.1% and 86.5%, respectively, for the EMP assumed in this paper. From the theoretical analysis, although the proposed fixed-time method cannot set the time freely, the control input is bounded and the optimal solution can be obtained in a fixed time.

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