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# Distributed Frequency Control Strategy for Islanded Microgrid with Consideration of Transmission Congestion

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***Abstract***

*To guarantee the security and stability of islanded microgrid, transmission congestion problem is considered during the frequency control so as to efficiently make use of power available without violating system constraints. A novel strategy was proposed, which combines distributed frequency control and congestion management and makes the distributive frequency control reasonable at the request of line congestion. It effectively solve multi-objective problem with multi-linear equality and inequality constraints. To testify the proposed strategy, an islanded microgrid with five-machines is provided in Matlab/Simulink. The results demonstrate that fast frequency regulation and effective settlement of transmission congestion are obtained by this approach.*

***Keywords***: *Distributed frequency control, transmission congestion, islanded microgrid*

## 1. Introduction

Microgrid is composed of various on-site distributed generators (DGs), electrical and thermal loads, and energy storages. This localized power network improves the penetration ratio of green energy and energy efficiency on account of not incurring transmission losses [1]. It not only operates connected to and synchronous with the external power grid, but also can disconnect and work autonomously in islanded mode. It is much easier for frequency control in grid-connected mode due to the frequency can be dictated by the main grid. However, in islanded mode, frequency regulation becomes vital to microgrid operation safely and stably, which reflects an independent power balance between generation and consumption. Because frequency has a close relationship with secure and stable operation of hugeness consumers' electrical equipment and power generation and supply, the research on frequency regulation in islanded microgrid is of great importance.

Two control configurations are mainly adopted for microgrid, master-slave structure and peer to peer structure, corresponding to centralized control methods and distributed control methods. The master-slave structure means a centralized management, which is performed from a central controller located at the global control level [2]. The main disadvantages of this structure are: 1. when a high amount of devices are connected at dispersed locations and their owners do not share the same interests, centralized control strategies become quite difficult [3]; 2. Once the centralized controller breaks down, the whole system will face the risk of system paralyses. It reduces the system flexibility. To solve the above problems, large amount of distributed control strategies have been presented for peer to peer structure. In [4], the frequency regulation problem of islanded microgrid is converted into the synchronization problem of phase-coupled Kuramoto oscillators. Based on the new perspective, a distributed integral controller based on averaging algorithms was proposed, which dynamically regulates the system frequency in

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the presence of a time-varying load. [5] designs a fully distributed secondary control strategy so that each distributed generator only requires its own information and the information of some neighbors. [6] puts forward distributed controllers based on neural networks. The distributed controllers are made adaptive and independent of the DG parameters and the connector specifications. [7] realizes a distributed control method based on the multi-agent technology. And optimization algorithm is utilized for lowering multi-agent coordination errors.

Controlling frequency in islanded microgrid by distributed control method can be characterized as a consensus problem via distributed control strategies. It is common to be solved by distributed linear-iterative algorithm [8, 9]. Profiting from distributed iteration, the outputs of every node will converge to a value that lies within an interval defined by upper and lower node-capacity limits; meanwhile, the sum of the values is equal to the amount of resources requested by the aggregator. Specifically, let $x_i[k]$ be the amount of resource requested from node at the $k$ times of information exchange between nodes, and satisfy $\lim_{k\to\infty} x_i[k] = x_{ista}$, where $i$=1, 2, 3…, $n$ is the number of nodes and $x_{ista}$ represents the steady-state value of the node $i$. The objective function will be $\sum_{i=1}^{n} x_{ista} = M_d \quad (i = 1, 2, ...n)$ and the constraint condition is: $x_{i\min} \le x_{ista} \le x_{i\max}$, where $x_{i\max}$ and $x_{i\min}$ are the maximum value and the minimum value of the output capability for node $i$. $M_d$ is the total amount of resource requested, which satisfies $\sum_{i=1}^{n} x_{i\min} \le M_d \le \sum_{i=1}^{n} x_{i\max}$. This algorithm possesses advantages as follows: 1. It is more economical on account of not requiring communication between a centralized controller and the various devices; 2. No complete knowledge of the distributed resources available is needed; 3. It is more resilient to faults and to unpredictable behavioral patterns of the distributed resources [10]. The balance between the distributed energies and the demand responses is achieved by a ratio-consensus algorithm whose dynamic weights have promoted the iterative speed in [11]. A distributed direct load control scheme for large-scale residential demand response is proposed in [12], via the average consensus algorithm to distribute portions of the desired aggregated demand to each EMC in a decentralized fashion. [13] presents a solution to economic dispatch problem based on a consensus-like iterative method. Its result shows that the iterative solution converges to the globally optimal solution under strong connectivity conditions and allowance for local communications. [14] studies the frequency regulation control in an islanded AC microgrid by linear-iterative distributed algorithm that is a completely distributed generation control. All these above consensus algorithms just require that the sum of output is equal to the total demand and output capability of every node meets its limited range. However, when every node needs to satisfy multi-group equality relations and complex equality and inequality constraints with other nodes, existing consensus algorithms are no longer applicable. Particularly for complex system as microgrid, among each node (generator unit, storage, load and etc.), there always exists complex equality and inequality constraints, and multi-objective. Therefore, making the consensus algorithm meet the prerequisites of multi-constraint and multi-objective is urgent and meaningful.

The main contributions of this paper are: 1. a new consensus algorithm, which is of generality, is proposed for solving multi-constraint and multi-objective problem; 2. we apply this extensional consensus algorithm to the frequency regulation of islanded microgrid with consideration of the transmission congestion. And the flow of transmission line is limited within safe range; 3. based on the new consensus algorithm, a distributed frequency regulation controller in view of the security margin is designed. The effectiveness of control effect is testified through a practical example.

 

The remainder of this paper is organized as follows. Section 2 provides some preliminaries including the graph theory model and overview of the conventional consensus algorithms. Moreover, some introductions of frequency regulation strategies are provided based on the existing consensus algorithm. Section 3 details the solution algorithm to the multi-constraint and multi-objective problem. Section 4 applies the designed method to transmission system congestion management, and realizes the frequency regulation for islanded microgrid considering transmission congestion. In Section 5, the operation of our proposed algorithm is illustrated by an example. Finally, some concluding remarks are provided in Section 6.

## 2. Preliminaries

In this subsection, some useful notations about graph theory are introduced firstly. Next, we provide a short overview of distributed linear-iterative algorithm for consensus problem. By extension of the algorithm, an application to distributed frequency regulation is shown.

### 2.1. Graph theoretic model

The communication between nodes where distributed resources are located can be described by a directed graph $G=\{v,\varepsilon\}$, where $v:=\{v_1,v_2,...v_n\}$ is the vertex set, with each vertex corresponding to a node; and where $\varepsilon \subseteq v\times v$ is the edge set, if node *i* can receive information from node *j*, the ordered pair $(v_i,v_j)\in\varepsilon$. Particularly, if node *i* has self-loop, then $(v_i,v_i)\in\varepsilon$. We define the set of vertices from which the node *i* can receive information to be $N_i^- :=\{v_j\in v:(v_i,v_j)\in\varepsilon\}$ and the number of neighbors of *i* is called the in-degree of *i*. Similarly, we define the set of vertices to which the node *i* can send information to be $N_i^+=\{v_i\in v:(v_j,v_i)\in\varepsilon\}$ and the number of nodes that have *i* as neighbor is called the out-degree of *i*. $N_i^-$ and $N_i^+$ are the in- and out-neighborhood of node *i*, respectively.

### 2.2. Overview of Consensus Algorithm

Traditional consensus algorithm is a kind of linear iterative algorithm based on the information of node status and interaction between each two adjacent nodes [10-14], which meets the coupling relationship:

$$x_i[k+1]=p_{ii}[k]x_i[k]+\sum_{j\in N_i^-}p_{ij}[k]x_j[k] \tag{1}$$

where both $p_{ii}$ and $p_{ij}$ indicate weight. It can be a constant or a variable, which satisfies $\sum_{i=1}^{n}p_{ij}[k]=1$. $k$ stands for the number of iterations, and $N_i^-$ represents the input neighborhood of node $v_i$. The state of $v_i$ can be denoted by the previous moment state of the current node and adjacent node. The iterative algorithm with fixed weight value can be described by the iterative equation of two state variables:

$$y_i[k+1]=\sum_{v_j\in N_i^-}\frac{1}{D_j^+}y_i[k] \tag{2}$$

$$z_i[k+1]=\sum_{v_j\in N_i^-}\frac{1}{D_j^+}z_j[k] \tag{3}$$

where both $y_i$ and $z_{\text{i}}$ indicate two internal iteration state of node $v_i$. $D_j^+$ indicates the out-degree of node $j$. And $\forall k$, $z_i[k] \neq 0$.

$$R_i[k] = \frac{y_i[k]}{z_i[k]} \tag{4}$$

After several iterations, $R_i[k]$ will be stable at a constant, namely $\lim_{k\to\infty} R_i[k] = \psi$, where $\psi$ is a proportional coefficient as shown in Lemma1.

***Lemma1:*** Set $y_i[0]$ is the initial state of $y_i[k]$ which is the state variable of node $v_i$, and $z_i[0]$ is the initial state of $z_i[k]$, where $z_i[k] \neq 0$. Then,

$$\begin{aligned}\lim_{k\to\infty} R_i[k] &= \lim_{k\to\infty} \frac{y_i[k]}{z_i[k]} \\ &= \frac{\sum_{v_j \in N_i^-} \frac{1}{D_j^+} y_j[k-1]}{\sum_{v_j \in N_i^-} \frac{1}{D_j^+} z_j[k-1]} \\ &= \frac{\sum_{j=1}^{n} y_j[0]}{\sum_{j=1}^{n} z_j[0]}\end{aligned} \tag{5}$$

The Perron-Frobenius theorem is applied in the above process, which is elaborated in [10-11]. The output of each node is:

$$x_i[k+1] = x_{i\min} + R_i[k] \times (x_{i\max} - x_{i\min}) \quad \text{i=1, 2…, n} \tag{6}$$

From Eq. (6), the output of each node must satisfy its upper and lower limit constraints. Therefore by designing the value of $\psi$, the sum of each node steady-state output can be equal to the demand. By using the inverse derivation method, we can obtain:

$$\psi = \frac{M_d - \sum_{i=1}^{n} x_{i\min}}{\sum_{i=1}^{n} (x_{i\max} - x_{i\min})} \tag{7}$$

From the value of $\psi$:

$$y_i[0] = x_i - x_{i\min} \quad z_i[0] = x_{i\max} - x_{i\min} \tag{8}$$

Through the distributed dynamic adjustment, the algorithm can maintain the balance between node input and demand quantity, at the same time satisfies upper and lower constraints.

### 2.3. Application to Distributed Frequency Regulation

The first aim of frequency regulation is to rapidly achieve the balance between supplies and consumers, and the second one is to eliminate the frequency deviation.

When the frequency deviation exceeds the allowed periphery, as showed in Fig.1, the properties of power frequency generator set suggests that the relationship between the power deviation and the frequency deviation of generating set is:

$$\Delta P_i^r = K_i (f^r - f_{ref}) \tag{9}$$

 

where $f_r$ is the practical frequency of r times iteration, $f_{ref}$ is the frequency reference, and $K_i$ is the power frequency characteristic coefficient of generating set *i*.

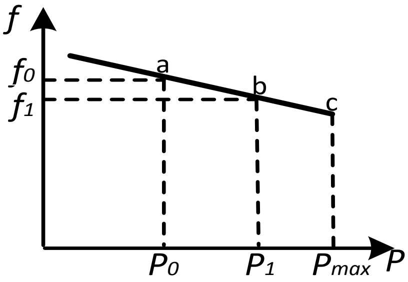


**Figure 1. Power Frequency Characteristics of Generator Set**

Set $\Delta P_{i\max}^{r} = P_{i\max} - P_{iref}^{r}$ , $\Delta P_{i\min}^{r} = P_{i\min} - P_{iref}^{r}$ (10)

where, $P_{i\max}$ and $P_{i\min}$ respectively indicates the maximum and minimum output ability of generating set *i*, $P_{iref}^{r}$ indicates the frequency reference of r times iteration, and $\Delta P_{i\max}^{r}$ and $\Delta P_{i\min}^{r}$ indicates the maximum and minimum power deviation of r times iteration, respectively. Then, the initial values of state variables $y_i$ and $z_i$ are set as:

$y_i[0] = \Delta P_i^r - \Delta P_{i\min}^{r}$ , $z_i[0] = \Delta P_{i\max}^{r} - \Delta P_{i\min}^{r}$ (11)

Then the proportionality coefficient is:

$$\psi^r = \lim_{k\to\infty} R_i^r[k] = \lim_{k\to\infty} \frac{y_i^r[k]}{z_i^r[k]}$$
$$= \frac{\sum_{j=1}^{n} K_i(f^r - f_{ref}) - \sum_{j=1}^{n} \Delta P_{j\min}^{r}}{\sum_{j=1}^{n} (\Delta P_{j\max}^{r} - \Delta P_{j\min}^{r})} \quad (12)$$

The dynamic deviation of power reference is:

$$\Delta P_{iref}^{r} = \Delta P_{i\min}^{r} + \psi^r (\Delta P_{i\max}^{r} - \Delta P_{i\min}^{r}) \quad (13)$$

The frequency reference of *r*+1 times iteration is:

$$P_{iref}^{r+1} = P_{iref}^{r} + \Delta P_{iref}^{r} \quad (14)$$

It can be seen that the power reference of generating set now dynamically follows the frequency. By using distributed control for the generator *i*, the balance of generator output and demands can be maintained according to the power reference; and by using coordination control among generating sets, the frequency deviation can be eliminated.

## 3. Algorithm based on Multi-objective

As shown in Section 2.2, conventional consensus algorithms only consider the simple upper and lower constraints and only achieve single objective. However, in practical application, complex constraints should be taken into consideration and multi-objective are also required to be achieved. Eq. (15) shows the objective functions and constraint conditions.

object to $\begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1n} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \alpha_{m1} & \alpha_{m2} & \cdots & \alpha_{mn} \end{bmatrix} \begin{bmatrix} x_{1sta} \\ x_{2sta} \\ \vdots \\ x_{nsta} \end{bmatrix} = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{bmatrix}$

subject to $x_{i\min} \le x_{ista} \le x_{i\max}$

$$\begin{bmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1n} \\ \beta_{21} & \beta_{22} & \cdots & \beta_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \beta_{p1} & \beta_{p2} & \cdots & \beta_{pn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_p \end{bmatrix}$$

$$\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_q \end{bmatrix} \le \begin{bmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1n} \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \gamma_{q1} & \gamma_{q2} & \cdots & \gamma_{qn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \le \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_q \end{bmatrix} \tag{15}$$

where $x_{ista}$ is the steady-state value of the node $v_i$; $\alpha$, $\beta$ and $\gamma$ represents the corresponding coefficients of nodes in objective function respectively; *m*, *p* and *q* represents numbers of equations in objective function, equality bounds and equality constraints, respectively; *A*, *B*, *a* and *b* are all constants. The multi-constraint and multi-objective problems widely exist in the practical projects. For example, transmission congestion problem is a multi-objective problem, and optimal power flow problem is a multi-constraint problem containing a lot of equality and inequality constraints. A general solution is designed as followed towards this kind of problem:

1) Convert inequality constraints to equality constraints. Conversion method is as followed:

For inequality: $a_j \le \gamma_{j1}x_1 + \gamma_{j2}x_2 + \ldots \gamma_{jn}x_n \le b_j$ (16)

Set $\gamma_{j1}x_1 + \gamma_{j2}x_2 + \ldots \gamma_{jn}x_n = x_{n+j}$, then $a_j \le x_{n+j} \le b_j$ In particular, $j$=*1, 2..., q*.

2) Construct the new multi-objective function. Combine the equality constraints, which include converted part from inequality constraints of each node, with original multi-objective function to construct a new objective function. The new objective function after construction will be:

$$\begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1n} & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_{m1} & \alpha_{m2} & \cdots & \alpha_{mn} & 0 & 0 & \cdots & 0 \\ \beta_{11} & \beta_{12} & \cdots & \beta_{1n} & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \beta_{p1} & \beta_{p2} & \cdots & \beta_{pn} & 0 & 0 & \cdots & 0 \\ \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1n} & -1 & 0 & \cdots & 0 \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2n} & 0 & -1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \gamma_{q1} & \gamma_{q2} & \cdots & \gamma_{qn} & 0 & 0 & \cdots & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ \vdots \\ x_n \\ x_{n+1} \\ x_{n+2} \\ \vdots \\ x_{n+q} \end{bmatrix} = \begin{bmatrix} A_1 \\ \vdots \\ A_m \\ B_1 \\ \vdots \\ B_p \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{17}$$

After an elementary transformation of matrix, the existence of solution can be judged by matrix rank. If there is a solution, determine the independent and the free unknown variables. Assume the independent unknown variables are $x_1 \to x_r$, and then the corresponding free unknown variables are $x_{r+1} \to x_{n+q}$. The relations between the independent and the free unknown variables are:

$$c_1x_1 + c_2x_2 + \ldots c_rx_r = M + c_{r+1}x_{r+1} + c_{r+2}x_{r+1} \ldots c_{n+q}x_{n+q} \tag{18}$$

where $M$ is a constant. All the free unknown variables can be expressed by the independent unknown variables. Therefore, if a solution exists, and the independent unknown variables meet the equality and inequality requirements, so that the free unknown variables satisfied constraint condition can be solved.

3) According to the new constructed objective function, establish equalities which contain all the independent unknown variables:

$$k_1x_1 + k_2x_2 + \ldots k_rx_r = D \tag{19}$$

where $k_i$ ($i=1, 2 \ldots R$), are all constants not equals to 0, and $D$ is also a constant.

4) Based on Eq. (19) and the upper and lower constraints ($x_{i\min} \le x_i \le x_{i\max}$ $i=1, 2, \ldots r$), through the consensus algorithm above, independent unknown variables which meet equality and inequality constraints can be obtained. Substitute the independent unknown variables into Eq. (18), the free unknown variables which meet requirements can be obtained.

The whole algorithm flow diagram is shown in Fig.2, which is suitable for multi-objective multi-constraint problem.

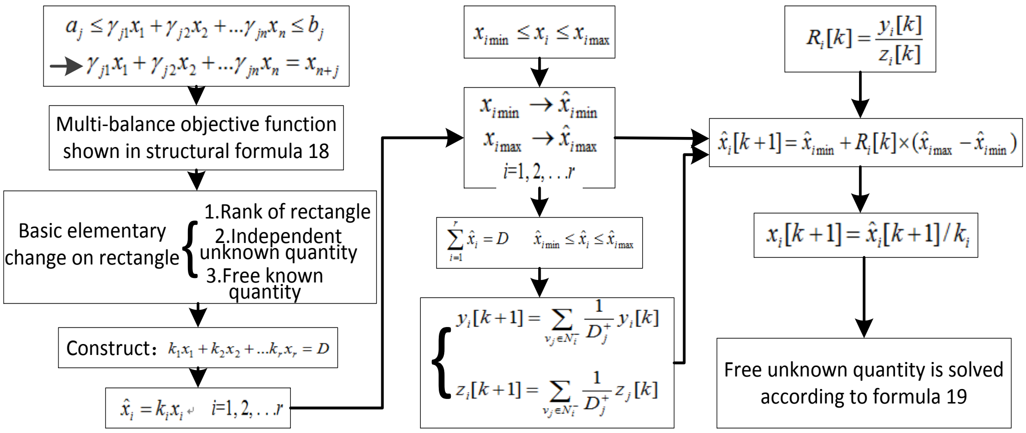


**Figure 3. Block Diagram of Algorithm**

Compared with the conventional algorithm, this improved one has advantages of rapid iterative convergence as original consensus algorithms and enabling to solve more complex equality and inequality constraints and multi-objective problem that can be extended to wide application field.

## 4. Application of Novel Consensus Algorithm in Frequency Regulation

### 4.1. Transmission Congestion Problem

The security is important factor which should be considered in Microgrid operation, and the transmission congestion is the core problem to affect the Microgrid operation security and stability. Many factors can cause transmission congestion including the heat limited capacity of the transmission line and stability of the system. When energy is delivered through transmission line, the Kirchhoff law and physical constraints should be satisfied, meanwhile the transmission congestion is a threat to system security and stability, as a result, transactions between suppliers and consumers is blocked and also the optimization relocation and utilization of resources are affected. Due to most of distributed generation units in Microgrid are renewable energy sources, the unpredictability and high fluctuation of intermittent energy increase the emergence odds of transmission congestion. Thus, research on congestion management is significant.

### 4.2. Application of Novel Consensus Algorithm

Transmission congestion problem is equivalent to multi-objective problem. The power delivered should satisfy the upper-lower limit capacity of transmission line. Meanwhile, when in equilibrium state, Kirchhoff law should be obeyed which requires the inflow and outflow of transmission power should be equal. The transmission congestion problem can be solved by the novel consensus algorithm demonstrated above.

Fig.2 shows the 6−node network. Each node corresponds to generating and load units of practical microgrid, maximum and minimum transmission capacity constraints exits among nodes, also power flow of each node should meet Kirchhoff law.

Making conversion between nodes and sides, the original 6−node network could be converted to 9−node network instead, which is illustrated in Fig.3, in which each node corresponds to transmission line, meanwhile coupling relations from node to node meets the Kirchhoff law, as showed in the Eq. (21) that is rewritten as $AX = D_{em}$.

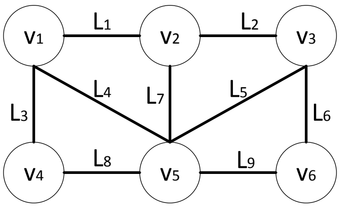


**Figure 3. Six−Node Network**

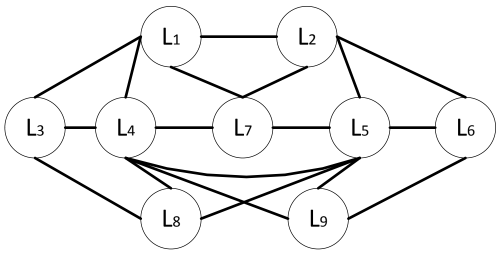


**Figure 4. Nine-Node Network**

A is incidence matrix, $D_{em}$ is constant matrix related to load demand and $\boldsymbol{X}$ = $\{x_1, x_2 ..., x_9\}$ is the transmission capacity of each line, which meets $x_{i\min} \le x_i \le x_{i\max}$.

$$\begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \end{bmatrix} = \begin{bmatrix} D_{em1} \\ D_{em2} \\ D_{em3} \\ D_{em4} \\ D_{em5} \\ D_{em6} \end{bmatrix} \tag{20}$$

Due to line congestion problem is merely multi-objective problem considering upper and lower constraints of transmission line, the conversion between equality bound and inequality constraints is not necessary. The free and independent unknown variables which indicate transmission capacity can be solved by the algorithm flow illustrated in Fig.2.

 

### 4.3. Design of Frequency Regulation Controller Considering Line Congestion

Fig.3 shows construction scheme of designed frequency regulation controller, in which the fore-end is responsible for frequency regulation control of Microgrid to rebalance the power flow between supplies and consumers, and the frequency deviation can be eliminated by coordination control among distributed generating units, meanwhile the rear-end is responsible for transmission management, the power reference of transmission line can be obtained by distributed linear iteration on the basis of the output power from fore-end frequency regulation controller and self-constraints of transmission line. The transmission power of all lines satisfies Kirchhoff law.

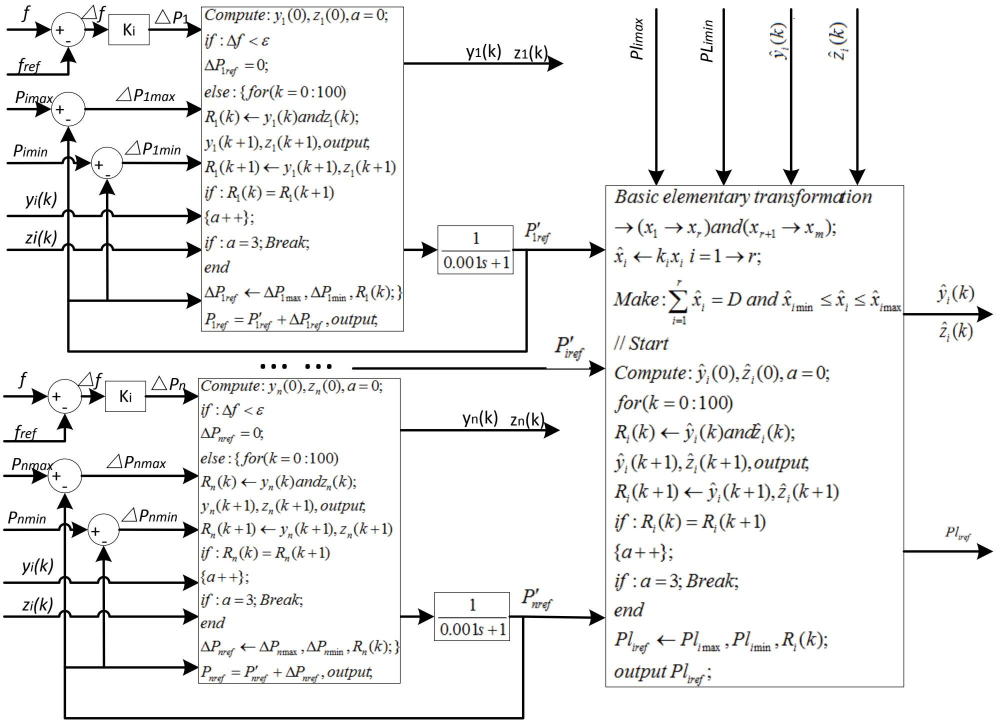


**Figure 5. The Scheme of Frequency Regulation Controller**

## 5. Analysis of examples

### 5.1. Introduction of models

To verify the algorithms and performances of designed controller, the conventional 5-nodes system is used to the simulation showed in Fig. 4. The system is divided into 5 areas: the generation unit and load unit are included in area 1, 2 and 3, while area 4 and 5 are simple load units. The maximum power flow constraints exit in the lines between nodes and the detailed parameters are demonstrated in table 1 and table 2. Fig. 5 shows the relevant graph theory model, where the direction of arrow is the specified forward direction of power flow, and the line parameters are the maximum flow constraints.

 

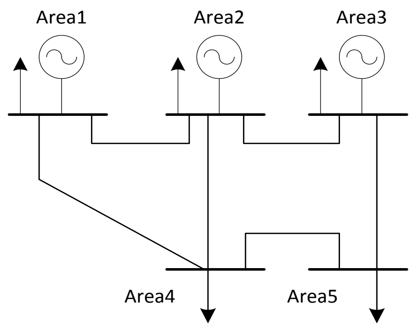


Figure 6. Node System

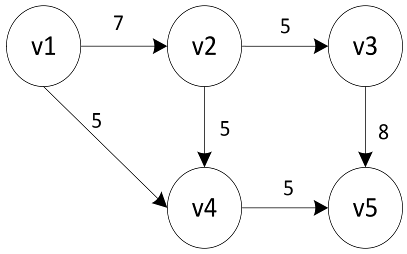


Figure 7. Graph Theory Model

**Table 1. Area Parameters**

| Area | Area1 | Area2 | Area3 | Area4 | Area5 |
|---|---|---|---|---|---|
| $P_{Gmax}$(MW) | 15 | 10 | 18 | 0 | 0 |
| $P_{Load}$ (MW) | 5 | 10 | 10 | 5 | 5 |

**Table 2. Transmission Line Parameters**

| Line | L12 | L23 | L14 | L24 | L35 | L45 |
|---|---|---|---|---|---|---|
| PL(MW) | 5.5 | 2.5 | 5 | 5 | 7 | 4 |

### 5.2. Simulation Result and Analysis

Modeling in MATLAB Simulink and unifying the transmission flow of UPFC control lines, in the initial state, the total load demand of system is 35MW, the output power of generators in area 1, 2 and 3 is respectively 14MW, 8MW and 13MW, which is showed in Fig.6. When 5MW load is merged into area 5, the system turns into unbalanced condition and after the 7 times iterations in controller, it gets back to balanced condition, and the output power of generators in area 1, 2 and 3 is respectively 13.95MW, 9.3MW and 16.75MW. The simulation result demonstrates this method has the capabilities of quick adjustment and equilibrium between generation and load demand, and has improved frequency regulation control performance. As shown in [14], the frequency performance of the algorithm is discussed. This paper mainly verifies the solving ability of improved algorithm and controller when facing line congestion.

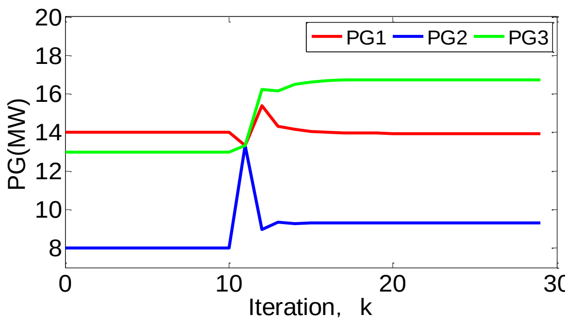


Figure 6. Rebalance When Demands Change

The transmission powers flow of each line when not using control algorithm in initial state are showed in Fig.7. From this figure, under non-control state, the power flows from area1 to area2 and area4 are 5.7MW and 3.3MW, also area2 deliver 3MW and 0.7MW of power relevantly to area3 and area4. Meanwhile, area3 transfers 6MW of power to area5 and area5 also transfers 1MW to area4. Moreover, the transmission power exceeds the maximum traffic capacities of the line between node1 and node2, the same situation also occurs between node1 and node2.

Fig.8 shows the simulation results of line transmission power under initial condition when using designed control algorithm and controller. As shown, area1 transfers 5.33MW and 3.67MW relevantly to area2 and area4, and area2 transfers 0.56MW and 2.77MW to area3 and area4. At the same time, area3 transfers 3.56MW of power to area5 and area4 transfers 1.44MW to area5. The flow in each line meets Kirchhoff law and compared to the Fig.7, the flows are in allowable range, validating the effectiveness of algorithm and controller designed.

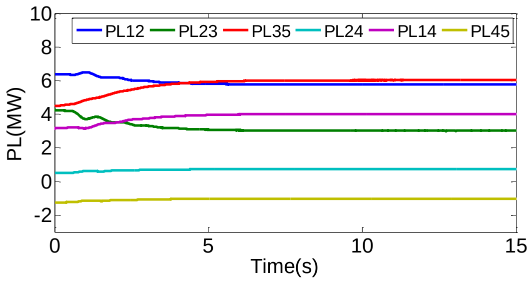


**Figure 7. Power flow without congestion management**

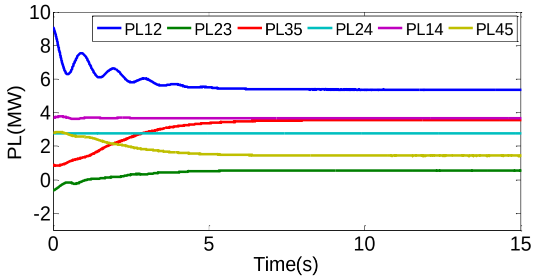


**Figure 8. Power flow with designed algorithm**

The power flow in transmission lines after 5MW load is merged into area 5 are demonstrated in Fig.9. The output power of generators in area1, 2 and 3 is respectively 13.95MW, 9.3MW and 16.75MW. Area1 transfers 4.6MW and 4.35MW relevantly to area2 and area4, and area2 delivers 3.95MW to area4. Area3 transfers 0.05MW and 6.7MW of power relevantly to area2 and area5, and area4 delivers 3.33MW to area5. Compared to Fig.8, the transmission line power flow between nodes 3-5 and the power flow between nodes 4-5 both increase significantly to meet load demand of area5. The result shows that after the demand of system changes, this algorithm also has improved capability of solving line congestion.

As showed in Fig. 10, the maximum transmission capacities of line between node 1 and 2 changes from 5.5MW and 4MW. Area 1 transfers 4MW and 5MW relevantly to area 2 and area 4, and area 2 delivers 2.33MW to area 4. Area 3 transfers 0.33MW and 2.67MW of power relevantly to area 2 and area 5, and area 4 delivers 2.33MW to area 5. Moreover, compare to Fig. 8, the transmission capacity between node 1 and 2 decreases, while between node1 and 4 it increases for meeting the constraint condition between node 1 and 2. The result shows that this algorithm can solve line congestion effectively after the change of maximum allowable line transmission capacity.

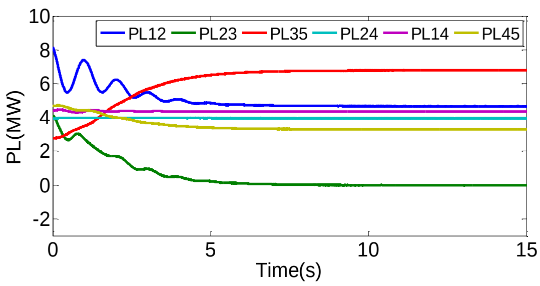


**Figure 9. Power flow without congestion management when Load Changes**

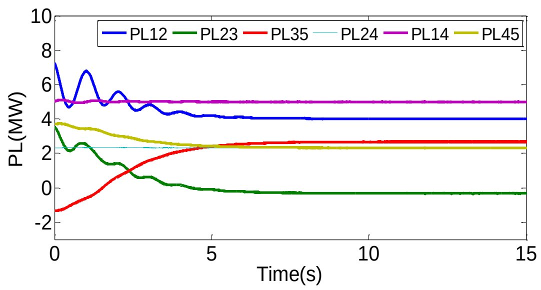


**Figure 10. Power flow with designed algorithm when Max-capacity Changes**

## 6. Conclusion

1) A novel algorithm based on conventional consensus algorithm to solve complex multi-linear equality and inequality constraints and multi-objective problem has been designed in this paper. New target function is constructed from the conversion between equality and inequality constraints, and the solution of target function can be obtained by linear iteration. The designed algorithm has generality to such kind of problems.

2) The designed algorithm is applied to transmission congestion problem which considers flow constraints with satisfying Kirchhoff law. A distributed frequency regulation controller considering transmission congestion has been designed through algorithm analysis.

3) Classical 5 node analysis model is applied in the simulation to verify control effect. And simulation results, which indicate that by using the designed algorithm, power flow between generator and load can be balanced rapidly, transmission congestion especially when overall demand or transmission maximum flow changes can be solved effectively.

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