# HIERARCHICAL CONTROL STRATEGY FOR UNBALANCED VOLTAGE IN AN ISLANDED MICROGRID

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*When the microgrid is running in an islanded mode, unbalanced loads result in microgrid voltage unbalance. The voltage unbalance factor at the Point of Common Coupling (PCC) is a key parameter in measurement of microgrid power quality. To improve microgrid power quality, many documents utilize micro-source voltage measurement results to help adjust the unbalance factor of microgrid voltage. However, due to line impedance presence, there are differences between micro-source output voltage and PCC voltage. Therefore, it is impossible for a micro-source to control the unbalance factor of PCC voltage with high precision by measuring its own output voltage. Based on equivalent circuit, the present paper analyzes the negative sequence component relationship among micro-source output voltage, line impedance voltage drop, and PCC voltage. It further proposes a hierarchical-control-based method to control the unbalance factor of PCC voltage with high accuracy, and analyzes the impact of secondary control delay on system stability by root locus calculating. Finally, the control strategy is validated in an islanded microgrid system with two micro-sources. The experimental results show the effectiveness and feasibility of the proposed control strategy.* References 8, figures 7.

***Key words:*** microgrid, hierarchical control, islanded mode, voltage unbalance, line impedance.

**Introduction.** To integrate advantages of distributed energy to the greatest extent and reduce various negative impacts brought by distributed generation (DG), the term “microgrid” is proposed [6]. The microgrid is one distribution network comprising various distributed generators (or micro-sources) and loads, and can either interconnect to the main distribution grid as a controllable unit or operate independently when isolated from the power grid. By substituting DG into the power grid in the microgrid, not only is the utilization rate of distributed power improved, but the power supply reliability of important loads is guaranteed effectively [8].

With the development of DG technology, microgrid capacity continues to increase, which helps to orient multi micro-source grid connection in parallel and multi microgrid coordinated operation as important developments of the microgrid. Microgrids with multi micro-source grid connection can be divided into three control methods, namely master-slave control, peer to peer control and hierarchical control [1,2]. In a master-slave approach, the main power provides supports for microgrid voltage and frequency in islanded modes. Thus, there emerge disadvantages such as robust dependence on main power source, small redundancy and low reliability, all of which confine the application of this approach [8]. A lack of unified adjustments of voltage and frequency in the peer to peer control method allows a possible phenomenon of which the microgrid voltage and frequency may exceed the operation range if they fluctuate acutely. Thus, this method can only implement primary control over the microgrid and fails to provide qualified voltage and frequency for loads [1]. The hierarchical control method mirrors a control thought in power system by adding central controller units in the microgrid system. Such units can not only respond to commands from upper-level adjustments but perform coordinated management between low-level micro-sources and loads. When voltage and frequency of the microgrid exceed the operation range, such units will guarantee the implementation of a control method in the microgrid system just as similar as adjustments of secondary voltage and frequency in the power system. The adoption of this method guarantees a safe and stable operation of the microgrid system and that microgrid voltage and frequency will stay within the operation range. Since hierarchical control performs an overall optimized control over the microgrid system, it has become a main research concern in recent years[2].

In islanded microgrid system, the unbalance factor of PCC voltage is a key parameter of power quality [7]. In order to improve the power quality of islanded microgrid, document [5] proposes a virtual-impedance-based control strategy to improve PCC power quality. This strategy allows a flexible control over PCC power quality under the working status of nonlinear load. Document [4] proposes a microgrid control

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strategy based on proportional-resonant controllers. This strategy utilizes the magnitude of harmonic currents to adjust corresponding resonant controller parameters of various harmonics, and then successfully control the current and voltage harmonics of microgrid. Despite effective improvement of microgrid power quality, this strategy utilizes more proportional-resonant controllers, which adds computational complexity.

This paper begins with the equivalent circuit; discusses the negative sequence voltage relationship of micro-sources, line impedances, and PCC; and analyzes the impact of line impedance negative sequence voltage drop on unbalanced voltage at PCC. Based on the above work, the paper proposes a hierarchical-control-based control method over unbalanced voltage at PCC, and discusses the impact of secondary control delay on system stability.

**The impact of line impedance of PCC voltage unbalance factor.** The microgrid of multi micro-sources network with concentrated load is shown as Fig. 1, where $L_1$ is the filter inductance of micro-source 1, $C_1$ is the filter capacitance of micro-source 1, $L_{o1}$ is the microgrid side filter inductance of micro-source 1, $v_{ref1}$ is micro-source 1 command voltage, $v_1$ is micro-source 1 output voltage, $v_{PCC}$ is PCC voltage, $v_{sref}$ is secondary control command voltage, $i_{Lref1}$ is micro-source 1 command current, $i_1$ is micro-source 1 output current, $i_L$ is the filter inductance current of micro-source 1, $R_{linei}$ (i=1,2,…,*n)* is resistance of line *i*, $L_{linei}$ is inductance of line *i*, $R_{Load}$ is local load resistance, $L_{Load}$ is local load inductance.

As shown in document [3], the micro-source can be equivalent to the series connection of an voltage source and output impedances, and the output voltage of micro-source *i* can be expressed as

$$v_i = G_{ui}(s)v_{ref\,i} - Z_{eoi}(s)i_i\,, \tag{1}$$

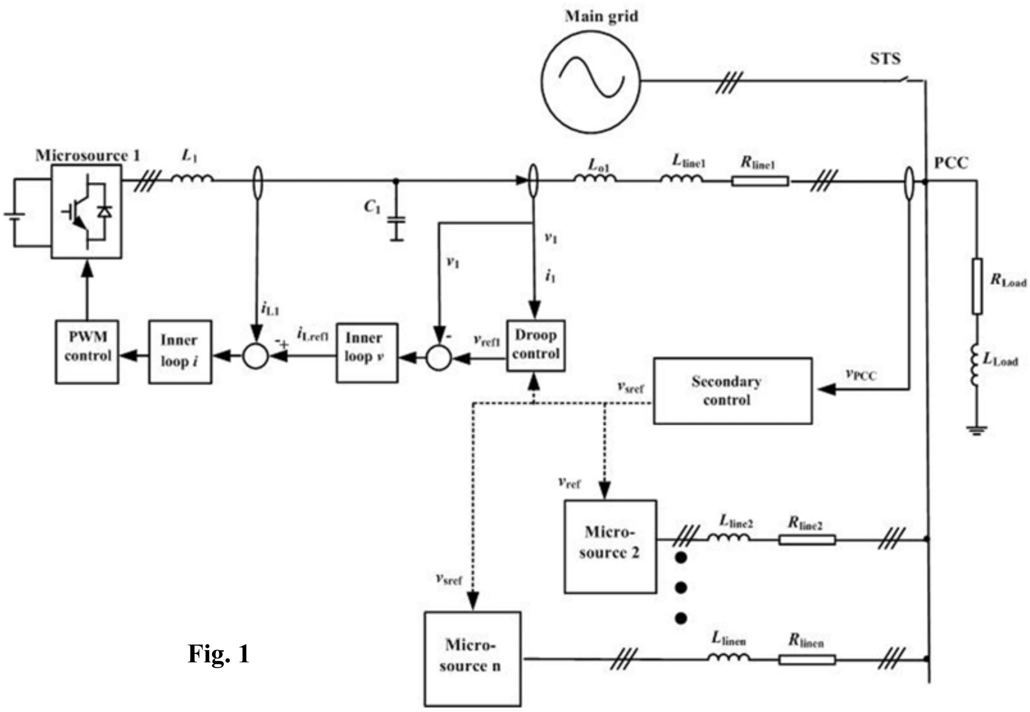


**Fig. 1**

where $v_i$ is micro-source *i* output voltage, $v_{refi}$ is micro-source *i* command voltage, $G_{ui}$ (s) is transfer function of micro-source *i* command voltage coefficient, $Z_{eoi}$(s) is transfer function of micro-source output impedance, and $i_i$ is micro-source *i* output current. According to (1), the equivalent circuit of the system in Fig. 1 can be obtained.

Assuming the line impedance voltage drop of micro-source *i* is $v_{linei}$, then $v_{PCC}$ that is calculated according to Fig. 2 can be expressed as

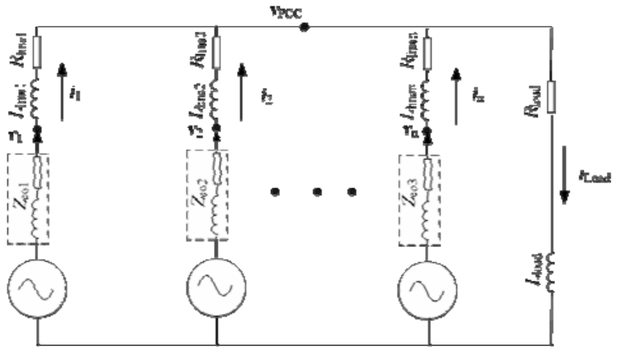


**Fig. 2**

$$\begin{cases} v_{\mathrm{PCC}} = v_{\mathrm{i}} - v_{\mathrm{linei}}, \\ v_{\mathrm{PCC}} = v_{\mathrm{PCC\_f}} + \sum\limits_{h=2}^{n} v_{\mathrm{PCC\_h}}, \\ v_{\mathrm{i}} = v_{\mathrm{i\_f}} + \sum\limits_{h=2}^{n} v_{\mathrm{i\_h}}, \\ v_{\mathrm{linei}} = v_{\mathrm{linei\_f}} + \sum\limits_{h=2}^{n} v_{\mathrm{linei\_h}}, \end{cases} \tag{2}$$

where $v_{\mathrm{PCC\_f}}$ is the fundamental component of PCC voltage, $v_{\mathrm{PCC\_h}}$ is the $h$-order harmonic component of PCC voltage, $v_{\mathrm{i\_f}}$ is the fundamental component of micro-source $i$ output voltage, $v_{\mathrm{i\_h}}$ is the $h$-order harmonic component of micro-source $i$ output voltage, $v_{\mathrm{linei\_f}}$ is the fundamental component of line $i$ impedance voltage drop, $v_{\mathrm{linei\_h}}$ is the $h$-order harmonic component of line $i$ impedance voltage drop.

With the above equation, the negative sequence component (h=2) of PCC voltage can be expressed as

$$v_{\mathrm{PCC\_n}} = v_{\mathrm{i\_n}} - v_{\mathrm{linei\_n}}, \tag{3}$$

where $v_{\mathrm{PCC\_n}}$ is the negative sequence component of PCC voltage, $\mathrm{v}_{\mathrm{i\_h}}$ is the negative sequence component of micro-source $i$, $v_{\mathrm{linei\_n}}$ is the negative sequence component of line $i$ impedance voltage drop. According to (3), the relationship of the three voltage vector can be illustrated as Fig. 3. Where $V_{\mathrm{PCC\_n}}$ is the negative sequence component of PCC voltage vector, $V_{\mathrm{i\_n}}$ is the negative sequence component of micro-source $i$ voltage vector, $V_{\mathrm{linei\_n}}$ is the negative sequence component of line $i$ impedance vector, and $\theta$ is the angle between $V_{\mathrm{i\_n}}$ and $V_{\mathrm{linei\_n}}$.

Fig. 3 shows that on the premise of fixed amplitude of $V_{\mathrm{i\_n}}$ and $V_{\mathrm{linei\_n}}$, the amplitude of $V_{\mathrm{PCC\_n}}$ will change with the changing of $\theta$. Inferences can be drawn that there are certain working status (e.g. $\theta$=90°) when the amplitude of $V_{\mathrm{PCC\_n}}$ exceeds that of $V_{\mathrm{i\_n}}$. According to the definition of voltage unbalance factor, the unbalance factor of a certain voltage is the division of its negative sequence voltage vector amplitude by its fundamental positive sequence voltage vector amplitude. Thus, it is deducible that with the line impedance presence, the respective negative sequence component of micro-source $i$ and PCC are different from each other, resulting in the different unbalance factors between them.

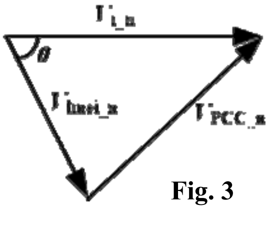


**Fig. 3**

**The control method of PCC voltage unbalance factor with high precision.** Based on (3), we can get that if the negative sequence component of micro-source $i$ output voltage is changed, the negative sequence component of PCC voltage will then adjust itself. As can be seen from the definition of secondary control, secondary control enables measurement of PCC voltage, and the corresponding results will be fed to micro-source $i$ through communication link [2]. The paper defines the negative sequence component of PCC feedback voltage under secondary control as

$$v_{\mathrm{fed\_in}} = k_{\mathrm{fed\_n}} v_{\mathrm{PCC\_n}}, \tag{4}$$

where $v_{\mathrm{fed\_in}}$ is the negative sequence component of micro-source $i$ feedback voltage under secondary control, and $k_{\mathrm{fed\_n}}$ is the negative sequence component proportional coefficient of the feedback voltage. Define the difference between $v_{\mathrm{refi}}$ and $v_{\mathrm{fed\_in}}$ as the negative sequence component of micro-source $i$ command voltage under secondary control. After substituting this value into equation (3), the negative sequence component of PCC voltage changes into $1\text{-}k_{\mathrm{fed\_n}}$ times that of the original value. As seen, through degeneration control of PCC voltage negative sequence component, the negative sequence component of microgrid PCC voltage can be controlled.

Based on the aforementioned analysis, the paper proposes a secondary-control-based control strategy to reduce PCC voltage unbalance. The control strategy to improve PCC voltage unbalance factor is drawn as Fig. 4, where ROR-FLL(reduced order resonant frequency-locked loop) is used to separate the fundamental and negative sequence component of PCC voltage, $G_{\mathrm{vuf}}(s)$ is the transfer coefficient of voltage unbalance factor controller(PI controller).

Based on Fig. 1 and Fig. 4, the transfer function diagram of PCC unbalanced voltage control system can be expressed as Fig. 5, where $\tau_{\mathrm{d}}$ is the time constant of communication delay links, $G_{\mathrm{oi}}(s)$ is

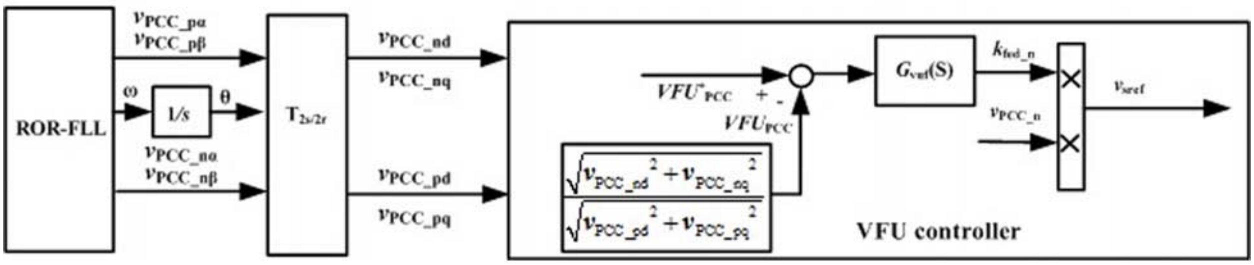


**Fig. 4**

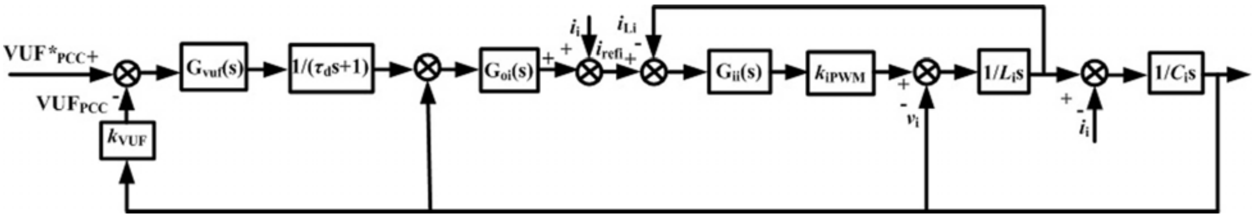


**Fig. 5**

the transfer function of micro-source $i$ outer loop controller, $G_{ii}(s)$ is the transfer function of micro-source $i$ inner loop controller, $k_{iPWM}$ is the PWM control equivalent gain of micro-source $i$, $k_{VUF}$ is the equivalent gain of voltage unbalance factor calculation link..

Since the time scale of secondary control is far larger than that of micro-source $i$ controller, the micro-source $i$ can be defined as the inertia element. The bandwidth of this inertia element is the same as that of the micro-source $i$ outer loop. Thus, the transfer function of secondary control is obtained as

$$G_{VUF}(s)=\frac{k_{p\_sec}s+k_{i\_sec}}{\tau_0\tau_d s^3+(\tau_0+\tau_d)s^2+(k_{p\_sec}+1)s+k_{i\_sec}k_{VUF}}, \qquad (5)$$

where $k_{p\_sec}$ is the proportional coefficient of secondary control link, and $k_{i\_sec}$ is the integral coefficient of secondary control link. Choose the secondary control delay link time from 20 ms to 100 ms, and then the root locus change of (5) is shown as Fig. 6.

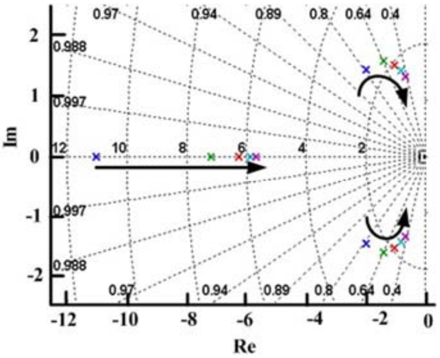
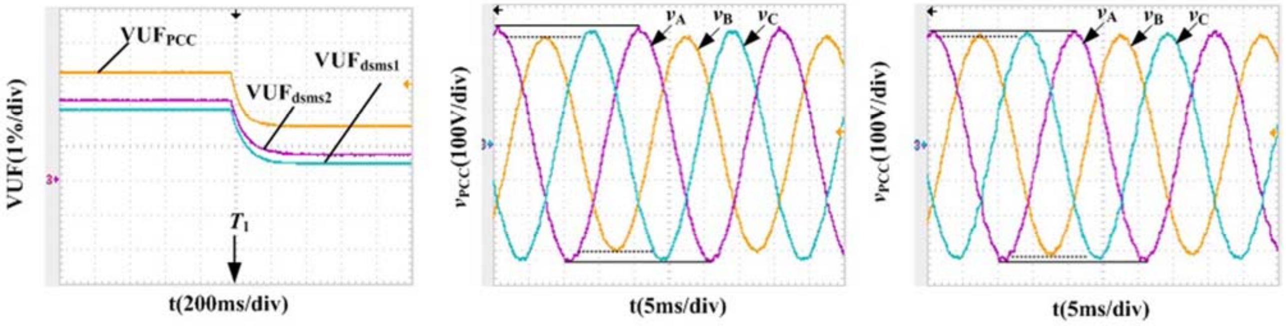


**Fig. 6**

Fig. 6 shows that the microgrid eigenvalues consist of a pair of complex conjugate and a real number. With the increase of delay time constant, the distance of three eigenvalues from the imaginary axis continues to decrease, and the dominant pole damping ratio of the system also decreases, then the system stability is reduced. According to the above analysis, reference is drawn that the delay time of secondary control should be reduced as much as possible in order to improve system stability.

**Experimental results.** The paper performs experiment on the proposed PCC unbalanced voltage control strategy with an islanded microgrid. The microgrid consists of two micro-sources and adopts the form of concentrated loads. The length of the two micro-sources' line impedance is 0.5 km and 1 km, respectively (the line resistance is $0.642\Omega\cdot km^{-1}$, and the line inductance is $0.083\Omega\cdot km^{-1}$). The reference value of PCC voltage unbalance factor is 1.5%. The three-phase load impedances are 5Ω, 10Ω, and 7Ω, respectively. At first, the microgrid runs stably in the islanded mode under the working status of unbalanced loads. At $T_1$, the PCC unbalanced voltage control strategy starts to be utilized. Relative experiment results are shown in Fig. 7.



(a) (b) (c)

**Fig. 7**

According to GB/T15543 standards, the long term VUF at PCC is no more than 2% and the short-term VUF is no more than 4%. Fig. 7(a) shows that when no unbalanced voltage control strategy is adopted, the voltage unbalanced percent at PCC is 3%, bigger than the regulated numeric value in GB/T 15543 standards. After adopting this strategy, the unbalanced percent of PCC voltage gradually decreases, and its VUF value is finally fixed at 1.5%, which coincides with what is regulated in GB/T 15543 standards. In the process of secondary control, and as PCC voltage unbalance factor decreases, the micro-source voltage unbalance factor also decreases, so the micro-source output voltage power quality obtains improvement. By comparing Fig. 7(b) with Fig. 7(c), it can be seen that if no unbalanced voltage control strategy is adopted, the voltage unbalance factor at PCC is much more obviously(voltage amplitude difference shows in Fig. 7(b)); while after it is adopted, the voltage unbalance factor at PCC decreases (voltage amplitude difference shows in Fig. 7(c)).

**Conclusion.** Through the equivalent circuit, the paper analyzes negative sequence component vector relationship among micro-source, line impedance and PCC voltage. The analysis result shows that PCC voltage can't be precisely controlled by just measuring micro-source output voltage, and that the adoption of secondary control can perform improvement on PCC voltage unbalance factor. Based on the analysis result, the paper proposes a control strategy for reducing PCC unbalanced voltage. This strategy adopts secondary control to calculate the negative sequence component compensation value of PCC voltage. The calculation result is then transmitted to all micro-sources through communication and tracked by micro-sources in local control. Finally, by performing experiments, the paper validates the feasibility of its proposed control strategy to implement improvement of PCC voltage unbalance factor under unbalanced loads working status.

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УДК 621.3

# СТРАТЕГИЯ ИЕРАРХИЧЕСКОГО КОНТРОЛЯ НЕСБАЛАНСИРОВАННОГО НАПРЯЖЕНИЯ В ИЗОЛИРОВАННОЙ МИКРОЭНЕРГОСИСТЕМЕ

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*При работе микроэнергосистемы (МЭ) в изолированном режиме несбалансированые нагрузки приводят к дисбалансу напряжения в ней. Фактор дисбаланса напряжения в точке общего присоединения (ТОП) является основным параметром при измерении качества электроэнергии МЭ. Для улучшения качества электроэнергии МЭ используют результаты измерений напряжения микроисточников для урегулирования дисбаланса напряжения МЭ. Однако из-за наличия полного входного сопротивления линии существуют различия между выходным напряжением микроисточника и напряжением ТОП. Поэтому микроисточник не может контролировать дисбаланс напряжения ТОП с высокой точностью путем измерения собственного выходного напряжения. На основании эквивалентной схемы в данной статье анализируется отношение составляющей обратной последовательности между выходным напряжением микроисточника, падением напряжения полного входного сопротивления линии и напряжением в ТОП. Также для контроля фактора дисбаланса напряжения ТОП с высокой точностью предлагается метод на основе иерархического контроля, анализируется влияние задержки вторичного контроля на стабильность системы. Стратегия контроля проверялась в изолированной микроэнергосистеме с двумя микроисточниками. Опытные данные показывают эффективность и целесообразность предлагаемой стратегии контроля.* Библ. 8, рис. 7.

***Ключевые слова***: микроэнергосистема, иерархический контроль, изолированный режим, дисбаланс напряжения, полное входное сопротивление линии.

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УДК 621.3

# СТРАТЕГІЯ ІЄРАРХІЧНОГО КОНТРОЛЮ НЕЗБАЛАНСОВАНОЇ НАПРУГИ В ІЗОЛЬОВАНІЙ МІКРОЕНЕРГОСИСТЕМІ

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*Під час роботи мікроенергосистеми (МЕ) в ізольованому режимі незбалансовані навантаження призводять до дисбалансу напруги у ній. Фактор дисбалансу напруги у точці спільного приєднання (ТСП) є основним параметром при вимірюванні якості електроенергії МЕ. Для підвищення якості електроенергії МЕ використовують результати вимірювань напруги мікроджерел для врегулювання фактора дисбалансу напруги МЕ. Проте через наявність повного вхідного опору лінії існують відмінності між вихідною напругою мікрожderела та напругою ТСП. Тому мікроджерело не може контролювати фактор дисбалансу напруги ТСП з високою точністю шляхом вимірювання власної вихідної напруги. На базі еквівалентної схеми у даній статті аналізуються відношення складової оберненої послідовності між вихідною напругою мікроджерела, падінням напруги повного вхідного опору лінії та напругою у ТСП. Також для контролю фактора дисбалансу напруги ТСП із високою точністю пропонується метод на основі ієрархічного контролю, аналізується вплив затримки вторинного контролю на стабільність системи. Стратегія контролю перевірялася в ізольованій мікроенергосистемі з двома мікроджерелами. Дослідні дані показують ефективність та доцільність запропонованої стратегії контролю.* Бібл. 8, рис. 7.

***Ключові слова***: мікроенергосистема, ієрархічний контроль, ізольований режим, дисбаланс напруги, повний вхідний опір лінії.

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