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Smart technologies and solutions for future sustainable and resilient energy systems

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Abstract. The main objective of this research is to analyze current problems and methods proposed for solving problems of design, operation and planning for the development of future sustainable electric power systems, taking into account the integration of renewable energy sources, the integration of heat and gas networks using high-speed communication channels. The author's method of ensuring system stability and protecting the integrity of electric power systems is outlined. To ensure stable operation of future electric power systems, it is proposed to use methods of multi-level optimization and control of digital power systems, smart grid technologies and methods for processing vector measurements based on cyber-secure communication channels. It has been established that the proposed schemes make it possible to ensure the stability of the system and protect its integrity. In order to demonstrate the effectiveness of such approaches, an example is given of solving the problem of preventing rolling blackouts of the power system by purposefully separating/isolating the system based on the author's two-stage controlled isolation algorithm. It is shown that to solve the problems of modern electric power industry, it is effective to use new telecommunication technologies, means of ensuring situational awareness and schemes for protecting the integrity of systems based on modern methods of operations research and artificial intelligence. The multicriteria optimization method proposed by the authors uses minimization of the objective function of power flow disruption and takes into account restrictions on the consistency of generator operation. The method was tested on an IEEE test circuit consisting of 118 nodes. Test calculations confirmed that the method allows for minimal power imbalance and minimal disruption of power flows. Thus, the results of the work open up new opportunities for improving the monitoring and protection of future sustainable electricity systems, including taking into account the integration of renewable energy sources, heat and gas networks.

Keywords: digitalization, smart grid, renewable energy sources, converter based generation, blackouts, cascading events

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ЭНЕРГЕТИКА

Научная статья
УДК 621.31

Умные технологии и решения для будущих устойчивых и надежных энергетических систем

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Резюме. Цель исследования – провести анализ актуальных проблем и методов, предлагаемых для решения задач проектирования, эксплуатации и планирования развития будущих устойчивых электроэнергетических систем с учетом интеграции возобновляемых источников энергии, объединения тепловых и газовых сетей с использованием высокоскоростных каналов связи. Излагается авторский метод обеспечения устойчивости системы и защиты целостности электроэнергетических систем. Для обеспечения устойчивой работы будущих электроэнергетических систем предлагается использовать методы многоуровневой оптимизации и управления цифровыми энергосистемами, технологии интеллектуальных сетей и методы обработки векторных измерений на основе кибербезопасных каналов связи. Установлено, что предложенные схемы позволяют обеспечить устойчивость системы и защитить ее целостность. С целью демонстрации эффективности таких подходов приведен пример решения задачи предотвращения веерных отключений энергосистемы путем целенаправленного разделения/изоляции системы на основе авторского двухэтапного алгоритма управляемой изоляции. Показано, что для решения поставленных задач современной электроэнергетики является эффективным использование новых телекоммуникационных технологий, средств обеспечения ситуационной осведомленности и схемы защиты целостности систем, основанных на современных методах исследования операций и искусственного интеллекта. Предложенный авторами метод многокритериальной оптимизации использует минимизацию целевой функции нарушения перетока мощности и учитывает ограничения на согласованность работы генераторов. Метод был протестирован на тестовой схеме IEEE, состоящей из 118 узлов. Тестовые расчеты подтвердили, что метод позволяет обеспечивать минимальный дисбаланс мощности и минимальное нарушение перетоков мощности. Таким образом, результаты работы открывают новые возможности для улучшения мониторинга и защиты будущих устойчивых электроэнергетических систем, в том числе с учетом интеграции возобновляемых источников энергии, тепловых и газовых сетей.

Ключевые слова: цифровизация, смарт-сети, возобновляемые источники энергии, генерация на основе преобразователя, отключения, веерные отключения

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INTRODUCTION

Massive integration of converter interfaced generation (CIG) and renewable energy sources (RESs) has significantly changed the nature and complexity of modern electrical power systems. This is obvious from Fig. 1, in which different new system components are shown, e.g. wind-farms, solar energy, battery, or electrical vehicles. Practically all components presented are connected to the grid over inverters/power electronics.

Historically, the penetration level of CIG and RES has been permanently increased, what is depicted in Fig. 2, in which the share of different renewable energy generation is depicted [2].

Through integration of CIGs and RESs the system is changing its fundamental properties. These changes can be summarized in a conclusion that the entire system became weak, or at least weaker than the system from the past. Here a definition of a strong system is *the system which stability cannot be significantly affected by different types of perturbations, e.g. sudden topological changes, faults, or loss of* generation. The reasons for the power system to become weaker are power electronics-based system components, particularly generation. For example, Type-3 and Type 4 generators, connected to the grid, do not contribute to the system inertia and fault level [3–5]. From Fig. 3 it can be concluded that only stator of the generator is synchronously connected to the grid, whereas the rotor is decoupled from it through inverters.

System inertia is directly related to the system frequency stability and under the term "inertia" we traditionally understand the rotational inertia, resulting from the rotation of rotors in synchronous generators and different types of ac motors. On the other hand, fault level determines those aspects related to voltage stability. A strong system is a system which

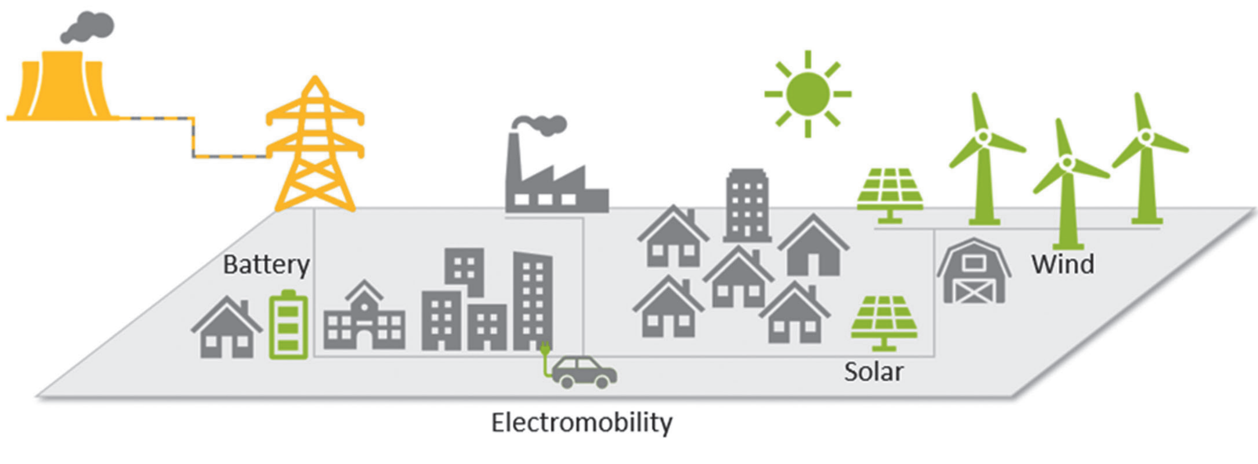

***Fig. 1.** Modern electrical power system with CIGs and RESs*
***Рис. 1.** Современная система электроснабжения с генерациями с интерфейсом преобразователя (CIG) и возобновляемыми источниками энергии (RES)*

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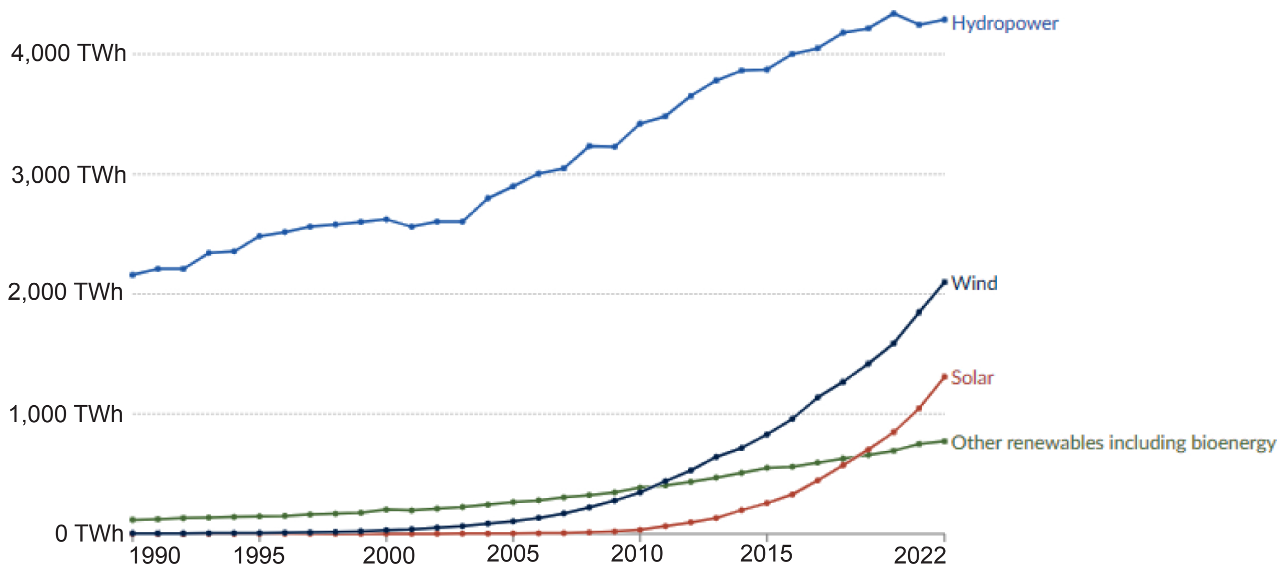

***Fig. 2.** Modern renewable energy generation by source [2]*
***Рис. 2.** Современная генерация энергии из возобновляемых источников [2]*

is stable, both from frequency and voltage stability perspective. Through connection of CIGs/RESs, the system is becoming weak and vulnerable from the perspective of frequency and voltage stability. In conclusion, system perturbations, e.g. faults, or sudden imbalances of active powers (*P*) caused by e.g. sudden disconnection/connection of generators, can provoke instabilities and start cascading events, which can lead to power system blackouts.

SYSTEM RESILIENCE

Power system resilience is one of the key attributes which modern power systems have to possess and satisfy. Traditionally, the focus was on the system security and reliability. Through integration of different energy systems, e.g. heat, gas, electricity, or hydrogen, the importance of the system flexibility became another important system attribute [6]. In Fig. 4 an example of such an integration is presented.

Resilience is related to low probability, but high impact events, which as such can lead to catastrophic power system blackouts and a number of consequences to the system and the society. The system can be characterized as resilient, if it can successfully go through large scale perturbation and manage to retain its key security and stability, or operational, characteristics. In this context even through the integration of different energy systems into integrated energy system (Fig. 4), the

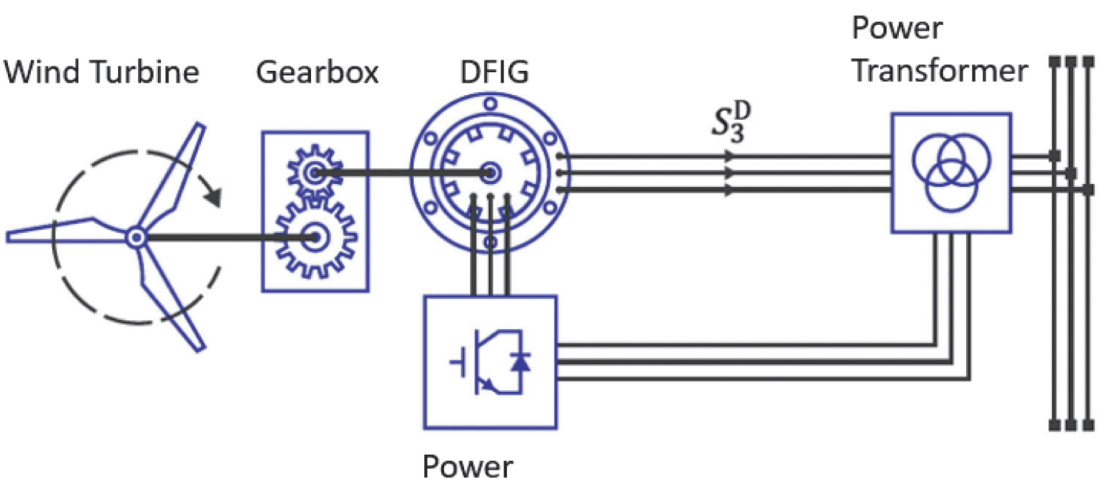

***Fig. 3.** Doubly-fed induction generator (DFIG) wind turbine, Type-3 wind generator*
***Рис. 3.** Ветряная турбина с асинхронным генератором двойного питания (DFIG), ветрогенератор 3-го типа*

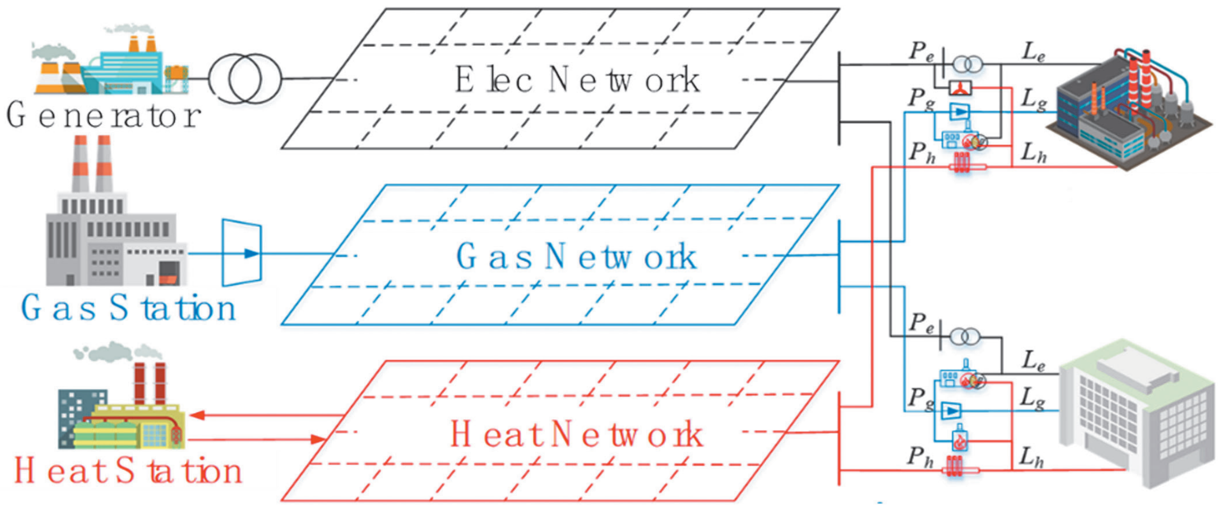

Fig. 4. *Integrated energy systems connected over different types of coupling technologies [6]*
Рис. 4. *Интегрированные энергетические системы, соединенные с помощью различных типов технологий сопряжения [6]*

system resilience can be further improved. According to [7], power system resilience is defined as "the system ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event". The term disruptive events refers to high impact and low probability unexpected perturbation, including extreme natural disasters, or man-made attacks. Typical examples are snow storms, or cyber-attacks [8, 9].

The system resilience can be improved through short-, mid- and long-term planning. Different types of investing strategies can bust the system resilience. This has to do with e.g. planning actions 20 years ahead. However, the system resilience can be also monitored in real-time, subject to the accepted resilience definition and metrics. Finally, the system resilience can be significantly improved through adequate monitoring, protection and control actions.

Large perturbations, e.g. simultaneous outage of a large number of system components, resulting from natural disasters and extreme weather conditions, traditionally cause so called cascading events, i.e. sequential/parallel outage/loss of the system components, e.g. transmission lines, power transformers, generators, or demand. By assessing the resilience level in the grid, it can be concluded how critical the system "resilience state" is. This is addressed in Fig. 5, in which the resilience level in a power system, connected to other energy systems, e.g. gas, heat, or hydrogen, is presented. The resilience trapezoids [10] changed over the time is used to quantify the resilience level.

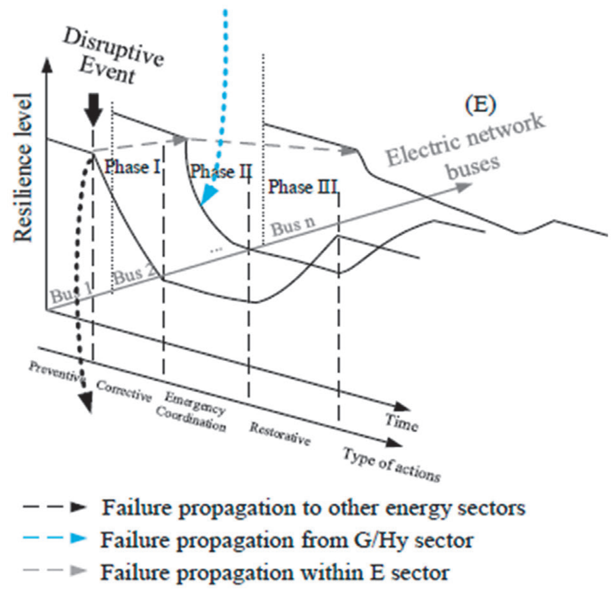

Fig. 5. *Resilience level changed of time in a power system connected to other energy systems/sectors [10]*
Рис. 5. *Изменение уровня устойчивости с течением времени в энергосистеме, подключенной к другим энергосистемам/секторам [10]*

DIGITALIZATION AND DIGITAL SUBSTATION

The quality of the system monitoring, protection and control significantly relies on data obtained, on their quality and quantity, as well as speed how quickly data are collected from the physical process observed. Smart grid technology is accelerating the speed of the digitalization of the modern electrical power systems. Novel sensors, like time synchronized

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Phasor Measurement Units (PMUs), or high speed and cyber secure communication channels are strongly supporting advanced monitoring, protection and control schemes. Here the quality of data, but also cyber security is critically important for the success of new protection and control schemes. In Fig. 6, a digital substation (right), presented next to the classical substation (left), is given [11]. Digital substation has non-conventional instrument transformers, precise conversion from analogue to digital voltages and currents, fibre-optic communication infrastructure having no problems with electromagnetic compatibility, fast data transfer to higher hierarchical levels and enables new protection solutions, both at the unit and system level (System Integrity Protection Schemes – SIPS), e.g. prevention of power system blackouts, as presented in the rest of the paper. It can be observed that the information from switchgear is transferred of the relay and substation control rooms to the central grid control room, in which the Energy Management System (EMS) is located. At this level, e.g. the system state is estimated.

Reliable information about the system state, which can be also linked to the entire situational awareness request, is a prerequisite for optimal operation of the entire power system, which is traditionally related to a series of actions undertaken under the umbrella of the EMS. In Fig. 7, major building blocks, creating a closed loop monitoring, protection and control based on different sources of input data, is presented [12, 13]. Here time-synchronized PMU data are integrated with other data obtained over traditional SCADA and those data forecasted, or obtained in any other way over EMS. Properly managed database is now a source from which key situational awareness attributes can be extracted, for example security margins, the level of the system flexibility, or resilience. From the perspective of advanced protection and control applications, the system state, information about load dynamics, system inertia, fault level, etc. can contribute to the quality of the SIPS actions and mitigating measures necessary for detecting cascading events and preventing power system blackouts.

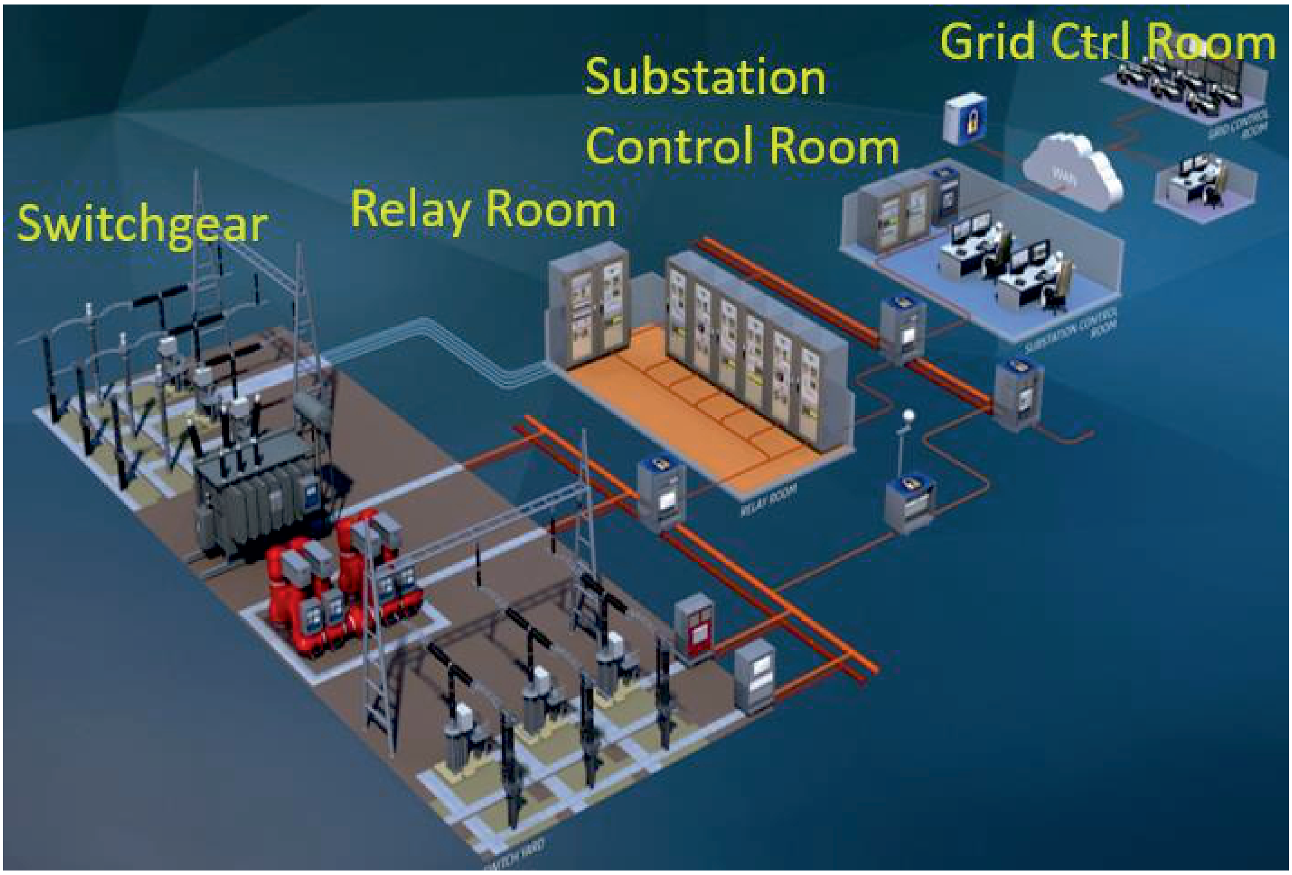

Fig. 6. *Digital substation (switchgear) [11]*
Рис. 6. *Цифровая подстанция (распределительное устройство) [11]*

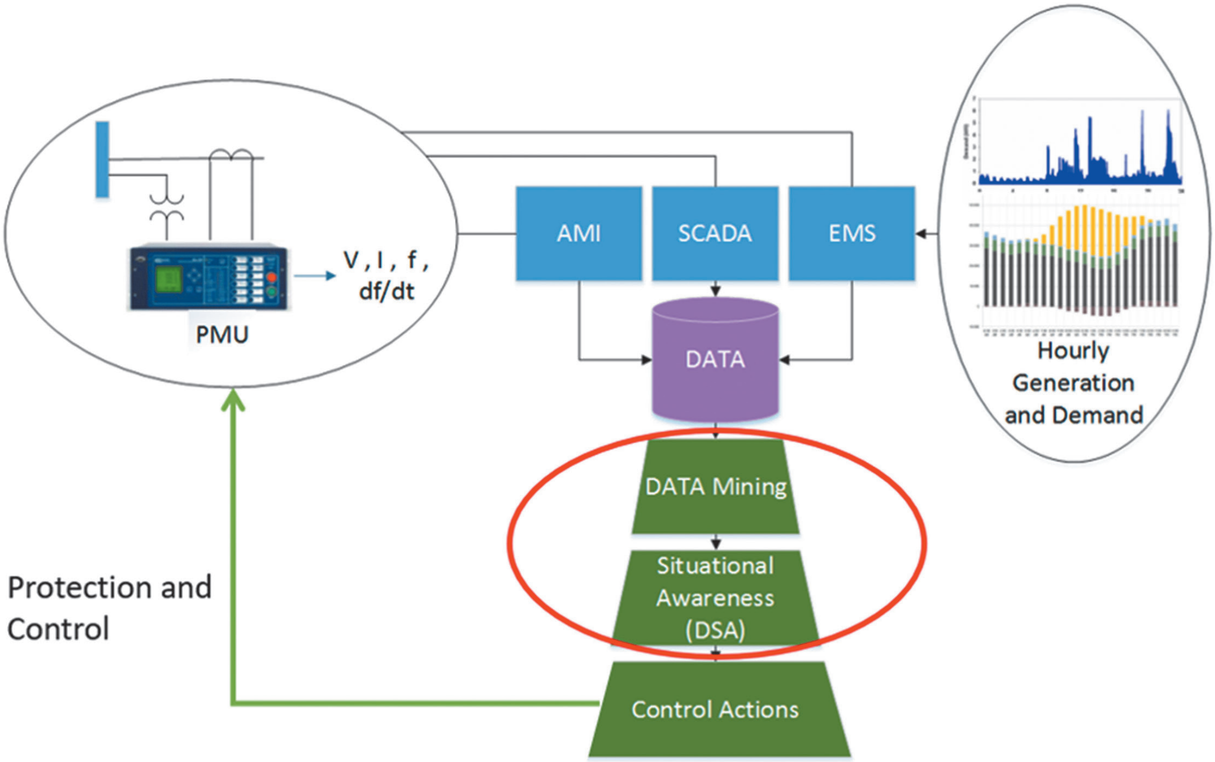

Fig. 7. *Building blocks, creating a closed loop power system monitoring, protection and control*
Рис. 7. *Строительные блоки, создающие замкнутый контур мониторинга, защиты и управления энергосистемой*

The example how PMUs can support advanced situational awareness, i.e. power system state estimation, are new installations worldwide, e.g. in the UK. In Fig. 8, PMUs are collecting real-time data from different locations of the grid. Data are collected at different locations (Data Concentrators - DC) and centrally stored at the Super Data Concentrator (Super DC). Such a hierarchical structure can enable fast state estimation, or protection and control functions which were impossible to be realized without such a smart grid technology supporting the overall system digitalization. Using PMUs and fast communication channels, the system state can be obtained within 0.1-1 s, whereas the traditional, purely SCADA-based estimator, required more than 5-10 min to accomplish the state estimation procedure.

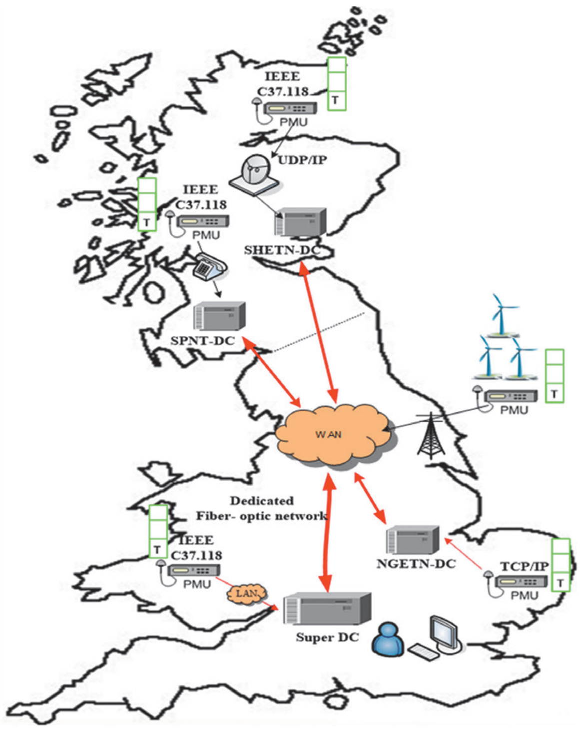

Fig. 8. *Integration of PMUs for advanced monitoring, protection and control of power systems with CIGs and RESs*
Рис. 8. *Интеграция устройств синхронизированных векторных измерений (PMU) для расширенного мониторинга, защиты и управления энергосистемами с генерациями с интерфейсом преобразователя (CIG) и возобновляемыми источниками энергии (RES)*

SYSTEM INTEGRITY PROTECTION SCHEMES

The role of power system protection is a) to protect individual system components – unit protection, or b) to protect the entire power system – System Integrity Protection Schemes (SIPS). SIPS is defined as an automatic protection system designed to identify abnormal system conditions and

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to perform predictive or remedial actions necessary for maintaining system integrity. In the past, conventional protection devices were designed to protect individual elements of equipment from being damaged during faults by quickly detecting overcurrent conditions, or other dangerous operating conditions, and then selectively and quickly isolating the faulty equipment from the system. In contrast, SIPS are designed to maintain the integrity of the entire power system by simultaneously monitoring and controlling multiple elements of the system. It integrates and analyses both local and system level information against wide area contingencies. This approach allows SIPS to improve the efficiency and security of system operation under specific conditions. SIPS encompass few different levels or schemes: Special Protection Schemes (SPS), Remedial Action Schemes (RAS), as well as additional schemes such as, underfrequency, undervoltage, out-of-step, etc. It is commonly believed that modern SIPS are derived from the coordination of different levels of local protection schemes.

Both unit protection and SIPSs can prevent negative development of cascading events and support the system integrity. In Fig. 9 a block diagram of a typical SIPS is presented. The following three key SIPS stages can be observed: a) disturbance identification, which must be secure and robust, b) decision making, which must be reliable and fast enough and c) action, which has to be reliably forwarded back to the system.

The quality of SIPS input data is critically important for its efficacy. Modern SIPSs rely on wide-area measurements and availability of novel sensor and ICT technology. Phasor Measurement Units (PMUs) and fast and cyber secure communication infrastructure are the backbone of modern Wide Area Monitoring, Protection and Control (WAMPAC) systems [14]. Nowadays they are enablers of modern SIPSs. Intentional controlled islanding of a power system is an efficient SIPS for preventing power system blackouts caused by large system disturbances. This kind of SIPSs limits the occurrence and consequences of blackouts by splitting the power system into a group of smaller, islanded power systems, called islands. The essence of an islanding solution is in determining a suitable set of transmission lines that must be disconnected to create a set of electrically isolated/independent islands. This paper describes an algorithm for determining suitable islanding solutions.

The prerequisite for a successful system islanding is selection of lines/cables which must be opened to create independent islands. It is necessary to create stable islands and in this context the instant at which the islanding is undertaken plays an important role for preventing blackouts.

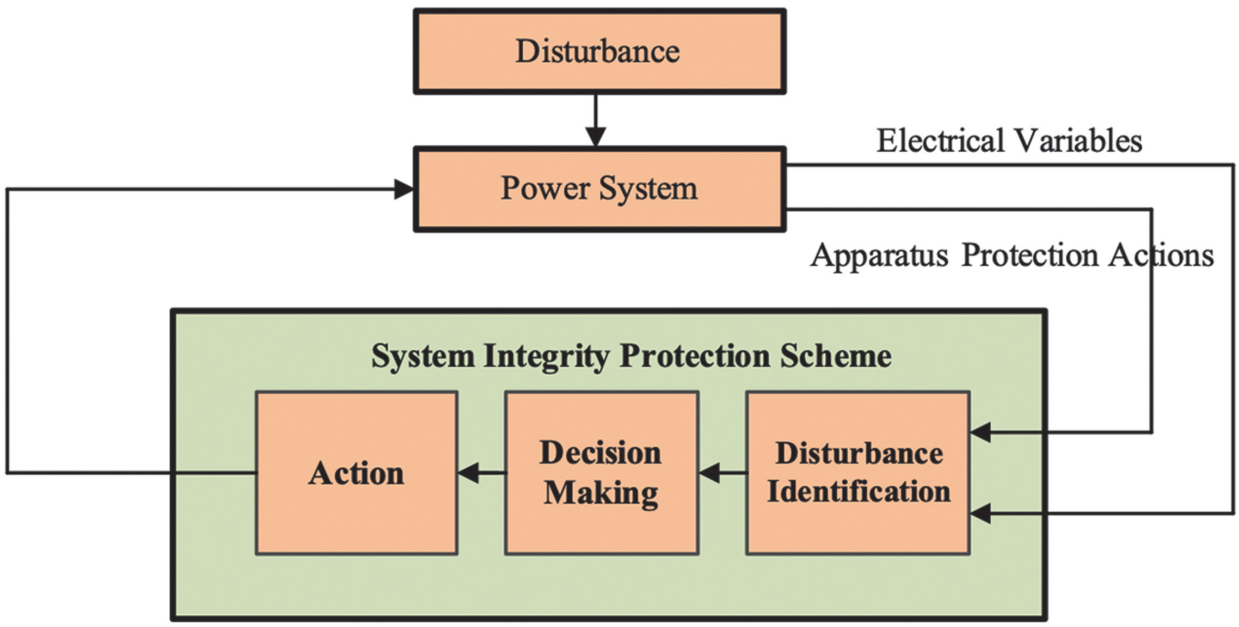

Fig. 9. *Block diagram of a typical SIPS*
Рис. 9. *Структурная схема типичной схемы защиты целостности системы (SIPS)*

However, the schemes for prevention of power system blackouts rely on the quality of input data, as well as the system monitoring, which is traditionally linked to the issue of power system state estimation. Modern system estimation algorithms rely on PMUs integrated into the existing SCADA system (hybrid state estimator), or on PMUs only (PMU-based linear state estimator).

FUNDAMENTALS OF INTENTIONAL CONTROL ISLANDING

To create stable islands, the islanding solution must satisfy a large number of constraints, such as load-generation balance, generator coherency, availability of transmission lines and their thermal limits, voltage stability, transient stability, etc. It would be far too complicated to search for a solution satisfying all these constraints. In extreme cases it is likely that such a solution even does not exist. Considering only a sub-set of these constraints, e.g. a) load-generation active power balance and b) generator coherency, a set of feasible candidate islanding solutions could be created. This set of candidates can be coordinated with other corrective measures to find the final islanding solution that satisfies all possible constraints [15].

The existing islanding methods can be classified according to the objective function used for decision making, i.e. creation of the islanding solution. Two main types of objective functions are used here:

a) minimal power imbalance and

b) minimal power-flow disruption.

Methodologies for minimal power imbalance minimize the power imbalance within the islands formed to reduce the amount of load that must be shed after the system splitting.

Methodologies for finding islanding solutions based on the minimal power-flow disruption minimize the change of the power flow pattern within the system following the system splitting.

The difference between power imbalance and power-flow disruption is that the power imbalance can be expressed by the algebraic sum of active power (considering the direction of power flow) on each disconnected transmission line, while the power-flow disruption can be expressed by the arithmetical sum of active power on each disconnected transmission line. Finding a solution with the minimal power imbalance belongs to a class of the so-called *np*-hard problems which are computationally exceptionally demanding. This is the reason for designing new approaches which are practical and particularly capable of coping with large power networks and a requirement for the real-time decision making. Most of existing algorithms overcome this challenge by using heuristic search methods, or by solving the problem by creating small dimension network equivalents of the original large size network. Heuristic search methods are usually quite flexible and have satisfactory computational efficiency. However, the solution quality cannot be guaranteed since these methods tend to converge to local, rather than global, solutions. Consequently, the islanding solution might be not effective enough.

In the Section below, the two-step Spectral Clustering Controlled Islanding algorithm (the SCCI algorithm) will be presented and used to demonstrate its efficacy [16]. In the first step of the SCCI algorithm, the generator nodes are grouped using normalized spectral clustering. The results of this grouping serve as pair-wise constraints in the next step of the SCCI algorithm, in which every node is grouped based on constrained spectral clustering. This constrained spectral clustering uses power flow data to producing an islanding solution with minimal power-flow disruption. Therefore, the two-step SCCI algorithm proposed here can identify, in real time, an islanding solution that has minimal power-flow disruption and satisfies the constraint of generator coherency.

CONTROLLED ISLANDING PROBLEM

The problem of finding coherent generator groups is equivalent to an optimization problem of finding the weakest dynamic coupling between different generator groups, as shown in (1) below [16].

$$\min S = \min_{\mathbf{V}_{G1}, \mathbf{V}_{G2} \subset \mathbf{V}_G} \left(\sum_{j \in \mathbf{V}_{G2}} \sum_{i \in \mathbf{V}_{G1}} \left(\frac{\partial P_{ij}}{\partial \delta_{ij}} \cdot \left(\frac{1}{H_i} + \frac{1}{H_j} \right) \right) \right). \quad (1)$$

Minimal power imbalance and minimal power-flow disruption, defined according to (2) and (3) respectively, can both be used as objective functions of controlled islanding. Each objective will produce a different solution with different advantages and disadvantages.

$$\min_{V_1,V_2\subset V}\left(\left|\sum_{i\in V_1, j\in V_2} P_{ij}\right|\right); \quad (2)$$

$$\min_{V_1,V_2\subset V}\left(\sum_{i\in V_1, j\in V_2} |P_{ij}|\right), \quad (3)$$

where P_{ij} denotes the value of the active power on the transmission line between node *i* and *j*.

The controlled islanding problem that is solved in this paper consists of the minimal power-flow disruption objective function (3) and the generator coherency constraint (1). These two optimization problems are combined together to form the final SCCI algorithm expressed through (4). This is done by firstly solving (1), to find the set of coherent generator groups, and secondly by solving (2) subject to these generator groups [11].

$$[V^*_{G1}, V^*_{G2}] = \arg\min_{V_{G1},V_{G2}\subset V_G}\left(\sum_{j\in V_{G2}}\sum_{i\in V_{G1}}\left(\frac{\partial P_{ij}}{\partial \delta_{ij}}\cdot\left(\frac{1}{H_i}+\frac{1}{H_j}\right)\right)\right); \quad (4)$$

$$\min_{V_1,V_2\subset V}\left(\sum_{i\in V_1, j\in V_2}|P_{ij}|\right) \text{ subject to } V^*_{G1}\subset V_1, V^*_{G2}\subset V_2.$$

Here, *argmin* stands for the *argument of the minimum*, i.e. $[V^*_{G1}, V^*_{G2}]$ is the node grouping that minimizes the objective function of (1). Spectral clustering is the tool used in this paper to solve the islanding problem. In the next Section the two-step spectral clustering controlled islanding algorithm will be presented.

The two-step Spectral Clustering Controlled Islanding (**SCCI**) algorithm can solve the optimization problem expressed in (4). Its solution is equivalent to determining a suitable islanding solution.

This solution can be found by constructing two graphs, based on the objective function and constraint from (4), and applying the **SCCI** algorithm to find the minimum cut of these two graphs.

In the *first step* of the **SCCI** algorithm, the dynamic graph G_D is constructed. It only contains the generator nodes and its edge weights of this graph are the synchronizing coefficients $\partial P_{ij}/\partial\delta_{ij}$ that describe the dynamic coupling between the nodes *i* and *j*. To satisfy the generator coherency constraint (1) the generator nodes are grouped using the *normalized spectral clustering* algorithm. These groups of generator nodes then serve as constraints for the second step of the **SCCI** algorithm.

In the *second step* of the algorithm, the static graph G_D is constructed using power flow data. It contains every node and the edge weights are defined as the absolute value of the active power exchange between nodes *i* and *j*,$|P_{ij}|$.ускакало вверх The nodes are then grouped using *constrained spectral clustering*, which will be described in this Section, to solve the optimization problem described in (4).

In Fig. 10 a flowchart depicting the execution of the **SCCI** algorithm is presented [16].

Obviously, a prerequisite for a successful algorithm execution is the information about the system state. This can be achieved by using PMU-based linear state estimators, which can be executed practically in real-time. For this purpose, approximately 30% of nodes of the transmission grid should be covered by PMUs.

To demonstrate the advantages and efficacy of the proposed SCCI algorithm, the IEEE 118-bus test system was used.

After executing the first algorithm step, the following three coherent groups of generators are obtained (see Table).

After executing the second algorithm step, the splitting solution presented in Fig. 11 was obtained. The two cutsets produced in the second step of the **SCCI** algorithm, separated Group 1 from Groups 2 and 3, and then separated Group 2 from Group 3, respectively. Combined, these two cutsets form the final islanding solution marked in Fig. 11.

As it was shown in [16], this method outperforms other methods aimed to be applied for controlled islanding. The method relies on understanding the system state and fast communication infrastructure needed to send centralized commands from the ESM to circuit breakers through which the islanding is happening.

The above islanding scheme is obviously quite advanced and it can be also extended to

Generator groups for the assessed IEEE 118-bus test system
Группы генераторов для оцениваемой 118-шинной тестовой системы IEEE

Group 1	Group 2	Group 3
10, 12, 25, 26, 31	46, 49, 54, 59, 61, 65, 66, 69, 80	87, 89, 100, 103, 111

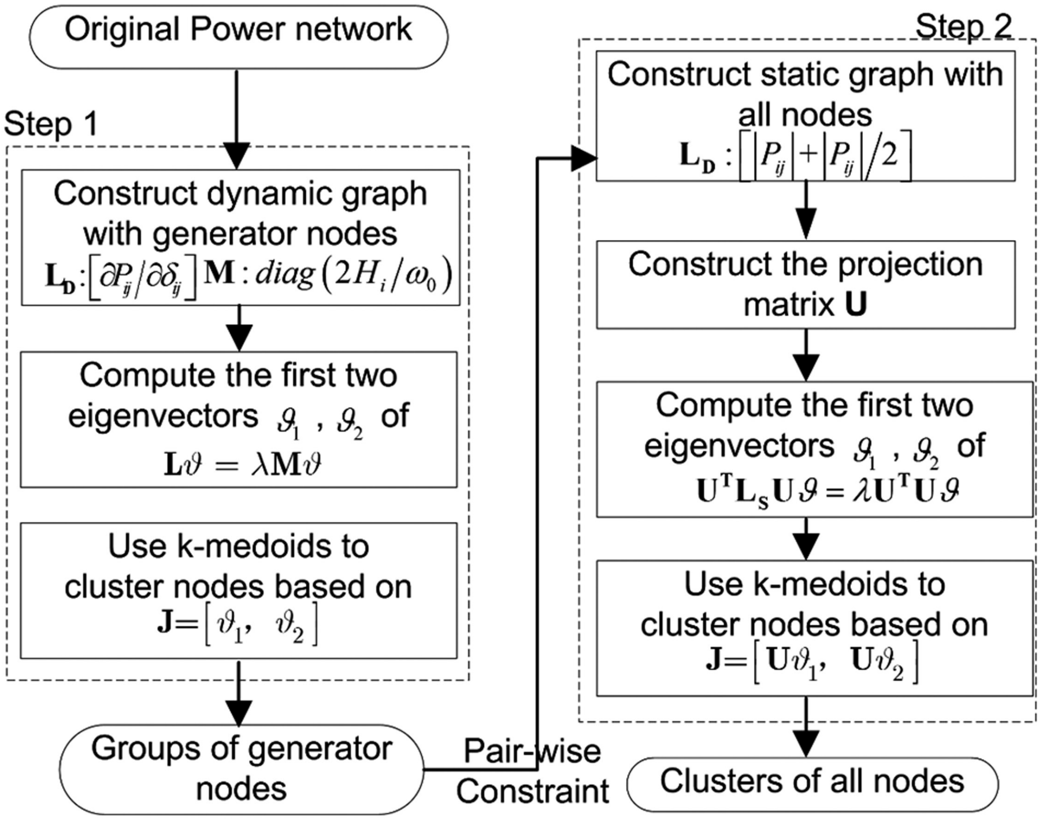

Fig. 10. *Flowchart of the* ***SCCI*** *algorithm [16]*
Рис. 10. *Блок-схема алгоритма SCCI [16]*

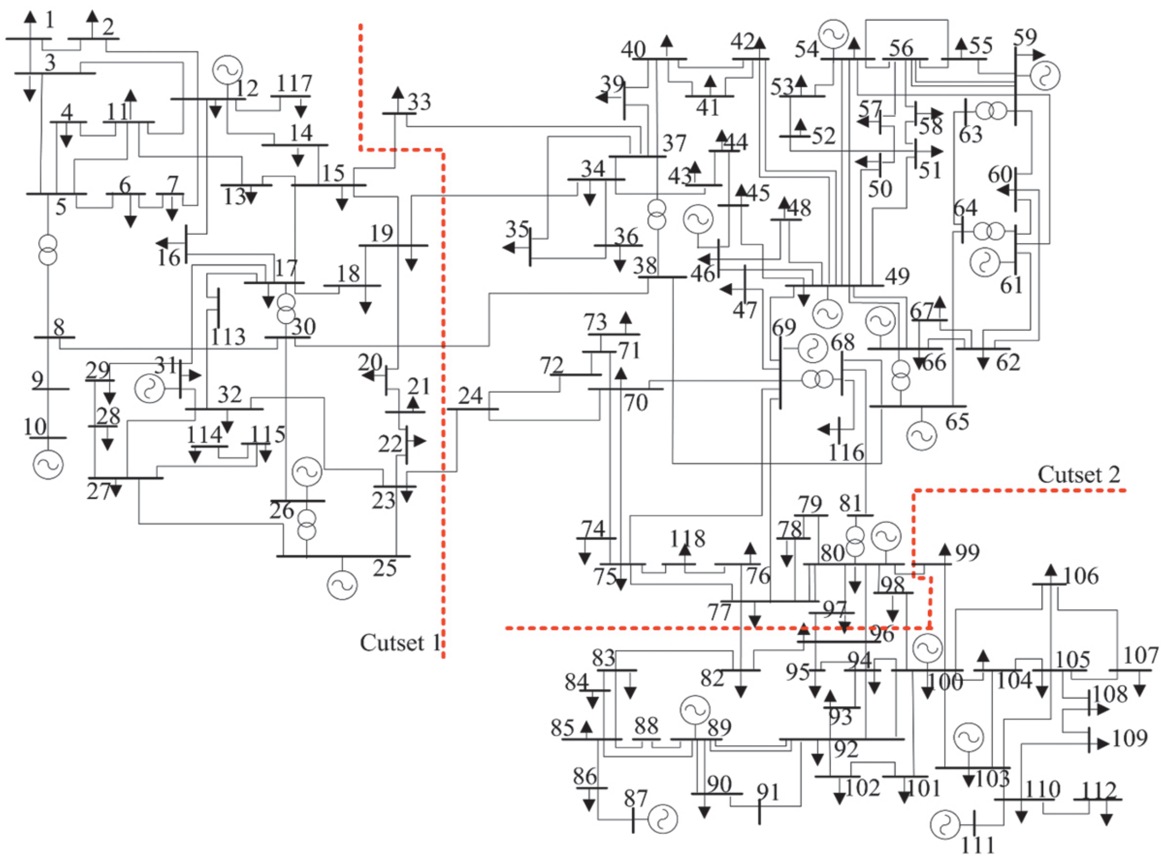

Fig. 11. *Single-line diagram of the IEEE 118-bus test network and the islanding solution [16]*
Рис. 11. *Однолинейная схема 118-шинной тестовой сети IEEE и изолированного решения [16]*

approaches focused on voltage stability. Fir, this purpose, real-time information about reactive powers in the grid would be critical [17]. On the other hand, information about the power flow in the grid with e.g. electric vehicles can be equally important to be known [18]. From the perspective of the understanding of the grid parameters measurement-based transmission line parameter estimation methods (e.g. [19]) can improve the confidence in the system data and consequently protection and control schemes supporting the system resilience.

The proposed control and protection schemes must be properly tested using e.g. hardware in the loop testing facilities [20]. Furthermore, the presented islanding methodology should also involve the assessment of the instant/moment when the islanding should occur, i.e. be applied. A research on this topic is addressed in [21]. Next, the islanding has to be effective in low inertia power systems, in which the quality of the system dynamics is different and application of islanding schemes even more challenging [22]. Last but not least, since the entire scheme relies on real-time data from the grid and commands to circuit breakers responsible for network splitting are sent over communication infrastructure (ICT), the security of this infrastructure must be extremely high and immune to potential cyber-attacks.

CONCLUSION

The paper discusses the challenges with future power networks in which the penetration level of converter interfaced generation and renewable energy sources is permanently increased, so that networks are becoming weak and prone to different types of instabilities. Digitalization and advanced technologies, based on novel sensor and communication infrastructure can support solutions for prevention of cascading events and power system blackouts. Discussing structure of typical SIPSs, it was concluded that modern situational awareness tools, integrated into modern EMSs can enable next generation of SIPSs, capable of preventing power system blackouts. The paper also describes a novel two-step Spectral Clustering Controlled Islanding Algorithm, for determining islanding solutions for power systems. At the core of this algorithm is a single optimization problem that uses the minimal power-flow disruption as objective function and considers ensuring generator coherency as a constraint. A more secure communication infrastructure (ICT) will enable practical solutions leading to advanced Wide Area Protection solutions. These will support even higher deployment of renewable energy sources and clean energy targets.

References

1. Marvin A. Konzeptionierung und erprobung von dezentralen frequenzhaltungsmaßnahmen und leistungsflussorientierten lastabwurfverfahren im verteilnetz. *Eldorado - Repositorium der TU Dortmund*. 2021. http://doi.org/10.17877/DE290R-22255.

2. Bendong T., Zhao Junbo, Netto M., Krishnan V., Terzija V., Zhang Yingchen. Power system inertia estimation: Review of methods and the impacts of converter-interfaced generations. *International Journal of Electrical Power & Energy Systems*. 2022;134:107362. https://doi.org/10.1016/j.ijepes.2021.107362.

3. Ritchie H., Roser M., Rosado P. Renewable energy sources are growing quickly and will play a vital role in tackling climate change. *Renewable Energy*. Available from: https://ourworldindata.org/renewable-energy [Accessed 29th September 2023].

4. Zhao Junbo, Tang Yi, Terzija V. Robust online estimation of power system center of inertia frequency. *IEEE Transactions on Power Systems*. 2018;34(1):821-825. http://doi.org/10.1109/TPWRS.2018.2879782.

5. Sun M., Feng Y., Wall P., Azizi S., Yu J., Terzija V. On-line power system inertia calculation using wide area measurements. *International Journal of Electrical Power & Energy Systems*. 2019;109:325-331. https://doi.org/10.1016/j.ijepes.2019.02.013.

6. Taylor P.C., Abeysekera M., Bian Y., Ćetenović D., Deakin M., Ehsan A., et al. An interdisciplinary research perspective on the future of multi-vector energy networks. *International Journal of Electrical Power & Energy Systems*. 2022;135:107492. https://doi.org/10.1016/j.ijepes.2021.107492.

7. Stankovic A. The definition and quantification of resilience. *IEEE PES. Power & Energy Society*. 2018. Available from: https://grouper.ieee.org/groups/transformers/subcommittees/distr/C57.167/F18-Definition&QuantificationOfResilience.pdf [Accessed 29th September 2023].

8. Panteli M., Mancarella P. The grid: stronger, bigger, smarter?: presenting a conceptual framework of power system resilience. *IEEE Power and Energy Magazine*. 2015;13(3):58-66. https://doi.org/10.1109/MPE.2015.2397334.

9. Bie Zhaohong, Lin Yanling, Li Gengfeng, Li Furong. Battling the extreme: a study on the power system resilience. *Proceedings of the IEEE*. 2017;105(7):1253-1266. https://doi.org/10.1109/JPROC.2017.2679040.

10. Wang Jiawei, Pinson P., Chatzivasileiadis S., Panteli M., Strbac G., Terzija V. On machine learning-based techniques for future sustainable and resilient energy systems. *IEEE Transactions on Sustainable Energy*. 2022;14(2):1230-1243. https://doi.org/10.1109/TSTE.2022.3194728.
11. Mohapatra P. Fitness project final report, network innovation and competition scheme, Ofgem. *Future Intelligent Transmission NEtwork SubStation*. 2015. Available from: https://www.ofgem.gov.uk/sites/default/files/docs/fitness_submission.pdf [Accessed 30th September 2023].
12. Clark S., Wilson D., Al-Ashwal N., Macleod F., Mohapatra P., Yu James, et al. Addressing emerging network management needs with enhanced WAMS in the GB VISOR project. In: *Power Systems Computation Conference*. 2016. https://doi.org/10.1109/PSCC.2016.7540948.
13. Wall P., Shams N., Terzija V., Hamidi V., Grant C., Wilson D., et al. Smart frequency control for the future GB power system. In: *IEEE PES Innovative Smart Grid Technologies Conference Europe*. 2016. https://doi.org/10.1109/ISGTEurope.2016.7856265.
14. Terzija V., Valverde G., Cai D., Regulski P., Madani V. Fitch Jo., et al. Wide-area monitoring, protection, and control of future electric power networks. In: *Proceedings of the IEEE*. 2010;99(1):80-93. https://doi.org/10.1109/JPROC.2010.2060450.
15. Terzija V. Adaptive underfrequency load shedding based on the magnitude of the disturbance estimation. *IEEE Transactions on Power Systems*. 2006;21(3):1260-1266. https://doi.org/10.1109/TPWRS.2006.879315.
16. Ding Lei, Gonzalez-Longatt F.M., Wall P., Terzija V. Two-step spectral clustering controlled islanding algorithm. *IEEE Transactions on Power Systems*. 2013;28(1):75-84. https://doi.org/10.1109/tpwrs.2012.2197640.
17. Dragosavac Ja., Janda Z., Milanovic Jo.V., Arnautovic D., Radojicic B. On-line estimation of available generator reactive power for network voltage support. In: *8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion*. 2012. https://doi.org/10.1049/cp.2012.2014.
18. Azizipanah-Abarghooee R., Terzija V., Golestaneh F., Roosta A. Multiobjective dynamic optimal power flow considering fuzzy-based smart utilization of mobile electric vehicles. *IEEE Transactions on Industrial Informatics*. 2016;12(2):503-514. https://doi.org/10.1109/TII.2016.2518484.
19. Li Changgang, Zhang Yaping, Zhang Hengxu, Wu Qiuwei, Terzija V. Measurement-based transmission line parameter estimation with adaptive data selection scheme. *IEEE Transactions on Smart Grid.* 2017;9(6):5764-5773. https://doi.org/10.1109/TSG.2017.2696619.
20. Shair Ja., Xie Xiaorong, Li Yunhong, Terzija V. Hardware-in-the-loop and field validation of a rotor-side subsynchronous damping controller for a series compensated DFIG system. *IEEE Transactions on Power Delivery*. 2020;36(2):698-709. https://doi.org/10.1109/TPWRD.2020.2989475.
21. Ding Lei, Guo Yichen, Wall P., Sun Kai, Terzija V. Identifying the timing of controlled islanding using a controlling UEP based method. *IEEE Transactions on Power Systems*. 2018;33(6):5913-5922. https://doi.org/10.1109/TPWRS.2018.2842709.
22. Ding Lei, Ma Zhenbin, Wall P., Terzija V. Graph spectra based controlled islanding for low inertia power systems. *IEEE Transactions on Power Delivery*. 2016;32(1):302-309. https://doi.org/10.1109/TPWRD.2016.2582519.

Список источников

1. Marvin A. Konzeptionierung und erprobung von dezentralen frequenzhaltungsmaßnahmen und leistungsflussorientierten lastabwurfverfahren im verteilnetz // Eldorado - Repositorium der TU Dortmund. 2021. http://doi.org/10.17877/DE290R-22255.
2. Bendong T., Zhao Junbo, Netto M., Krishnan V., Terzija V., Zhang Yingchen. Power system inertia estimation: Review of methods and the impacts of converter-interfaced generations // International Journal of Electrical Power & Energy Systems. 2022. Vol. 134. P. 107362. https://doi.org/10.1016/j.ijepes.2021.107362.
3. Ritchie H., Roser M., Rosado P. Renewable energy sources are growing quickly and will play a vital role in tackling climate change // Renewable Energy. Режим доступа: https://ourworldindata.org/renewable-energy (дата обращее ния: 29.09.2023).
4. Zhao Junbo, Tang Yi, Terzija V. Robust online estimation of power system center of inertia frequency // IEEE Transactions on Power Systems. 2018. Vol. 34. Iss. 1. 821–825. http://doi.org/10.1109/TPWRS.2018.2879782.
5. Sun M., Feng Y., Wall P., Azizi S., Yu J., Terzija V. On-line power system inertia calculation using wide area measurements // International Journal of Electrical Power & Energy Systems. 2019. Vol. 109. P. 325–331. https://doi.org/10.1016/j.ijepes.2019.02.013.
6. Taylor P.C., Abeysekera M., Bian Y., Ćetenović D., Deakin M., Ehsan A., et al. An interdisciplinary research perspective on the future of multi-vector energy networks // International Journal of Electrical Power & Energy Systems. 2022. Vol. 135. P. 107492. https://doi.org/10.1016/j.ijepes.2021.107492.
7. Stankovic A. The definition and quantification of resilience // IEEE PES. Power & Energy Society. 2018. Режим доступа: https://grouper.ieee.org/groups/transformers/subcommittees/distr/C57.167/F18-Definition&QuantificationOfResilience.pdf (дата обращения: 29.09.2023).
8. Panteli M., Mancarella P. The grid: stronger, bigger, smarter?: presenting a conceptual framework of power system resilience // IEEE Power and Energy Magazine. 2015. Vol. 13. Iss. 3. P. 58–66. https://doi.org/10.1109/MPE.2015.2397334.

9. Bie Zhaohong, Lin Yanling, Li Gengfeng, Li Furong. Battling the extreme: a study on the power system resilience // Proceedings of the IEEE. 2017. Vol. 105. Iss. 7. P. 1253–1266. https://doi.org/10.1109/JPROC.2017.2679040.
10. Wang Jiawei, Pinson P., Chatzivasileiadis S., Panteli M., Strbac G., Terzija V. On machine learning-based techniques for future sustainable and resilient energy systems // IEEE Transactions on Sustainable Energy. 2022. Vol. 14. Iss. 2. P. 1230–1243. https://doi.org/10.1109/TSTE.2022.3194728.
11. Mohapatra P. Fitness project final report, network innovation and competition scheme, Ofgem // Future Intelligent Transmission NEtwork SubStation. 2015. Режим доступа: https://www.ofgem.gov.uk/sites/default/files/docs/fitness_submission.pdf (дата обращения: 30.09.2023).
12. Clark S., Wilson D., Al-Ashwal N., Macleod F., Mohapatra P., Yu James, et al. Addressing emerging network management needs with enhanced WAMS in the GB VISOR project // Power Systems Computation Conference. 2016. https://doi.org/10.1109/PSCC.2016.7540948.
13. Wall P., Shams N., Terzija V., Hamidi V., Grant C., Wilson D., et al. Smart frequency control for the future GB power system // IEEE PES Innovative Smart Grid Technologies Conference Europe. 2016. https://doi.org/10.1109/ISGTEurope.2016.7856265.
14. Terzija V., Valverde G., Cai D., Regulski P., Madani V. Fitch Jo., et al. Wide-area monitoring, protection, and control of future electric power networks // Proceedings of the IEEE. 2010. Vol. 99. Iss. 1. P. 80–93. https://doi.org/10.1109/JPROC.2010.2060450.
15. Terzija V. Adaptive underfrequency load shedding based on the magnitude of the disturbance estimation // IEEE Transactions on Power Systems. 2006. Vol. 21. Iss. 3. P. 1260–1266. https://doi.org/10.1109/TPWRS.2006.879315.
16. Ding Lei, Gonzalez-Longatt F.M., Wall P., Terzija V. Two-step spectral clustering controlled islanding algorithm // IEEE Transactions on Power Systems. 2013. Vol. 28. Iss. 1. P. 75–84. https://doi.org/10.1109/tpwrs.2012.2197640.
17. Dragosavac Ja., Janda Z., Milanovic Jo.V., Arnautovic D., Radojicic B. On-line estimation of available generator reactive power for network voltage support // 8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion. 2012. https://doi.org/10.1049/cp.2012.2014.
18. Azizipanah-Abarghooee R., Terzija V., Golestaneh F., Roosta A. Multiobjective dynamic optimal power flow considering fuzzy-based smart utilization of mobile electric vehicles // IEEE Transactions on Industrial Informatics. 2016. Vol. 12. Iss. 2. P. 503–514. https://doi.org/10.1109/TII.2016.2518484.
19. Li Changgang, Zhang Yaping, Zhang Hengxu, Wu Qiuwei, Terzija V. Measurement-based transmission line parameter estimation with adaptive data selection scheme // IEEE Transactions on Smart Grid. 2017. Vol. 9. Iss. 6. P. 5764–5773. https://doi.org/10.1109/TSG.2017.2696619.
20. Shair Ja., Xie Xiaorong, Li Yunhong, Terzija V. Hardware-in-the-loop and field validation of a rotor-side subsynchronous damping controller for a series compensated DFIG system // IEEE Transactions on Power Delivery. 2020. Vol. 36. Iss. 2. P. 698–709. https://doi.org/10.1109/TPWRD.2020.2989475.
21. Ding Lei, Guo Yichen, Wall P., Sun Kai, Terzija V. Identifying the timing of controlled islanding using a controlling UEP based method // IEEE Transactions on Power Systems. 2018. Vol. 33. Iss. 6. P. 5913–5922. https://doi.org/10.1109/TPWRS.2018.2842709.
22. Ding Lei, Ma Zhenbin, Wall P., Terzija V. Graph spectra based controlled islanding for low inertia power systems // IEEE Transactions on Power Delivery. 2016. Vol. 32. Iss. 1. P. 302–309. https://doi.org/10.1109/TPWRD.2016.2582519.

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