PANEVĖŽIO KOLEGIJA ISSN 2029-1280, eISSN 2669-0071. Taikomieji tyrimai studijose ir praktikoje – Applied Research in Studies and Practice, 2024, 20.

REVIEW OF TECHNOLOGIES FOR STABILIZING ELECTRICAL NETWORKS THROUGH REACTIVE POWER COMPENSATION AS THE PENETRATION OF RENEWABLE ENERGY SOURCES INCREASES

Rokas BAGOČIŪNAS[a], Daiva STANELYTĖ[ab]

[a] *Klaipedos valstybine kolegija – Higher Education Institution, Lithuania*
[b] *Lithuanian Energy Institute, Lithuania*

Abstract. Technologies for generating electricity from renewable energy sources (RES) are becoming an integral and highly important part of the electricity generation market. The integration of these technologies into distribution networks is gaining momentum. However, alongside the benefits offered by these technologies, maintaining the stability of electric networks is becoming increasingly complex. This study analyses the impact of RES based power plants on the stability of network parameters and compares several technologies that are often the subject of scientific research to maintain their stability. The study found that RES plants have a negative impact on the stability of network parameters. The technologies most often considered in scientific research as alternatives for stabilizing network parameters are STATCOM, SVC and SC technologies. STATCOM technology is superior to SVC technology, which is a predecessor of the FACTS controller group, due to its characteristics. Comparing STATCOM and SC technologies is challenging due to the different operating principles and characteristics of these technologies. However, the choice between these three technologies should be based on the characteristics of the electrical network into which the technology will be integrated, as well as a cost-benefit analysis.

Keywords: reactive power compensation, Synchronous Condenser; Static Synchronous Compensator; Static Var Compensator

INTRODUCTION

Relevance. The European Union's (EU) Renewable Energy Directive (REDIII) states that by 2030, the EU aims to reduce greenhouse gas (CO_2) emissions by 55% and by 2050, the EU will achieve the climate neutrality target set by the Intergovernmental Panel for Climate Change (IPCC). This target represents a balance between the amount of CO_2 emitted and the amount of CO_2 naturally removed from the atmosphere, allowing the EU to be considered a climate-neutral entity. In September 2023, the European Parliament supported an agreement with the EU Council, which states that renewable energy will account for 42.5% of the total electricity generated in the EU by 2030 (up from the previous target of 32%).

Problem Statement. The increasing share of electrical energy generated by RES in the distribution networks poses significant challenges to the stability, inertia, balance, and efficiency of electric networks. As the characteristics of electricity generated from RES differ from those of electricity generated from fossil fuels, this integration creates significant complications in the energy sector and needs to be balanced. The parameters affected by the penetration of RES into the electricity networks can be divided into two main groups: those related to frequency stability and those related to voltage stability. Both parameters are crucial for the further integration of RES into the distribution networks, and therefore both will be examined in this article. However, due to the broad scope of these parameters, the focus is on the analysis of voltage stability.

Subject. Integration of RES into distribution networks.

The aim of the research: To analyze methods of electric grid stabilization through reactive power (Q) compensation as RES penetration increases in distribution networks.

The objectives of the research:

1. Investigate the impact of RES penetration in distribution networks.
2. Analize methods for stabilizing electric network parameters.
3. Provide a comparison of methods for stabilizing electric network parameters and identify the most effective reactive power (Q) compensation method.

Research methods: analysis of scientific literature.

Value of the Research: Given the lack of scientific research specifically focused on the impact of RES on the stability of electric grids followed by the analysis and comparison of different technologies aimed at stabilizing this impact, the primary objective of this article is to fill this research gap.

RESEARCH METHODOLOGY

This study employed a quantitative research method aimed at analyzing synthesized data from various primary studies. To analyze the negative impact of RES to the electrical network and technologies used to reduce it, a review of scientific literature sources was conducted. The reviewed sources included works by foreign authors, which allowed for

PANEVĖŽIO KOLEGIJA ISSN 2029-1280, eISSN 2669-0071. Taikomieji tyrimai studijose ir praktikoje – Applied Research in Studies and Practice, 2024, 20.

a detailed examination of the subject. Research data and theoretical reviews published in *Science Direct* and *IEEE* were analyzed. The suitability of scientific articles for analysis was assessed by reviewing titles, abstracts, and full texts. The literature search was methodical, thorough, as the most relevant databases were selected, where results of studies on the subject were published. A literature search was conducted, and all possible search terms describing the investigated concept were used. Based on the applied keyword combinations, 89,164 publications were identified. The results are presented in the table below.

Table 1

Results of the literature search in scientific article databases

Key words	Science Direct	IEEE	Total
Synchronous Condenser	5197	767	5964
Static Var Compensator	7586	5936	13522
Static Synchronous Compensator	7522	14067	21589
Reactive power compensation	11396	36693	48089
Total	31701	57436	89164

The study adheres to the principles of research ethics, as the information required for the study is accessible in scientific databases.

ISSUES WITH THE INTEGRATION OF RES INTO ELECTRICAL GRID

Most researchers analyzing mechanisms to compensate the negative impact of RES power plants to the grid stability note that as the development of RES technologies accelerates, the negative impact of these technologies on electric grids also accelerates. The last few decades have seen unprecedented growth in two technologies, solar and wind, which now account for 13% of total electricity generation. The annual growth rate of electricity generated by solar power plants is 27% and that of wind power plants is 13% over the last five years (Sinsel et al., 2020). The integration of RES is a crucial tool for reducing emissions and mitigating the effects of climate change (Musau et al., 2017). As the amount of electricity generated from RES power plants increases, the share of electricity generated from fossil fuels is continuously decreasing, which is beneficial for emissions control (Wang et al., 2017). However, as the share of electricity generated from RES increases globally, its impact on power grids becomes more significant, which poses challenges in planning, development and ensuring stable grid operation (Yan et al., 2019).

The main reasons often cited are the variability of RES power plants and their different technological characteristics compared to conventional electric power plants. RES generators have several disadvantages: their generated output is variable as it depends directly on natural conditions, the amount of power generated can be predicted but not controlled (Ghosh et al., 2020). As a result, voltage regulation in distribution system becomes more complex (Knittel et al., 2020). Energy generated from RES has different static and dynamic characteristics than traditional energy generated by synchronous generators (Yan et al., 2019). Traditional synchronous generators can provide inertia and primary frequency response to the electric grid, which RES generators cannot provide because they are connected to the grid through inverters and usually operate in a mode of maximum power generation to the grid (Fanglei et al., 2020). Most of the scientific research published agrees about the impact that RES to the electric grid, as well as the reasons for this type of impact.

ANALYSIS OF POWER GRID INERTIA AND FREQUENCY STABILITY

One of the most important parameters in electrical grids is the grid frequency and its stability. Frequency stability refers to the ability of the electric system to maintain a constant grid frequency when deviations from the normal operating mode occur, resulting in a significant imbalance between the power generated and consumed (Musau et al., 2017). The rapidly increasing integration of RES into distribution networks negatively affects the network inertia and the primary system response to frequency deviations (Qin et al., 2018). The inertia of a generator is described by its inertia constant H:

$$E = \frac{1}{2}J\omega^2;\ H = \frac{E}{S_B} = 1/2\,\frac{J\omega^2}{S_B} \qquad (1)$$

where **E** - kinetic energy stored in the rotating mass, **ω -** angular frequency, **J** - moment of inertia, $\mathbf{S_B}$ generator's rated power, **H** - inertia constant (indicates how long the generator can supply the grid with nominal power solely from the stored kinetic energy) (Musau et al., 2017).

The graph below shows the response of a traditional generator with a given inertia constant to a frequency drop in the electrical network.

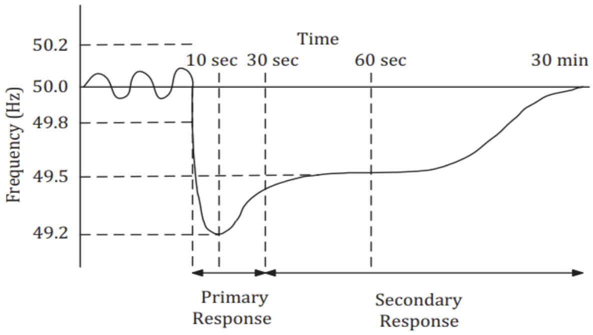

Figure 1. **Response of a traditional generator with a given inertia constant to a frequency drop in the system**

Low inertia levels may lead to large frequency swings under any circumstances, making it necessary to raise concerns about the security of power system (Huang et al., 2017).

The table below presents the inertia constants of different sources.

Table 2

Inertia constants

Source of electrical energy	H(s)
Steam	4-9
Gas	3-4
Water	2-4
Wind	2-5
Solar	0

As shown in the table above, RES have a lower inertia constant than other sources of energy.

ANALYSIS OF POWER GRID VOLTAGE STABILITY

Grid voltage is another parameter affected by the integration of RES technologies into distribution grids. Researchers in analyzed studies identify the nature and characteristics of RES power plant technologies as the main reasons for this impact. Parameters related to voltage in the electrical system play an important role in evaluating the quality of electrical power. Quality refers to the absence of deviation from the ideal parameter - a sine wave of constant frequency and amplitude (Okoń et al., 2016). The integration of RES into distribution networks significantly changes the characteristics of the electric network, making it more static due to the power electronic devices used to connect RES power plants to the grid, which complicates the voltage stabilization in the electrical network (Li et al., 2017). Due to the instability of RES sources, their accelerated integration has a negative impact on maintaining grid stability (Li et al., 2020). One way to stabilize the voltage in the grid is through Q compensation (Okoń et al., 2016). Q compensation involves the regulation of the Q component to increase the efficiency of AC power generation in power grids (Zhou et al., 2018).

The equation describing the dependence of transmission line voltage on Q is:

$$\frac{\partial V_j}{\partial Q_{ij}} = \frac{X+\left(R^2+X^2\right)*\frac{Q_{ij}^{(r)}}{V_i^2}}{\sqrt{V_i^2+2\left(R*P_{ij}+X*Q_{ij}^{(r)}\right)+\left(R^2+X^2\right)*\frac{P_{ij}^2+Q_{ij}^{(r)2}}{V_i^2}}} \quad (2)$$

Where **V_i, V_j** – voltages at different ends of the transmission line; **P_{ij}, Q_{ij}** – active and reactive power **R**, **B, X** **-** transmission line branch parameters (Okoń et al., 2016).

The graph below presents the dependence of voltage at different ends of the transmission line from Q.

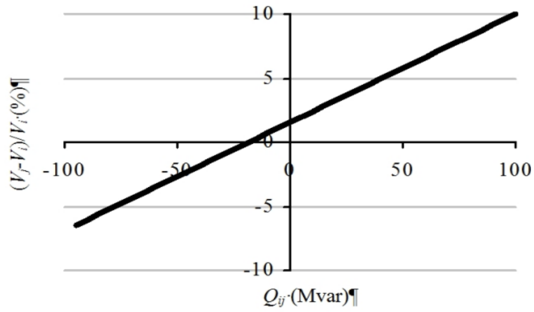

Figure 2. **the dependence of voltage at different ends of the transmission line on Q**

Q compensation can improve the network power factor, effectively stabilize the voltage and its fluctuations, and reduce transmission line power losses (Zhou et al., 2018). Compensation of Q is a widely used technology for stabilizing the voltage in electric network.

METHODS FOR VOLTAGE STABILIZATION BY COMPENSATING Q
STATIC VAR COMPENSATORS

It is observed that one of the most frequently analyzed technologies in scientific research for quality compensation and network parameter stabilization is the Static Var Compensator (SVC). SVC is a type of controller in the family of flexible AC transmission systems (FACTS), which is controlled by thyristors (hence called static) and can generate reactive power with lagging or leading power factor (Zhou et al., 2018). FACTS controllers are very fast acting power electronic devices that influence the characteristics of the electrical network (Bharti et al., 2016). This type of controller is designed to increase the efficiency of the electrical network by reducing losses in transmission lines (Qatamin et al., 2017).

A typical SVC controller schematic and its main components are shown below:

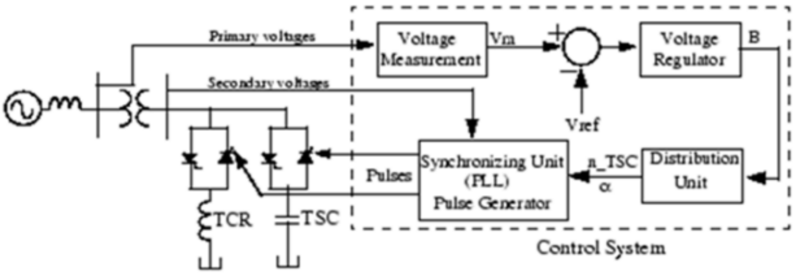

Figure 3. **Typical SVC controller schematic and its main components**

A typical SVC system consists of two main components: a thyristor-controlled reactor (TCR) and a thyristor switched capacitor (TSC) (Zhou et al., 2018). When the SVC system connects the TCR or TSC to the circuit, it generates reactive power with a lagging or leading power factor (Qatamin et al., 2017). Therefore, by connection of TCR or TSC a shift of the phase angle between the voltage and the current is achieved.

STATIC SYNCHRONOUS COMPENSATOR

The Static Synchronous Compensator (STATCOM) is another widely researched technology that is considered a superior and more modern modification of the SVC. STATCOM is a member of the FACTS controller's family, typically used in long-distance power transmission lines, substations, and industries where voltage stability is critical (Rijesh et al., 2017).

STATCOM generates variable Q for the electrical network by modulating the amplitude and phase angle of the current (Zhou et al., 2018).

A typical STATCOM controller schematic and its major components are shown below:

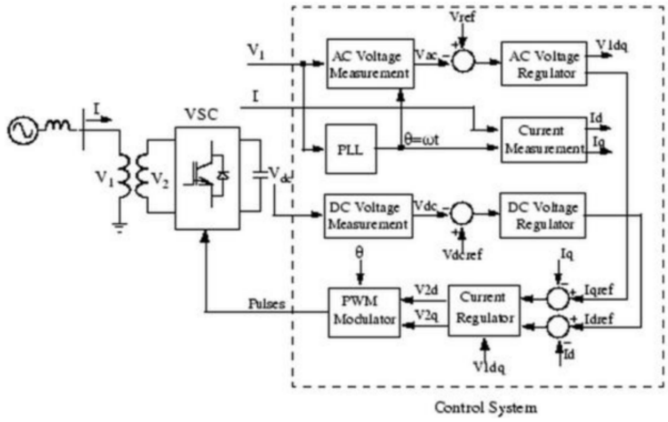

Figure 4. **Typical STATCOM controller schematic and its main components**

A typical STATCOM system: 3-phase voltage source converter (VSC) based on gate turn-off thyristors (GTO) or insulated gate bipolar transistors (IGBT), a step-down transformer, direct current (DC) capacitor, and a VSC controller (Bao et al., 2021). The controller changes the amplitude and phase angle of the modulated parameter through the VSC (Rijesh et al., 2017). STATCOM technology is widely used in compensation of Q.

PANEVĖŽIO KOLEGIJA ISSN 2029-1280, eISSN 2669-0071. Taikomieji tyrimai studijose ir praktikoje – Applied Research in Studies and Practice, 2024, 20.

SYNCHRONOUS CONDENSER

Researchers claim that the technology of the synchronous condenser (SC) is a long-known and widely used technology in electrical networks, which is currently undergoing a revolution. It often becomes the subject of scientific research as one of the alternatives for Q compensation and electrical network stabilization. SC is a system that has played an important role in voltage regulation and reactive power compensation for more than 50 years (Zhou et al., 2018). The excitation system of an SC can be classified as DC or AC, depending on the nature of its power source (Bao et al., 2021). Below is an example of a SC DC excitation system.

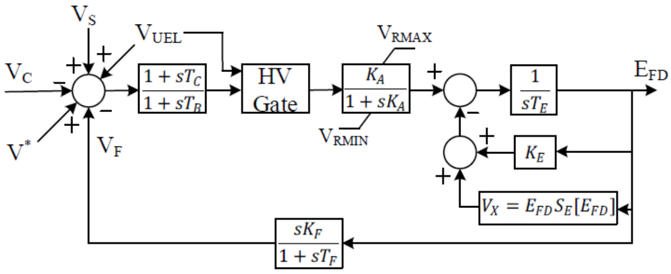

Figure 5. **Typical SC controller schematic and its main components**

Where **V_c** – input voltage, **V_s** – voltage obtained from the stabilizer, **V_{REF}** – reference voltage, **V_F** – output voltage, **T_A** and **T_B** – time constants of the voltage regulator. An SC is a rotating synchronous electric machine connected to the electric network without a mechanical load, controlled by a voltage regulator, and used for Q compensation (Huang et al., 2017). After the machine is connected to the electric network, by changing the excitation current of the machine, it generates Q with a leading or lagging power factor (Zhou et al., 2018). A synchronous machine with an excitation current control system can provide the electrical network with continuous Q compensation (Zhou et al., 2018). SC is a well-known and effective technology.

COMPARISON OF DIFFERENT TECHNOLOGIES
COMPARISON OF STATCOMC AND SVC SYSTEMS

At this point, there is no doubt that STATCOM is a superior FACTS controller technology for Q compensation. Numerous scientific studies, researchers, and practical applications confirm this, with the only cited drawback being the relatively higher cost of STATCOM systems. It is observed that when comparing the performance of SVC and STATCOM systems of the same rating in the electrical network, the STATCOM system is more effective during grid disturbances (Bharti et al., 2016). Currently, SVC technology is advanced and widely deployed. However, the influence and the importance of STATCOM (as a more advanced technology) in maintaining grid stability is growing. The only factor slowing down this growth is the relatively higher system cost (Zhou et al., 2018). The graph below shows the impact of FACTS devices on network voltage.

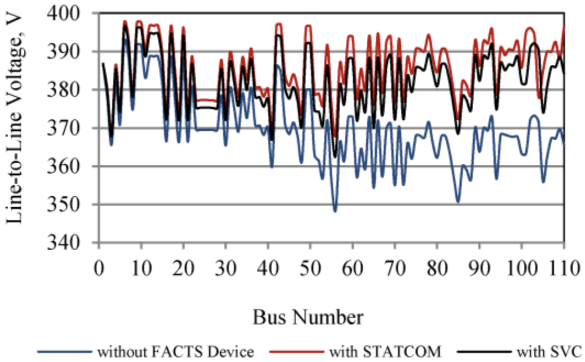

Figure 6. **The impact of FACTS devices on electrical network voltage**

As shown, the best measured voltage profile in the electrical network is achieved with STATCOM.

COMPARISON OF STATCOM AND SC SYSTEMS

When comparing STATCOM with SC systems, the opinions of different researchers vary. Some of them state that SC systems are rarely used today due to their complex structure. These systems have a negative impact on short-circuit currents in electrical networks and cannot be controlled quickly enough to compensate for load changes (Zhou et al., 2018). The graphs below show the voltage fluctuations in the electrical network during a disturbance.

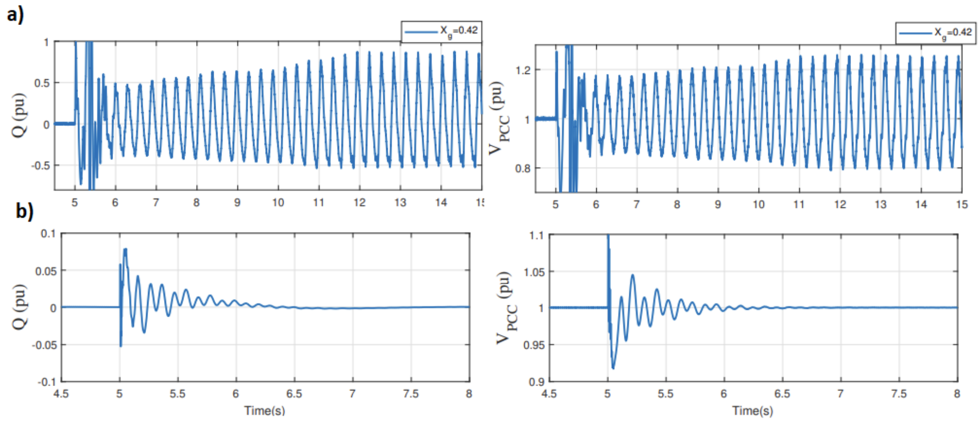

Figure 7. **Voltage fluctuations in the electrical network during a fault**

The graphs in the previous page indicate two scenarios of electric grid disturbance: a) disturbance of electric grid connected with STATCOM without compensation of Q. b) disturbance of electrical grid of the same magnitude connected with SC instead of STATCOM without compensation of Q. At the moment the disturbance occurs the electric system connected to STATCOM, and its parameters start to fluctuate greatly and become unstable, resulting in a system collapse. However, the electrical system connected to SC shows signs of grid stabilization even without Q compensation, only because of its stored inertia in the rotating mass. Therefore, according to other researchers, before mentioned disadvantages of SC systems are being questioned. As they state, it is observed that SC systems have several advantages compared to STATCOM and SVC: these systems positively affect the network inertia due to the energy stored in their rotating masses, thereby improving stability. In addition, they have a positive effect on the network's resistance to short-circuit currents during faults (Geis-Schroer et al., 2020). To continue, some of the authors state that, the losses in SC systems are high, and compared to STATCOM, these systems are more expensive (Zhou et al., 2018). However, other authors in their study publications provide examples of how the installation cost of these systems can be reduced. In many cases, decommissioned synchronous generators from traditional power plants can be converted to SC systems at minimal cost. For example, Siemens has implemented several such systems in Germany (Geis-Schroer et al., 2020).

According to some researchers, when comparing SVC, SC, and STATCOM technologies, the STATCOM system is the most advanced, has better dynamic characteristics, and will be the most widely used in the future (Zhou et al., 2018). However, the operating mechanisms of these systems are different, making direct comparison a complex task. The choice between one system or the other is not simple. The choice must consider the characteristics of the electrical network in which the device will be installed, which requires a more comprehensive study to evaluate these characteristics (Kynev et al., 2016). As stated before, the results of scientific research vary and the comparison of the two systems is complex.

CONCLUSIONS

Technologies for generating electricity from renewable energy sources (RES) are becoming an integral and highly important part of the electricity generation market. The integration of these technologies into distribution networks is gaining momentum. However, alongside the benefits offered by these technologies, maintaining the stability of electricity networks is becoming increasingly complex. After analyzing the impact of RES based power plants on the stability of network parameters and comparison of several technologies that are often the subject of scientific research to maintain their stability, it is concluded that:

1. RES power plants have a negative impact on the stability of network parameters due to the characteristics of electricity generation from RES compared to electricity generated by conventional plants.
2. The most common subjects of scientific research as alternatives for stabilizing network parameters and minimizing the impact of RES to electric grids are: STATCOM, SVC, and SC technologies.
3. When comparing STATCOM and SVC technologies, STATCOM is undoubtedly the superior type of FACTS controller. However, the relatively high cost of these technologies necessitates a proper cost-benefit analysis of the electrical network into which the technology will be integrated to select the appropriate technology. On the other hand, STATCOM and SC technologies differ in their operating principles, making their comparison quite complex. Therefore, only a proper assessment of the characteristics of the electrical network into which the technology will be integrated and a conducted cost-benefit analysis can provide more information for technology selection.

Throughout this study it has been observed that the analyzed methods for voltage stabilization through Q compensation rely on reacting to events or disturbances in the electrical grid. Consequently, there is always a delay before corrective actions are taken in response to these events or disturbances. As the integration of RES into distribution networks continues, the impact on the electrical grid is likely to intensify. Therefore, to balance the integration of RES it might become necessary to develop prediction and forecast-based Q compensation and load control systems. The digitalization of electrical networks is likely to gain great importance. Furthermore, the rapid advancement of artificial intelligence technology may play a crucial role in the development of such prediction-based control systems to achieve a controlled and balanced integration.

REFERENCES

1. Bharti, S. Dewangan, S. Ram (2017). Performance of wind farm distribution system under balanced and unbalanced condition with SVC & STATCOM, 1-4. Retrieved from: https://doi.org/10.1109/IREC.2017.7926048.
2. Bao, L. Fan, L. Miao, Z. (2020). Comparison of Synchronous Condenser and STATCOM for Wind Farms in Weak Grids, 1-6, Retrieved from: https://doi.org/10.1109/NAPS50074.2021.9449775.
3. Fanglei, L. Fan, W. Jiaming, Y. Guoyi, X. Tianshu, B. (2020). Estimating Maximum Penetration Level of Renewable Energy Based on Frequency Stability Constrains in Power Grid, 607-611, Retrieved from: https://doi.org/10.1109/ACPEE48638.2020.9136471.
4. Geis-Schroer, J. Nair, A. R. Patel, S. Kamalasadan, S. (2020). Modeling and Analysis of Weak Grid Considering Phase Locked Loop and Synchronous Condenser Effect on Grid Stability, 1-6, Retrieved from: https://doi.org/10.1109/PESGRE45664.2020.9070728.
5. Ghosh, R. Tummuru, N. R. Rajpurohit, B. S. Monti, A. (2020). Virtual Inertia from Renewable Energy Sources: Mathematical Representation and Control Strategy, 1-6, Retrieved from: https://doi.org/10.1109/PESGRE45664.2020.9070733.
6. Huang, H. Chu, X. (2017). Improving rotational inertia of power system with variable speed synchronous condenser, 1-5, Retrieved from: https://doi.org/10.1109/PESGM.2017.8274191.
7. Knittel, M. Majumdar, N. Schneider, M. Thie, N. Moser, A. (2020). Voltage Control in Transmission Grids Considering Uncertainties of Renewable Energy Sources, 580-585, Retrieved from: https://doi.org/10.1109/ENERGYCon48941.2020.9236597.
8. Kynev, S. Pilz, G. Schmitt, H. (2016). Comparison of modern STATCOM and synchronous condenser for power transmission systems, 1-6, Retrieved from: https://doi.org/10.1109/EPEC.2016.7771769.
9. Li, Y. Chi, Y. Tian, X. Liu, C. Hu, J. Fan, Y. Fan, X. Xiao, Y. Wang, C. et al. (2020). Research on Capacity Planning of Renewable Energy Grid Integration Based on Effective Short Circuit Ratio, 622-627, Retrieved from: https://doi.org/10.1109/iSPEC50848.2020.9351108.
10. Li, Y. Tian, X. Liu, C. Su, Y. Li, L. Zhang, L. Sun, Y. Li, J. et al. (2017). Study on voltage control in distribution network with renewable energy integration, 1-5, Retrieved from: https://doi.org/10.1109/EI2.2017.8245755.
11. Musau, M. P. Chepkania, T. L. Odero, A. N. Wekesa, C. W. (2017). Effects of renewable energy on frequency stability: A proposed case study of the Kenyan grid, 12-15, Retrieved from: https://doi.org/10.1109/PowerAfrica.2017.7991192.
12. Okoń, T. Wilkosz, K. (2016). Impact of reactive-power optimization on voltages in a power system, 674-678, doi: 10.1109/ICHQP.2016.7783403.
13. Qatamin, A. Etawi, A. Safasfeh, G. Ajarmah, N. Al-Jufout, S. Drous, I. Wang, C. Soliman, A. H. (2017). SVC versus STATCOM for improving power system loadability: A case study, 1-4, Retrieved from: https://doi.org/10.1109/IREC.2017.7926048.
14. Qin, X. Su, L. Jiang, Y. Zhou, Q. Chen, J. Xu, X. Chi, Y. An, N. (2018). Study on Inertia Support Capability and Its Impact in Large Scale Power Grid with Increasing Penetration of Renewable Energy Sources, 1018-1024, Retrieved from: https://doi.org/10.1109/POWERCON.2018.8601687.
15. Rijesh, A. Chakraborty, S. (2017). Performance analysis of smart device — STATCOM for grid application, 1-5, Retrieved from: https://doi.org/10.1109/TENCONSpring.2017.8069999.
16. Sinsel, S. R., Rimkie, R. L., Hoffmann., V. H. (2020) Challenges and solution technologies for the integration of variable renewable energy sources – a review. Renewable Energy, 2271-2285, Retrieved from: https://doi.org/10.1016/j.renene.2019.06.147.
17. Wang, Z. Luo, D. Li, R. Zhang, L. Liu, C. Tian, X. Li, Y. Su, Y. He, J. (2017). Research on the active power coordination control system for wind/photovoltaic/energy storage, 1-5, Retrieved from: https://doi.org/101109/EI2.2017.8245403.
18. Yan L., Xiaohui Q., Yongning C., Xinshou T., Sujuan S., Shenglun Z., Xiangmei K., Lei S. (2019). Study on Requirement of Control and Stability with Renewable Energy Generation Grid Integration, 26-30. Retrieved from: https://doi.org/10.1109/APAP47170.2019.9224875.
19. Zhou, X. Wei, K. Ma, Y. Gao, Z. (2018). A Review of Reactive Power Compensation Devices, 2020-2024, Retrieved from: https://doi.org/10.1109/ICMA.2018.8484519.