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REVIEW OF VARIOUS TECHNOLOGIES OF SMART GRID MANAGEMENT FOR INCREASING THE FLEXIBILITY OF THE POWER SYSTEM AND ENABLING MASS INTEGRATION OF RENEWABLE ENERGY SOURCES

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Summary

Over the last 15 years, major changes have taken place in the electricity sector. A significant increase in the share of renewable energy sources (RES) with variable generation, followed by the decommissioning of conventional power plants based on fossil fuels, has dramatically changed the way of the power system (EPS) operation. During this time, there has been inadequate and untimely investment in the transmission infrastructure. This occurred partly due to the lack of funding, and partly due to the climate change and the rising environmental awareness, as well as the influence of green activists making it difficult to obtain permits to build electrical grid facilities. Additionally, electricity consumption is steadily increasing due to population growth in the undeveloped and developing countries, and due to the rising living standard in the developed countries. Therefore, global electricity consumption is expected to triple by 2050. To meet the new demands, Transmission System Operators (TSOs) are deploying advanced transmission technologies based on a comprehensive application of information and communication solutions. These technologies increase the capacity, efficiency, and reliability of both the existing and new elements of the transmission system. These solutions applied vary from system to system and depend on many influencing factors. The application of these advanced technologies is particularly important for congestion management, as the power system operates closer and closer to stability limits, increasing the risk of collapse. The paper describes the technologies that transform the existing network into smart grids, primarily from the point of view of increasing the capacity of the existing infrastructure through different smart grid investments.

Keywords: renewable energy sources; smart grid; flexibility; transmission grid.

1. INTRODUCTION

Restructuring of the electricity sector is significantly affecting the operation and the management of electric power systems. Different countries have different reasons for introducing changes to the energy sector and select different ways to cope with the necessary changes. Some of them tend to decrease greenhouse gas emissions, while othere try to meet the rapidly increasing consumption [1]:

Under the European Green Deal, the EU has committed itself to climate neutrality by mid-century, which will require more ambitious transformations than do currently exist. The main path to climate neutrality is followed by the accelerated decommissioning of conventional power plants based on fossil fuels and their replacement with renewable energy sources (RES). Consequently, the RES production units with variable generation (solar, wind) represent an increasing share of the total generation combined with rigid environmental requirements, which makes it difficult to obtain new corridors for the construction of a new transmission infrastructure.

In North America, overloads and congestions and a high average age of infrastructure and plants is resulting in relatively frequent outages in separate segments of the system. Problems are evident especially during peak hours, and with an increasing share of the RES, the volatility of electricity prices is also significantly increased, which further worsens the peak hour problems. In addition thereto, the problem of cybersecurity has become more evident recently.

In South America, there is a trend toward modernization of the distribution network due to rising standards and population growth, and the resulting increase in electricity consumption. Furthermore, due to large technical and special commercial losses, the construction of new generation and transmission facilities has recently been intensified.

In Asia, there is also a significant increase in population, migration to cities, and a high level of industrialization, resulting in an increase in consumption and the construction of new generation plants, which is not accompanied by an adequate expansion of the transmission network, often leading to congestion. Apart from this, there are large economic losses and enormous environmental pollution due to CO_2 emissions.

A growing share of renewable energy, i.e. wind and photovoltaic (PV) power plants, in the overall power generation mix, combined with the simultaneous retirement of conventional coal-fired power plants, is putting increasing pressure on power system operations. Massive penetration of power electronic based devices (renewable and conventional energy generation, loads, electric vehicles, energy storages) due to the need for synchronization of various AC and DC sources to the AC power grid is also significantly changing the characteristics of a conventional bulk power system. Some of the key operational challenges include:

- faster dynamics
- reduced system inertia
- shorter time delays
- weakened damping ability
- reduced frequency regulation
- insufficient reactive power for voltage regulation
- steep load ramps
- over-generation
- adequacy risks
- grid congestion
- negative load
- energy trading effectiveness

To meet the new requirements, Transmission and Distribution System Operators have begun deploying advanced technologies based on the extensive application of information and communication solutions, better known as advanced networks. These technologies increase the capacity, efficiency, and reliability of the existing and new elements of the power system, although the solutions applied vary from system to system.

2. SMART GRIDS

The concept of smart grids can be clearly explained using the example of telecommunications by comparing the functions of an ordinary telephone with those of a smartphone, which offers many different features in addition to voice communication, such as e-mail, short message services – SMS, various Internet services, etc.

Similarly, in today's power system (Fig. 1), various innovative technologies are introduced, which complement each other and form the basis for tomorrow's advanced intelligent grids (Fig. 2) [2]. An intelligent or a smart grid integrates advanced sensing technologies, control methods and integrated communications into the current electricity grid. Rapid modern development of information and communication technologies (ICT) is the key enabling factor for different smart grid applications.

In Fig. 1 and Fig. 2, it is important to see that the direction of power flows changes due to distributed generation and storage devices. In this way, the distribution grids become active, and the whole grid is shifting towards a more decentralized structure where 100% inverter-based islands or autonomous microgrids may occur. This significantly complicates its control, setting up the relay protections, and interactions occur between all participants in the system. Increased installations of distributed energy resources (DERs) lead to the need for smart power system operation in distribution grids [2], both at low-voltage (LV) and medium voltage (MV) levels (Fig. 3).

Fig. 1. Today's Power System [2]
Sl. 1. Današnji EES [2]

Fig. 2. Tomorrow's Power System: A Smart Grid [2]
Sl. 2. Budući EES [2]

Table 1 shows the fundamental differences between the today's and the foreseeable smart future networks [3][4].

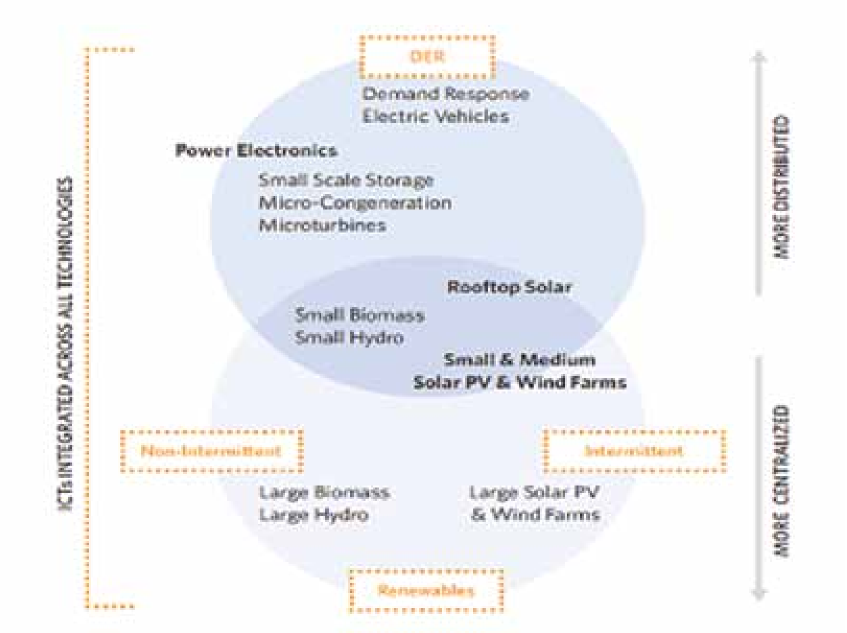

Fig. 3. ICT enables parallel operation of centralized and distributed resources
Sl. 3. IKT omogućuju paralelni rad centraliziranih i distribuiranih resursa

Table 1. Differences between todays and smart networks
Tablica 1. Razlike između današnjih i naprednih mreža

	current grid	**smart grid**
communication	*None or one-way,* *not real-time*	*Two-way, real time*
interaction with users	*limited*	*extensive*
metering	*electromechanical*	*digital*
operation	*manual*	*remote*
maintenance	*periodical*	*condition-based*
generation	*centralized*	*centralized and distributed*
power flows control	*limited*	*comprehensive*
reliability	*prone to failures and cascade outages*	*proactive, real-time predictions*
reconnection	*manual*	*self-healing*
topology	*radial,one-way power flow*	*network, multiple power flows*

Generally, there are three main definitions of smart grids:

The European Union Commission Task Force for Smart Grids [3]: an electricity network that can cost-efficiently integrate the behavior and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety. A smart grid employs innovative products and services, together with intelligent monitoring, control, communication, and self-healing technologies in order to:

1. Better facilitate the connection and operation of generators of all sizes and technologies.
2. Allow consumers to play a part in optimizing the operation of the system.
3. Provide consumers with greater information and options for how they use their supply.
4. Significantly reduce the environmental impact of the whole electricity supply system.
5. Maintain or even improve the existing high levels of system reliability, quality, and security of supply.
6. Maintain and improve the existing services efficiently.

US Energy Independence and Security Act of 2007 [6]: It is the policy of the United States to support the modernization of the Nation’s electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet the future demand growth, and to achieve each of the following, which together characterize a Smart Grid:

1. Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.
2. Dynamic optimization of grid operations and resources, with full cyber-security.
3. Deployment and integration of distributed resources and generation, including renewable energy resources.
4. Development and incorporation of demand response, demand-side resources, and energy-efficiency resources.
5. Deployment of ‘smart’ technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation.
6. Integration of ‘smart’ appliances and consumer devices.
7. Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal storage air conditioning.
8. Provision to consumers of timely information and control options.
9. Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.
10. Identification and lowering of unreasonable or unnecessary barriers to the adoption of smart grid technologies, practices, and services.

Smart Grid Strategic Group (IEC) [7]: a concept for modernizing the electricity networks, which integrates electrical and information technologies in any point of the network, from generation to consumption.

The concept of smart grids is often associated only with the distribution grids and the integration of the DER, advanced meters and active load control, including electric vehicles and energy storage, as well as the provision of various new services to customers and distribution system operators. However, the development of smart grids is also directly related to the transmission system, which is expected to become even more advanced than it is today [1].

The introduction of smart grids involves significant investments in the power system, the profitability of which should be encouraged by appropriate regulations, as well as clear incentives from the state and society. Throughout the process, the emphasis should be placed on educating consumers to create willingness in order to adopt new habits to take advantage of smart grids, from peak load reduction to automatic consumer switching driven by price signals (Fig. 4).

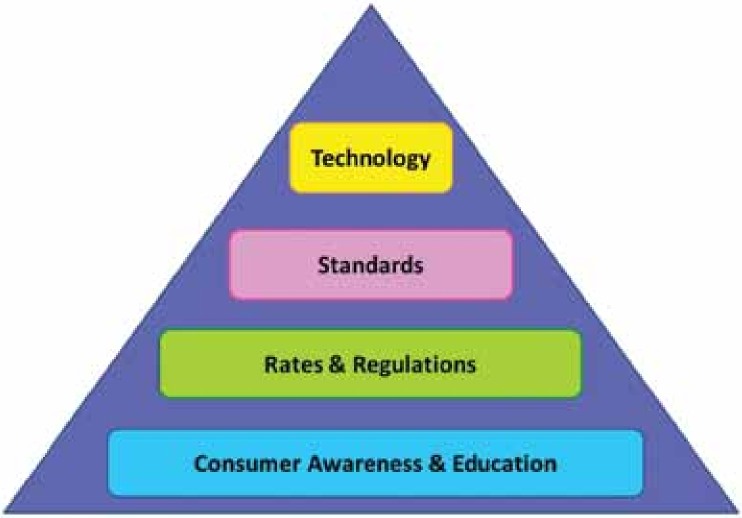

Fig. 4. Basic prerequisites for the introduction of smart grids [8]
Sl. 4. Osnovni preduvjeti za uvođenje naprednih mreža [8]

3. INTERNET OF THINGS (IOT) AND INTERNET OF ENERGY (IOE)

Smart Grids transform the future of utility infrastructure. The first step in the evolution plan is to add an end-to-end layer of digital sensors to existing electric power networks. Technology developments in sensors, robotics, unmanned vehicles, satellite, and wireless data communications significantly increase the opportunity for automated, unmanned/continuous monitoring of transmission and distribution lines and facilities. An important feature of the power system is flexibility and interoperability, with a wide variety of sensor types and communications methods. All of these characteristics are enabled by the implementation of the **Internet of Things**, an IT concept based on the idea that all common physical objects are connected to the Internet and have the ability to identify themselves with other devices.

The main characteristics of IoT concept are [9]:

- things that have unique identities can be easily found and therefore object + identity become more important than object alone;
- things that are traditionally not associated with the Internet (transformers, switchgear, lines, utility meters, motors, etc.) get their unique IoT identity;
- things communicate and exchange data (data base), and can be controlled from anywhere. Despite limited computing resources of single object connection to the global Internet network, new possibilities of monitoring, control and advanced services are still enabled.

The increase in the use of the Internet of Things (IoT) technologies in maintenance is particularly noticeable [9].

The Internet of Energy means universal connectivity for the entire power system chain, i.e. networking smart energy infrastructure components such as substations, circuit-breakers, energy storage, etc. This is achieved through the ICT-enabled information exchange and distribution platforms that enable access and management of energy resources through the multitude of mobile, PC, and Internet-connected device-based applications. The non-operational data from transformer and substation monitoring can account for 80% of the value gained from advanced monitoring and diagnostics.

As the networks continue to modernize, new sources of data and new, previously unimagined uses for the data have yet to be discovered and transformed into value for all stakeholders.

4. SMART TRANSMISSION GRIDS

In case of the transmission system, which still is and will continue to be the backbone of the electric power system, outages of parts of the transmission system are significantly less common today than in the distribution system, but the consequences are much greater when they do occur. This is the result of continuous monitoring of some elements of the transmission system. Using the advanced monitoring technologies, the major transformers are now continuously monitored by default. Monitoring of circuit breakers and transmission lines is still in its starting phase, although a number of technical solutions already exist.

A. Digitalization of the transmission system and control centers

Digitalization for power transmission primarily means generation and collection of data from sensors, automation equipment, and entire plants and its further usage for actionable insights to optimize grid operations, whether it's managing demand increase, transformer overload, or aging equipment insulation. In other words, digitalization means both ensuring the functionality of critical infrastructure and improving the TSO profitability. 5G networks, IoT technology, the ever-growing number of sensors, cloud and edge computing, advanced analytics, and intelligent cybersecurity give the tools to build the networks of the future, including new business models.

Today, an electrical substation is represented in a network control center as a single data point that attracts an operator's attention only when something goes seriously wrong, for example when a transformer or circuit breaker fails. In the near future, the system will be augmented by a data stream from the asset, which is equipped with all sorts of sensors and connectivity features and connected directly to a 'digital twin' of the substation on a secure cloud platform. This digital twin will be able to simulate the asset in real time, enabling better maintenance planning, easier asset management and higher availability of electricity supply [13].

Automation of the power grid at all levels is in full swing. The technical solutions used in the plants have been significantly improved (Fig. 5 and Fig. 6), and new ways of implementing and linking protection and control functions are applied. In general, efforts are made to simplify the design of primary equipment and extend its service life.

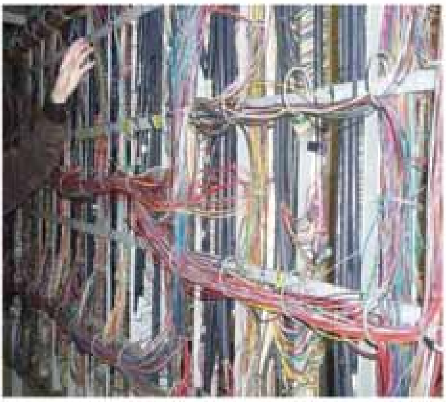

Fig. 5. Classic cabinet wiring in switchgear plants
Sl. 5. Klasično ožičenje ormara u rasklopnim postrojenjima

Fig. 6. Advanced ICT solutions with the same functionality
Sl. 6. Napredna ICT rješenja s istom funkcionalnošću

The basis of advanced transmission networks are advanced control centers, where the control of the power system is carried out at the level of individual primary equipment, whole plants, and the entire system. The subject centers have advanced remote-control systems with Energy Management System (EMS) / Market Management System (MMS) / Distribution Management System (DMS) / Outage Management System (OMS) functions, communicating with the equipment through advanced communication protocols such as IEC 61850, advanced visualization and alarm systems, integration of control systems with business systems of system operators, and interaction with market applications.

Due to the interconnectedness of energy and information flows, it is necessary to ensure two-way communication in real time, i.e. it is necessary to choose an appropriate strategy for the development of communication infrastructure based on the application of broadband technologies. This is a prerequisite for the inclusion of consumers in the concept of smart grids. This is very important, because the management of a large number of consumers in consumer facilities will facilitate the integration of intermittent renewable energy sources into the system. In addition thereto, it is also possible to facilitate the maintenance of stable operation of the power system operation in case of overload and congestion in the network. It should be emphasized that the application of information and communication solutions in modern power grids brings new challenges in terms of cybersecurity.

Great importance is attached to the improvement of the RES production forecasting and automatic determination of atmospheric discharges based on real-time weather monitoring, which ensures rapid intervention in case of failure, as well as intensive development of information systems for processing and managing failures, outages, and maintenance works. Modern control centers ought to ensure the supervision and management of all the participants in the network (Fig. 7).

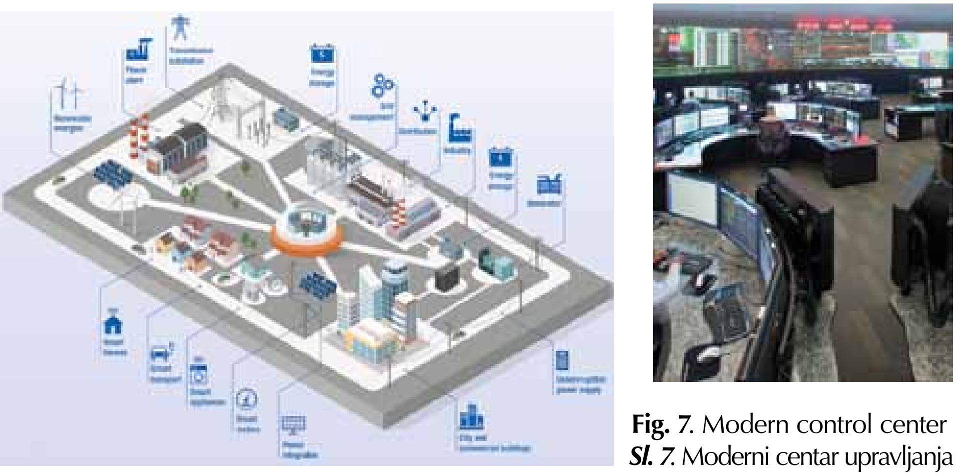

Fig. 7. Modern control center [7]
Sl. 7. Moderni centar upravljanja [7]

B. Transmission lines

In case of transmission lines, many causes of potential failures and threats have been identified (Fig. 8), and the proposed solutions are mainly based on the installation of various sensors that can monitor a number of parameters. Sensors are distributed on transmission structures and/or conductors, and have wireless or wired communication with the "hub" installed on the structure. Diagnostic data can be collected periodically or continuously, and enable power companies to always see the operating status and ambient conditions of devices and systems in real time. Power equipment and sensing devices with advanced networking connectivity and computing capabilities transform the centralized command and control of distributed grid architectures.

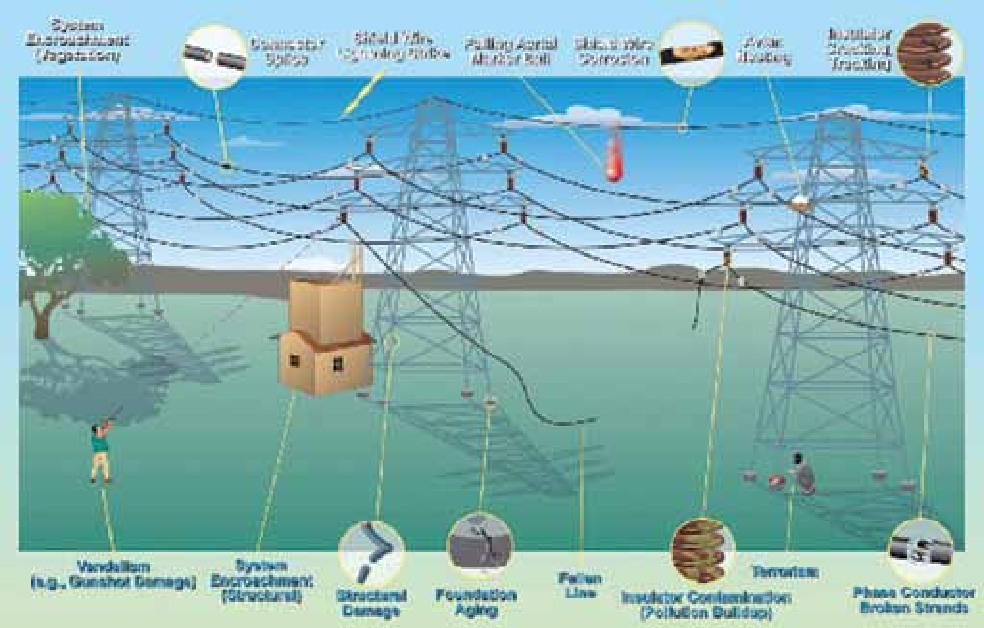

Fig. 8. Sensor Needs for transmission lines and towers [11]
Sl. 8. Potrebni senzori za dalekovode i stupove [11]

The main effort is to increase the security of power transmission while increasing the use of transmission capacity. The most-used method is real-time monitoring of conductor temperature and weather conditions. Fig. 9 show power lines with sensor technology designed to increase the efficiency, reliability, safety, and security of power transmission [7].

Given the expected evolution of power transmission systems, advanced transmission technologies can be divided into four main groups [12]: passive network elements, active network elements, real-time transmission system monitoring systems, and elements that have a direct effect on TSOs activities.

Passive network elements, mainly related to high-voltage elements of the alternating transmission system (High-Voltage Alternative Current – HVAC) such as: increasingly represented underground/submarine XLPE cables with voltage levels of 110 kV and higher, Gas Insulated Lines (GILs), high temperature conductors made of composite materials (High Temperature Conductor – HTC or High Temperature Low Sag conductors – HTLS), high temperature superconducting cables and compact overhead power lines with innovative towers with insulated or composite cross-arms and/or poles with multiple conductors (multiple wires), etc.

Active network elements with the possibility of load flows control, improving system stability or damping of inter-area oscillations. Subject elements include Phase Shifting Transformers (PSTs), High-Voltage Direct Current lines (HVDC), Flexible Alternating Current Transmission System devices (FACTS), and Fault Current Limiters (FCL).

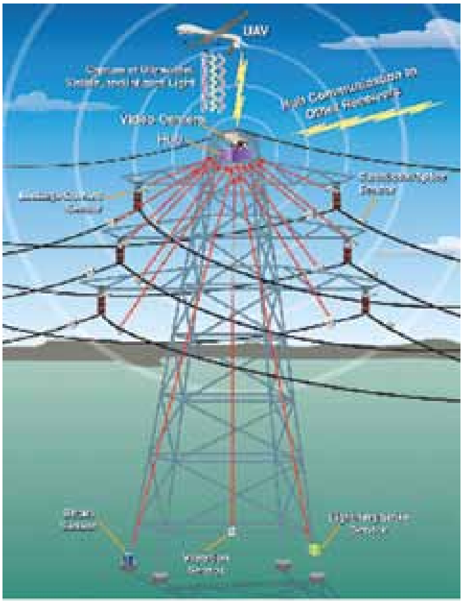

Fig. 9. Transmission line/tower monitoring applications
Sl. 9. Primjene nadzora prijenosnih vodova/stupova

Real-time transmission system monitoring includes Phasor Measurement Units (PMU), Wide Area Monitoring Systems (WAMS), weather monitoring (Lightning Location System – LLS), monitoring of important equipment (transformers, circuit breakers, etc.) and advanced lines and cables with the possibility of dynamic increase of transmission capacity by controlling the conductor temperature (Real Time Thermal Rating –RTTR).

Equipment with direct effects on TSOs operations, based on new technologies installed in the distribution system: Advanced Metering Infrastructure (AMI), various energy storage technologies, electric vehicles, etc.

The paper focuses on describing the operation of active network elements (HVDC, PST and FACTS) and systems for real-time monitoring the elements of the transmission system (WAMS and RTTR), as these are the technologies that increase the flexibility of the power system and enable the mass integration of renewable energy sources.

5. ACTIVE NETWORK ELEMENTS

A. High-voltage DC lines (HVDC)

The problem of distance between consumption and production, often concentrated in remote and difficult-to-access locations, contributed to the development of high-voltage direct transmission.

The invention of the controllable mercury rectifier in the 1930s launched the development of high-voltage DC transmission in Sweden. Experimental transmission of direct current overhead line was performed in the USSR in 1950 on the 100 kV overhead line Kashira–Moscow, 112 km long, and the transmitted power was 30 MW. The world's first commercial DC transmission was put into operation in 1954. It was a transmission link between the island of Gotland and the Swedish mainland, 96 km long, with a transmission voltage of 100 kV, a maximum transmission power of 20 MW (corresponding current of 200 A). The transmission line consisted of only one submarine cable (Cu 90 mm2), as the return path to the current was through the sea. Today, hundreds of DC transmission lines are in operation worldwide.

The introduction of DC transmission into practical application depended primarily on the development of devices called converters. This term is a common name for rectifiers – used to convert AC current to DC – and inverters, used to convert DC current to AC. The rapid development was initiated after the discovery of thyristor valves, which soon replaced the mercury valves used until then. As early as in 1967, the Swedish factory ASEA installed them in the converter station upstream of the aforementioned Gotland transmission, and the use of thyristors increased the transmission power of the direct energy link to the island of Gotland by 50%.

The basic component of thyristor valves is the thyristor, a common name for various types of silicon semiconductors. Thyristors are four-layer p-n-p-n solid-state semiconductor devices. It acts exclusively as a bistable switch, conducting current when the gate receives a current trigger, and continuing to conduct until the voltage across the device is reversed biased, or until the voltage is removed. Thyristors serve primarily as rectifiers, control and switching elements. Their greatest advantage over other semiconductor devices is their ability to control signals of large amounts of power with low power consumption, or the extremely low power required to control thyristor operation.

The longest (2500 km) HVDC in the world was put into operation in 2014 in Brazil. It connects the converter stations Porto Velho (Maideri River) and Sao Paulo, line voltage is 1200 kV (± 600 kV phase voltage), capacity 6300 MW, and transmission length 800 kilometers. One of the most significant DC transmission applications is the 2071 km long Xiangjiaba–Shanghai HVDC in China, ± 800 kV phase voltage, and 6400 MW transmission capacity. The Ekibastuz Center transmission system, from Central Asia (North Kazakhstan) to the central European part of Russia, which was designed in the mid-1970s, stands out too. The line voltage is 1500 kV (± 750 kV to ground), and the transmission power is 6000 MW. The HVDC transmission in bipolar configuration, 3000 MW, 940 km long, built in 2004, connects the world's largest hydropower plant HPP Three Gorges and Guandong (± 500 kV phase voltage).

Although the price of thyristor valves is continuously decreasing with the development of technology, converter plants are still very complex and expensive. The cost of their construction is significantly higher than the cost of conventional designs of transformer and switchgear stations. However, the additional investment required for converter stations in a DC transmission system can be offset by lower investment for DC transmission lines.

The requirement is that the transmission line is long enough. There is a certain limit for the transmission length, and if it is exceeded, the cost of building DC transmission systems becomes lower than the cost of building a suitable three-phase transmission line (given the possibility of transmitting the same electric power). It is not possible to say in advance, at the design stage, where this limit will be. The only thing that is certain is that the limit distance in question is much longer if the transmission is realized by overhead line than by cable. As a rough estimate, it is about 500-600 kilometers for overhead lines and 30-50 kilometers for submarine cables by today's standards, when AC transmission is not practical, since it requires the construction of a compensation facility because of high capacitive cable currents. The cost-effectiveness of the DC transmission comes from the fact that a DC transmission line needs two conductors, not three as a three-phase, and even one is enough if earth (or water) is used for the return path.

In case of the DC cable transmission, after connecting to the DC voltage, the cable is charged, and the charging current no longer flows. The DC transmission is further used for connection of lines between two systems in cases where a stability problem occurs or in cases of different rated frequencies (Fig. 10).

The DC transmission system consists of four main parts: two converter stations (terminals), the transmission line or cable, and the earthing system.

The DC terminals consist of converters, converter transformers, AC circuit breakers, AC and DC harmonic filters, reactive power compensator, DC reactors, DC switch-disconnectors, and control system.

According to the used technology for the power conversion process, the HVDC is divided into two main categories: Line Commutated Converters (LCC) and Voltage Source Converters (VSC).

1) LCC converters

Classical high-voltage DC transmission is based on the use of LCC converters. LCC is a current source converter (CSC). In its manufacturing, economical and robust high-capacity thyristors are used, which are suitable for the transmission system. Today’s thyristors are characterized by switching voltages (blocking) of up to 8 kV and maximum currents of up to 4 kA. In converter stations, thyristors are connected to bridges and form the so-called 6-pulse converters. They are connected in parallel or in series to form a 12-pulse converter to block voltages exceeding 100 kV that occur in the HVDC systems.

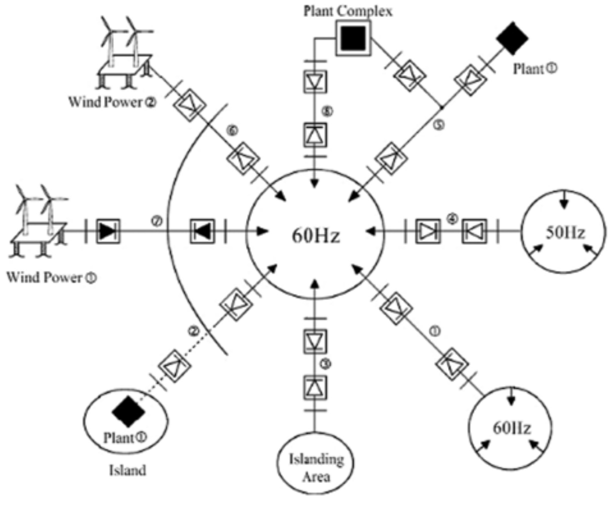

Fig. 10. Various applications of the HVDC systems
Sl. 10. Razne primjene HVDC sustava

Parallel thyristor connections cause operational difficulties, so phase-shifting transformers are used in converter stations. Two-winding transformers of vector group Yy and Yd are used. A 6-pulse bridge circuit is connected to the primary side, and another similar bridge to the secondary side rotated by 30°. It is also possible to use a three-winding transformer, although its use is avoided due to its large dimensions. Transformers further reduce harmonics, resulting in significant savings on filters. The LCC converter is an inductive load, and consumes reactive power during operation. The delay of the firing angle in case of thyristors delays the current relative to the voltage. A reactive power compensation of the order of 50% of the active power is necessary to adapt the current value of the compensation to the current value of the active power.

2) VSC converters

Gate Turn off Thyristor – GTO or Bipolar Insulated Gate Bipolar Transistor – IGBT can be used in this type of converter, and today the IGBT technology is mainly used. Their characteristic is that they can be turned on and off at any time, unlike thyristors used in LCC converters. IGBT cells are 1 cm^2 in size and connected in parallel with silicon IGBT chips, which operate for currents of 50 A to 100 A maximum. The IGBT chips are connected in parallel (up to 48 chips) in one package together with a diode and form an IGBT module of nominal current 2,4 kA and voltage 6,5 kV. The IGBT modules have significant losses during operation, the power of which can be several kilowatts. Therefore, special attention should be paid to their cooling and construction.

The possibility of independent use or generation of reactive and active power eliminates the need to install a device for compensating reactive power and reduces the number of filters installed. A Pulse-Width Modulation (PWM) is used to control the operation of the semiconductor switches to generate an approximate sine wave on the AC side in case of the inverter and vice versa in case of the rectifier. Only a standard transformer, reactor and capacitor are required to operate the VSC converter on the AC side.

The VSC converters have several advantages over the LCC converters, such as: lower harmonic generation, possibility of connection to relatively weak AC networks, no active power required to operate the converter, and good controllability. Their greatest advantage is the fast and independent control of reactive and active power and the possibility of black start. The switching is modulated by a self-generated signal, and both ends of the transmission line should not be connected to the active network, but one end can be passive. Due to the possibility of power control, it is possible to change the load flow without changing the polarity of the conductor.

The negative characteristics of the VSC converters are relatively high cost and losses, and lower operating voltage than the LCC converters. Despite these shortcomings, the VSC converters are often used to connect the RES (especially offshore wind farms), as in case of multi-terminal networks. The main reason for this is the possibility of flexible control of active and reactive power, and the ability to mitigate voltage dips and frequency oscillations due to changes in wind power.

There are three DC transmission system configurations: back-to-back systems, point-to-point systems, and multi-terminal systems. Each of these HVDC configurations typically consists of multiple cascade groups with several converters. The inverters are connected in parallel to the AC side of the transformer, and in series to the DC side (where the valves are located) to obtain the desired voltage level.

1. In high-voltage **back-to-back DC systems**, the converters are located in the same station. In this case, there is no DC transmission line, only the conversion of power in the converter stations. The back-to-back configuration is used when connecting networks with different nominal frequencies, when connecting asynchronous networks with the same frequency, or in cases where it is necessary to prevent an increase in short-circuit currents when connecting a large power plant or two large power systems, or to increase the stability of the connection.

2. Point-to-point systems consist of two converters and a DC line, and three main types exist: 1) monopolar, 2) bipolar, and 3) homopolar.

In *monopolar transmission (UmkV)*, only one conductor is used, which is at a potential above (+) or below the ground potential (-), depending on the direction of power flow, and earth or water is used as the return line (Fig. 11). The subject configuration is the cheapest solution not only due to the fact that one conductor is used and not two or more. When using a single conductor, the DC poles carry half the load and are therefore smaller, cheaper to manufacture, and easier to lift during construction. Monopolar or unipolar transmission is mainly used for submarine cables. Monopolar transmission can also be used with overhead lines. In this case, there is no risk of harmful effects from the current flowing through the earth, which otherwise prevents the earth from being used as a return path for electricity in the AC circuits. Since the current flow in the DC circuits is not affected by inductance, but only by resistance, the DC return current flows only in well-conducting deeper layers of the earth's crust. Only at the end points of the transmission line, in the immediate vicinity of the grounding

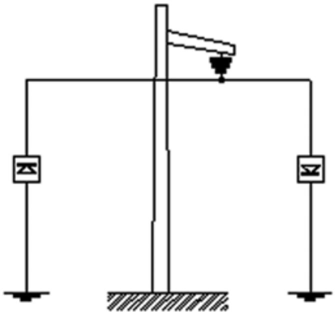

Fig. 11. Monopolar DC transmission
Sl. 11. Monopolarni DC prijenos

electrodes, where the current still flows close to the earth's surface, the current through the earth can be dangerous for humans and animals. In case of overhead lines, *symmetrical monopolar transmission* is usually used when two conductors are used. If the transmission system is not grounded, then two DC lines with full insulation are required.

Bipolar transmission (± UmkV), The DC line consists of two conductors (Fig. 12) with opposite polarity (main and return line). The advantage is that if a fault occurs on a single line or converter, the system can operate as a monopolar configuration. In case of overhead DC transmission lines, it is more advantageous for construction reasons to use a transmission line with two conductors instead of only one.

Earth is regularly used as a return path, allowing each pole to operate independently of the other. When the current in both conductors is equal, no current flows through the earth, which is the most common case. In the event of a fault in one conductor, transmission occurs through another conductor without interruption, using the earth as a return path, which is particularly advantageous during a thunderstorm. In normal operation, bipolar transmission causes considerably less harmonic interference to the nearby objects and equipment than monopolar transmission. The change in current flow direction is achieved by changing the polarity of the poles with no need for switching operations.

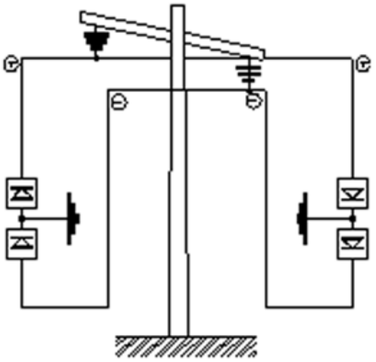

Fig. 12. Bipolar DC transmission
Sl. 12. Bipolarni DC prijenos

Homopolar transmission consists of two or more conductors with the same polarity (Fig. 13). The negative polarity is usually used, since it causes less radio interference during corona. The return path in this case is the earth. In the event of a fault in one of the conductors, the entire converter is available to supply power to the other conductor, which can transmit more than the rated power due to the possibility of overload, which is sometimes very important for normal system operation. Switching the entire router to one conductor in case of bipolar transmission is either not possible or very complex.

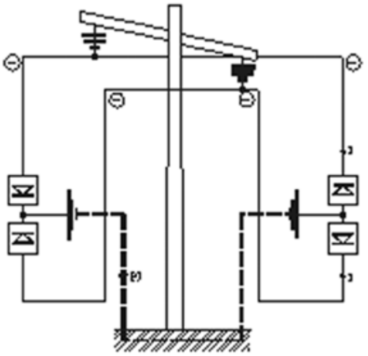

Fig. 13. Homopolar DC transmission
Sl. 13. Homopolarni DC prijenos

In case of the conversion of the HVAC line into the HVDC line, it is the so-called **three-pole DC transmission**. Then one bipolar and one monopolar DC transmission system is used.

3. Multiterminal systems include three or more converter stations that are geographically distant from each other and are connected by the DC transmission lines or cables. The converter stations may be connected in parallel or in series, and may be of any type, although the most used combination is of the VSC and the LCC converters. The multi-terminal interconnection method enables the creation of a DC transmission network, to which several different AC transmission systems are connected.

3) Comparison of DC and AC transmission

The first indicator comparing the economics of transmission with a three-phase AC line with three conductors and a DC line with two conductors provides an answer to the question: how much power can we transmit with the first line, and how much with the second? It is assumed that both lines have the same conductors (design, material, and cross-section) and the same insulation (dimensions and insulating medium).

In general, the transmission power of a line depends on the level of the transmission voltage to ground and on the current in the conductor. Specifically in this case, it depends on the number of conductors, since it affects the total power of the line too. If in both cases the voltages to ground are equal and the load is such that the current in the conductors of both lines is equal (equal mean (rms) values of the AC current and the DC current value), and the power factor in case of the AC transmission is very close to 0,95, the transmitted power per conductor on both lines is the same.

It follows that the total power transmitted by the AC line is about 1.5 times greater than in case of the DC line. Since both currents, the effective current of the AC line and the direct current of the DC line, heat the conductors equally, the same conclusion applies to the limits of power transfer in terms of conductor heating when the conductor temperature is at the thermal limit. It is easy to prove that in case of equal insulation on both lines, a voltage $\sqrt{2}$ times higher than the rms value of the voltage on the conductor AC line can be applied to the conductor DC line (Fig. 14). The ratio of the power that can be transmitted from a DC line, and a one conductor of the three-phase AC line is:

$$\frac{p_{(=)}}{p_{(\sim)}} = \frac{V_{(=)}}{V_{(\sim)}} \cdot \frac{I_{(=)}}{I_{(\sim)}} \cdot \frac{1}{\cos\varphi} = \frac{\sqrt{2}\,V_{(\sim)}}{V_{(\sim)}} \cdot \frac{I}{I} \cdot \frac{1}{\cos\varphi} = \frac{\sqrt{2}}{\cos\varphi} = 1{,}5 \qquad (1)$$

In reality, this ratio is even greater than 1.5 (per conductor) for overhead lines and, according to the literature, ranges up to about 4 (Fig. 15), since transmission capacities depend on other factors (besides those discussed here). It follows that an AC line with three conductors and a DC bipolar line with two conductors can transmit about the same electrical power:

$$\frac{P_{(istosmj.)}}{P_{(izmjen.)}} = \frac{2 \cdot p_{(=)}}{3 \cdot p_{(\sim)}} = \frac{2}{3} \cdot 1{,}5 = 1 \qquad (2)$$

It should further be noted that the capital cost of building the DC line is much lower than for the AC line. When building a bipolar DC line, two conductors are needed instead of three conductors as in case of a three-phase AC line (same conductors and insulation on both lines). Moreover, the DC requires 2/3 of the insulators with respect to the three-phase AC line. Towers for lines with two conductors (the DC transmission) are simpler and narrower, and therefore cheaper, resulting in a narrower corridor through which the line passes, and smaller foundations are needed for the towers. All this affects the lower price for the purchase, preparation, and maintenance of the overhead line corridor.

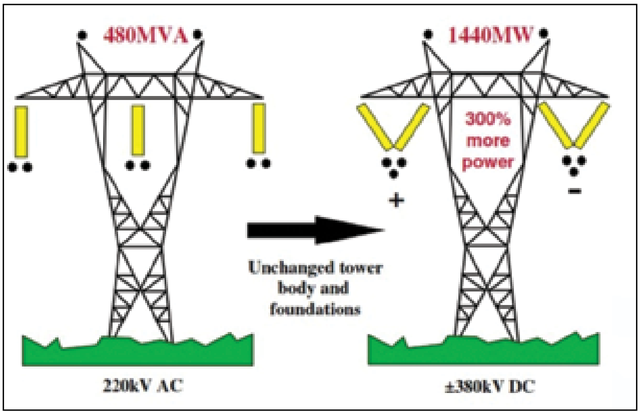

Fig. 14. Comparison of capacities of the AC and the DC lines on the same towers with different voltage levels
Sl. 14. Usporedba kapaciteta AC i DC vodova na istim stupovima s različitim naponskim razinama

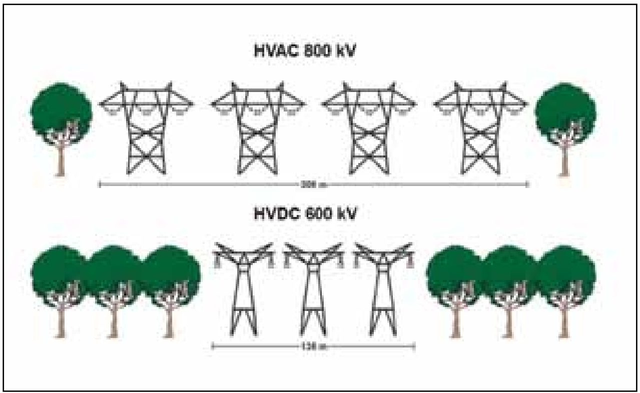

Fig. 15. Comparison of corridors of the AC and the DC lines of the same capacity with different towers and voltage levels
Sl. 15. Usporedba koridora AC i DC vodova istog kapaciteta s različitim stupovima i naponskim razinama

A comparison of the total power losses in the conductors in case of bipolar DC line and the three-phase AC line, with the same transmitted power through both lines, also argues in favor of the DC transmission of electricity. The power losses per conductor are about the same for equal currents, although they would be slightly higher for the AC transmission due to the skin effect. Given the number of conductors on both lines, it follows that the percent power loss in a bipolar DC line with two conductors is about 2/3 that in a three-phase AC line with three conductors. If the comparison of the two lines were based on equal power losses, then it would be true that a DC line can transmit $\sqrt{3}/2$ times more power (about 22% more power) than with a three-phase AC line with three conductors.

All of the above applies to overhead lines. For cable lines because of the different spatial distances between conductors and the different relative permeability of the insulation, and they are even more favorable for the case of the DC transmission. For the same conductors and the same insulation dimensions, the transmission power of a DC cable is several times higher than the transmission power of a three-phase AC cable. This is so because the allowable voltage per unit of insulation thickness is higher for the DC cables than for the AC cables, and the power factor for transmission with the AC cables is much lower than the values applicable to overhead lines. Therefore, it is possible to transmit 5-10 times more power with a DC cable than with an AC cable.

In cases where transmission distances are long enough, it is worth investing money in converters to convert the AC to the DC. In addition thereto, the DC transmission has other advantages over the AC, e.g.: reducing problems with voltage stability in the system, lower short-circuit currents, and easier system management, because the current flows are controlled, high reliability and long life of the equipment.

In short, the DC transmission solves the following shortcomings of the AC transmission:

- simpler and cheaper construction of transmission lines;
- no technical limitations on the length of submarine cables;
- no requirement for synchronous operation of connected systems; it is thus possible to connect the AC systems with different frequencies;
- no effect on the level of short-circuit currents in the AC; it is thus unnecessary to replace circuit breakers and other equipment in the facilities after the construction of the DC lines, and disturbances in the AC networks are not transmitted through the DC;
- no sensitivity to changes in impedance, angle, frequency and voltage;
- facilitates frequency and load control;
- transmission losses are lower (active power losses are lower and reactive power losses are zero), although the inverters consume a lot of active power from the AC system during operation;

- improves the stability of the AC system by enabling load flow control through the system while reducing power fluctuations and line overloads.

A major disadvantage of the HVDC transmission is the cause of harmonics in the AC network due to the operation of the converter and the lack of standardized high-speed DC circuit breakers below [14]. The existing mechanical HVDC circuit breakers can interrupt direct currents for tens of milliseconds, which is not satisfactory for reliable operation of a direct current system. In practice, standard AC switches are used, to which a capacitor bank (rated voltage of several kilovolts) is added, which discharges at the moment of switching off, generating a current opposite to the fault current in the HVDC system, thus extinguishing the arc.

The problem is that in the event of a short circuit in the HVDC network, the fault will propagate much faster and more strongly than in the AC grid due to the relatively low impedance, causing a collapse of the HVDC grid, so the requirements for the DC circuit breakers are much more rigorous. A prerequisite for normal operation of converter stations is to maintain the voltage in the HVDC network at the prescribed minimum levels (usually above 80% of the rated voltage), and the time of disconnection of short circuits is only a few milliseconds (about 5 milliseconds in case of high-voltage DC cables). Therefore, the HVDC circuit breakers based on power electronics have been developed, which are fast enough, but generate extremely high losses, reaching up to 30% of the consumption of the entire converter station. A few years ago, the ABB introduced a hybrid DC switch that switches off 1 GW of power in 5 milliseconds [14]. The leading companies in the development of high-voltage DC technology are Siemens, ABB and Alstom.

In the Croatian power systems, there are no installed HVDC facilities.

B. Flexible Alternating Current Transmission Systems

Flexible AC Transmission System (FACTS) are devices based on power electronics (electronic valves and thyristors similarly as in case of HVDC) and other static devices that increase the stability and flexibility of the transmission system by controlling the flows of active and reactive power [15]. The operation of FACTS devices is focused on damping electromechanical oscillations, control of active and reactive power flows, serial and shunt compensation, and power angle control. They increase the capacity utilization of transmission lines. The control time of FACTS devices is within a few milliseconds, which means that they are able to continuously control the characteristic variables. FACTS devices are installed in existing facilities and do not take up much space. They are expensive, but cheaper than building additional transmission lines, and the maintenance costs of FACTS devices are moderate.

The FACTS devices use standard thyristors in simpler devices or, in more complex devices, thyristors with the possibility of current interruption even before passing through the zero value (GTO – Gate Turn-Off Thyristor, IGBT – Insulated-Gate Bipolar Transistor and MCT – MOS – Controlled Thyristor). Advantages of the good features of power electronics devices: fast response, frequent variation of output power, and adjustable output magnitude are thereby utilized, which enables two basic advantages of the FACTS devices: higher transmission power and better power regulation. Almost all of the FACTS devices require the installation of additional filters to prevent the injection of higher harmonics into the AC system.

The backbone of the application of FACTS devices is the voltage source injected into the series and/or parallel branch. By changing the magnitude of the injected voltage and angle relative to the bus voltage of the incident line, it is possible to simultaneously change the flow of active and reactive power. FACTS devices allow controlling characteristic variables of the power system: series impedance, parallel impedance, currents, voltages, phase angle, damping ratio, and oscillations at different frequencies below the nominal value.

Depending on the type of connection to the transmission system, FACTS devices can be divided into serial FACTS devices, shunt FACTS devices, combined serial-serial devices, and combined serial-parallel devices [16].

Series FACTS devices regulate serial power flows using an injected voltage source in serial line connection. The serial device is made in the form of a variable impedance (capacitor or reactor), or a variable voltage source based on power electronics. Some of the main series connected FACTS devices are Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC), Thyristor Controlled Series Reactor (TCSR), Thyristor Switched Series Capacitor (TSSC), Thyristor Switched Series Reactor (TSSR), etc. (Fig. 16).

The TCSC is a capacitive reactance compensator consisting of a series capacitor bank connected in parallel with a thyristor-controlled reactor. Enables compensation via a continuously variable total capacitive reactance in series. The

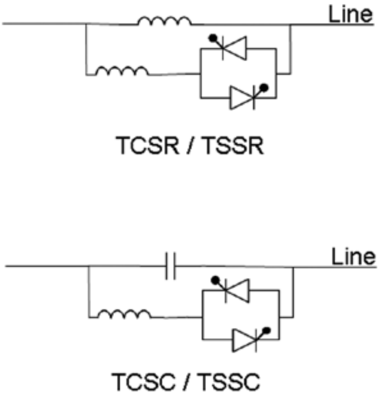

Fig. 16. Thyristor Controlled / Switched Series Reactor and Capacitor
Sl. 16. Tiristorski upravljiva serijska prigušnica i kondenzator

TCSC is one of the main FACTS devices and an alternative to the SSSC. It can be one large unit or consist of several identical or different smaller capacitors to achieve better device characteristics.

The SSSC is operated without an external power supply as a series compensator, whose output voltage is 90° with respect to the line current (from which it is completely independent) to increase or decrease the reactive component of the line voltage drop, and thus control the transmitted power. It can include energy storage to improve transients in the system by providing additional temporary active power compensation.

Shunt FACTS devices regulate the level of voltage by controlled injection of reactive power. As with series devices, shunt device designs can take the form of variable impedances, variable electronic voltage sources, or a combination of the two. All the shunt devices inject current into the bus that is connected to the system. Some of the major shunt FACTS devices are Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor Controlled Reactor (TCR), Thyristor Switched Reactor (TSR), Thyristor Switched Capacitor (TSC), Superconducting Energy Magnetic Storage (SMES), etc. The SVC and STATCOM are the most commonly used among the shunt FACTS devices.

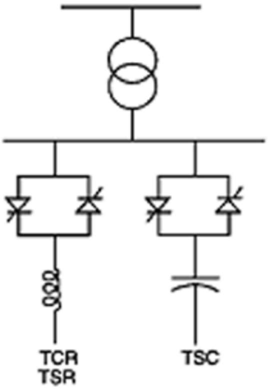

Fig. 17. Static var Compensator
Sl. 17. Statički var kompenzator

The SVC (Fig. 17) combines several different devices, mostly thyristor-controlled, the most important of which are the TCR, in which the reactance of the reactor changes continuously depending on the thyristor control, and the TSC, in which the reactance of the reactor changes step by step depending on the thyristor switching to achieve fast and continuous control. In this way, greater flexibility in operations control is achieved, the injection of currents with higher harmonics is reduced, and characteristics of the device itself are improved in case of failure. The more elements are incorporated into the SVC, the better and more extensive are its characteristics, which is accompanied by an increase in the price of the device itself, but still cheaper than STATCOM. In the Croatian system, there is one SVC installed in TS 400/220/110 kV Konjsko (Fig. 18).

STATCOM is one of the most important FACTS devices. It can be based on voltage or current converters. From a general cost point of view, voltage converters are preferred. In them, the output AC voltage is controlled in such a way that by automatically regulating the voltage of the DC capacitor, which serves as the voltage source of the converter, the required level of injected reactive current in the AC hub is affected. STATCOM can also be used as an active filter to neutralize harmonics.

Fig. 18. SVC 250 Mvar in the TS 400/220/110/10 kV Konjsko located near Split
Sl. 18. 250 Mvar SVC u TS 400/220/110/10 kV Konjsko blizu Splita

Combined **serial-serial FACTS devices** have two possible forms. In the first form, separate serial devices are coordinated in a multi-line system, and in the second form, it is a unified device, in which serial branches provide not only independent serial compensation of reactive power for each line, but also transfer of active power between lines over an existing link. The most important representative is the Interline Power Flow Controller (IPFC).

The IPFC is a newer generation device. It is a combination of two or more SSSC devices connected to a common DC link to provide two-way active power flow between the AC terminals. It may also include a STATCOM connected to the common DC connection of the IPFC to allow shunt reactive power compensation and active power deficit exchange between the combined SSSCs.

Combined series-parallel FACTS devices take the form of separate parallel and series devices with coordinated control or the form of a unified power flow controller with integrated parallel and series devices. Combined parallel and series devices inject current into the system using a shunt device and voltage into the line using a series device. Some of the major combined series-parallel devices are Unified Power Flow Controller (UPFC), Thyristor Controlled Phase Shifting Transformer (TCPST), Interphase Power Controller (IPC), etc.

The UPFC is a combination of STATCOM and the SSSC connected through a common DC link to provide bidirectional active power flow between the serial SSSC output terminal and the STATCOM shunt output terminal. The UPFC allows the compensation of the series impedance of active and reactive components without an external power source. By injecting a serial voltage source that is not angle-limited, it is possible to control (simultaneously or selectively) the transmission line bus voltage, impedance, and angle. Alternatively, the active and reactive power flows of the line can be controlled. The UPFC further allows independent compensation of the shunt reactive power.

Nowadays, distributed FACTS devices (D FACTS) installed directly on conductors (Fig. 19) are used too. The devices in question inject small amounts of intermediate inductance into the conductor on which they are installed, thus changing its impedance and control load flows.

Fig. 19. Distributed FACTS device
Sl. 19. Distribuirani FACTS uređaj

C. Phase shifting transformer

Phase-shifting transformers (PST) are devices that control active power flows in the EPS by changing the voltage angle, and are therefore often included in serial FACTS devices. They do not change the established generator scheduling (except for minimal changes due to different losses caused by changing power flows), nor do they change the existing network topology. Recently, power electronic devices have been combined with the PST transformers, as their application leads to faster and better quality of response [17].

The PST transformers are very useful and efficient devices for system operators to meet system security criteria, and optimize system losses with no additional cost. The operation of the PST is relatively simple: there is a certain phase shift between the primary (input) and the secondary (output) voltage. Typically, the phase shifting at the PST can be changed in two directions: by forward shift $|\alpha_{La}| = \alpha_0 - \beta$ (output voltage leads input voltage), and by backward shift $|\alpha_{Lr}| = \alpha_0 + \beta$ (output voltage lags input voltage), Fig. 20.

The basic principles of transformer operation and the control are shown in the simplified vector diagram on Fig. 21, where are a) in-phase control i.e. voltage magnitude control; b) phase-shift control, i.e. phase angle and voltage magnitude control; c) quadrature control, i.e. phase angle control only.

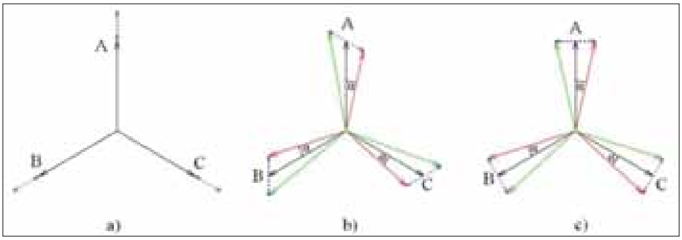

Fig. 21. Simplified vector diagram of voltage control types: a) in-phase; b) phase-shift; c) quadrature [18]
Sl. 21. Pojednostavljeni vektorski dijagram vrsta regulacije napona: a) uzdužna; b) kosa; c) poprečna [18]

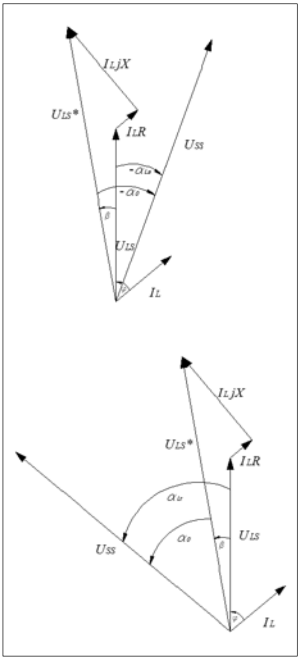

Fig. 20. Phasor diagram of the forward and backward shifts
Sl. 20. Fazorski dijagram pomaka

In-phase voltage control is the most common type of voltage regulation. It is characterized by the fact that the control voltage is in phase with the main-winding voltage. The goal is to achieve the best possible voltage support using on-load tap-changers (OLTC).

Phase-shift voltage control is such a design, in which the desired change in the angle of the output voltage with respect to the input voltage varies to a certain extent and the magnitude of this voltage. This is achieved by connecting the control winding in series with the base winding, i.e. a small amount of phase C voltage is added to phase A voltage. Phase shift control can regulate both the reactive and the active power flows.

Quadrature voltage control is such a voltage regulation, in which only the angle of the voltage between the input and the output voltages changes, without changing their magnitude. With an additional voltage at an angle of 90° to the main-winding voltage, it is used to regulate the active power flow via transformer.

A number of possibilities open up in the design of a phase-shifting transformer. When choosing the basic concept of a transformer, various options are possible. Depending on the output voltage, they are divided into either symmetrical or asymmetrical. Depending on the number of cores, it is possible to choose one or two cores in one or two separate tanks [20]:

- Direct PSTs are based on one 3-phase core. The phase shift is achieved by an appropriate connection of the windings.
- Indirect PSTs are based on a design with two separate transformers: one variable-tap exciter to regulate the amplitude of the quadrature voltage, and one series transformer to inject the quadrature voltage in the right phase to regulate the angle of the voltage.
- Asymmetrical PSTs create an output voltage with an altered phase angle and amplitude compared to the input voltage.
- Symmetrical PSTs create an output voltage with an altered phase angle compared to the input voltage, but with the same amplitude.

Each of these options has not only advantages, but also limitations. Therefore, on-site network research is necessary to determine what is expected from the PST, and thus select its characteristics.

Regulating transformers – areas of application and advantages for power supply companies:

- Avoidance/reduction of circulating currents.
- Avoidance of unwanted exchange of reactive power.
- Regulation of exchange power.
- Minimization of losses in parallel transmission corridors with different voltage levels and/or different lengths.
- Redistribution of power transmission to higher voltage levels that are often underutilized.
- Redistribution of power flows in heavily loaded networks.
- Power transmission over defined contract paths with minimal / without loading of third-party networks.
- Increased reliability of power supply and improved distribution of power flow.
- Highly robust FACTS components achieved in combination with reactors and capacitors.

In Croatia, there are two PSTs – in TS 400/220/110 kV Žerjavinec (Sn=400 MVA) and in TS 220/110 kV Senj (Sn=200 MVA). Voltage regulation is performed in loaded condition at the autotransformer zero point, which means that the control winding acts simultaneously on the high-voltage and the low-voltage sides. It follows that regulation at the autotransformer zero point is nonlinear, and the control range is asymmetrical. Transformers can regulate either the voltage or the angle. It is important to emphasize that the transition from one mode to another occurs in the unloaded state. They have 27 positions for both voltage and angle regulation, with three zero positions (position 13).

6. REAL-TIME TRANSMISSION SYSTEM MONITORING

Controlling the system at maximum load is becoming more and more complex; thus, the Decision Support System (DSS) is being developed to help System operators' staff safely manage the power system, monitoring the power system in real time, signaling of dynamic phenomena, etc.

A. Wide Area Monitoring Systems (WAMS)

Current monitoring and control of the power system is based on local measurements of the static process values of the power system (voltage, power, frequency, etc.). After major power outages ten years ago, systems for monitoring, control, and protection of the power system based on current values of process parameters were intensively developed and applied. Wide Area Monitoring (WAM), Wide Area Control (WAC), Wide Area Protection (WAP), and Wide Area Monitoring, Protection And Control (WAMPAC) are new technologies that enable a completely different concept of the EPS control based on real-time measurements, which was not possible before. The WAM system is a technology that was conceived in the 1980s, and the first commercial devices were developed in the early 1990s.

The WAMS is very useful in: monitoring of load flows and system dynamic phenomena in real time, secure management, support in planning and improving the operation of the relay protection system, support in setting of dynamic limits and dynamic overloads, support in the restoration of the power system, early warning before the disturbance occurs giving the operator sufficient time to act and prevent cascade disturbances, and support in better planning of the transmission network.

The WAM system is based on the installation of Phasor Measurement Units (PMU) in the particularly important nodes of the power system. A phasor is a vector that rotates in a complex plane with an angular velocity equal to the difference between the nominal frequency of the system and the current frequency of the system per circle with a radius equal to the amplitude of the sinusoidal function. Phasors are the basic tools of the AC circuit analysis, usually introduced to represent sinusoidal waveforms in steady state with the fundamental frequency of the system. Even if the power system is not stationary, phasors are often useful to describe its behavior. For example, when electromechanical oscillations occur in the power system during disturbances, the voltage and current waveforms are not the same as those in steady state, and the frequency of the system is not the nominal value. Since the changes in voltage and current under such conditions are relatively slow, phasors can still be used to describe the behavior of the power system in a way that treats the changes as a series of steady states.

In the early 1990s, it was recognized that phasors are also applicable when waveforms change relatively rapidly, and contain significant amounts of transient components. Advances in time synchronization and computer-aided measurement techniques have led to new capabilities for measuring phasors and phase angle differences in real time.

Synchronization signals can be distributed over any conventional communication medium currently used in the power system, but most communication systems have limitations in the synchronization accuracy that can be achieved. The technology currently in use is the Navstar Global Positioning System (GPS) satellite system. This system was developed primarily for navigation purposes, but provides a common time synchronization signal that is accurate to within 1 μs at any location on Earth. The antenna needs only one visible satellite to accurately receive the time synchronization signal. A further advantage is that the antenna is small and can easily be placed on the roof of the facility at the station. The experience with the availability of the GPS satellite transmission is extremely good. The WAM platform enables a realistic dynamic picture of the power system, higher measurement accuracy, fast data exchange and algorithms in the applied applications that allow coordination, and timely alarming in case of instability.

The architecture of a WAM system (Fig. 22) consists of several basic elements, three of which are the most important: 1) Phasor Measurement Unit (PMU), its architecture is shown in Fig. 22, 2) Phasor Data Concentrator (PDC), in which the recorded measurements are compared (Fig. 24), and 3) telecommunications infrastructure. The PMUs (Fig. 23) are electronic phasor measurement devices that use GPS system synchronization signals. They combine the functions of classic secondary equipment devices with a new real-time data acquisition function. Like any secondary device, they convert the analog signal into a digital one, with some filtering and sampling rate. Today, more and more optical current and voltage measuring transformers are used, from which the measuring signals are introduced into the PMU directly (no A/D conversion required), which greatly accelerates the operation of the entire WAM system and the accuracy of measured data. The main advantage of the PMU is that it is equipped with a GPS receiver that provides a pulse-per- second (pps) signal with an accuracy of 1 μs, corresponding to a phase error of 0.018° at 50 Hz, and assigns a time stamp (year, day, hour, minute, and second) to each sample.

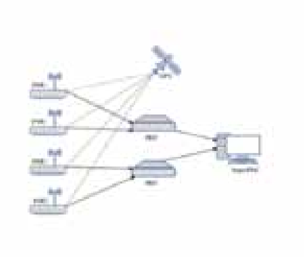

Fig. 22. WAMS architecture
Sl. 22. WAMS arhitektura

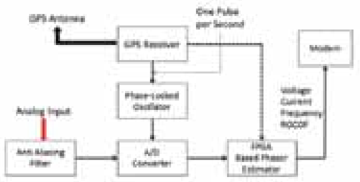

Fig. 23. Architecture of PMU
Sl. 23. PMU arhitektura

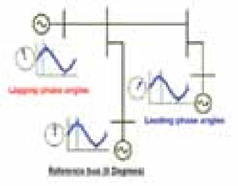

Fig. 24. Comparison of measured voltages in system buses
Sl. 24. Usporedba izmjerenih napona sabirnica sustava

The 1-pps signal is usually divided by the PLL oscillator into the required number of pulses per second used to sample the analog signals. In most systems today, 12 pulses per period of the fundamental frequency are used. The analog signals are obtained from secondary voltage and current transformers through appropriate filters to avoid undersampling and overvoltage limitation. The microprocessor in the PMU calculates the phasors of the direct system according to the recursive algorithm and the phasor associates the timestamp obtained from the GPS. The phasor list is sent to the remote-control center via the communication channel. The transfer speeds are not required to be high, since the measurement message itself is relatively small; therefore, even ordinary modems can meet the data transfer requirements for one PMU.

In practice, various telecommunication paths are used for data transmission, fiber optic cables, microwaves, power line communication (PLC), telephone lines, satellite links, etc. When there are multiple PMUs in the power system, high quality operation of the WAM systems requires fast and reliable telecommunication links (fiber optic cables, Ethernet (TCP/IP) network) to ensure fast and reliable data transmission.

The Phasor Data Concentrator (PDC) consists of hardware and software parts. The server combines several functions such as: receiving measurement data from all installed PMUs, data processing, monitoring functions, data archiving, and operator interface.

The server (SPDC and PDC) collects and processes real-time data from thee PMUs in less than 20 milliseconds. Real-time means insight into the state of the power system and data refresh in less than 200 milliseconds. They communicate with synchronized phasor meters via IEEE 1344-1995 and IEEE PC37.118-2005 input protocols, and IEEE PC37.118-2005, TCP/IP and often OPC XML Servers output protocols. They typically support dozens of the PMUs over Ethernet ports, RS -232 serial ports with 64-byte packets, and with refresh rate of 20 to 60 messages per second.

1) Functions in the WAMS:

- **Data collection and archiving**, which can be very useful for post-failure analysis. Based on the archived data, it is possible to reconstruct faults, identify correct or incorrect actions of system operators, etc., using other specialized programs and tools. The data can be archived continuously or triggered by the fault registration.
- **Visualization of the collected data**. The interface between the WAMS and dynamic monitoring allows the PMU data, dynamic data and alarms to be transmitted to the Energy Management System (EMS) for visualization purposes through a single interface. The WAM system provides operational visualization of concise system indicators – alarms (thresholds, gradients), traffic lights, bar graphs, etc., which significantly facilitates the operator's management of the system.
- **Monitoring of voltage and current amplitudes** in the power system. The WAM system transmits the DC current and voltage components to the remote-control center. Inverse and zero components are generally not exchanged. Frequency, rate of change of frequency (ROCOF), power (MVA, MW, Mvar) are calculated from the direct components in the PDC.
- **Improved alarm system**. The WAMS provides timely warnings to the operator about potential and impending disturbances in the power system, enabling preventive and corrective actions to prevent or mitigate the consequences of a power system collapse.
- **System state estimation**. Modern dispatch centers use state estimators to monitor the state of the power system. The state estimator uses various measurements (power, voltage and current) received from different nodes in the system, and calculates the state of the power system using iterative nonlinear estimation. The state vector is a set of all phasors of the direct mains voltage system, and it may take a few seconds or minutes from the initial measurement to the time the state estimation is completed. Due to the varying timing of the data arrival, as well as the time required for the state estimator to converge, the state vector obtained is at best a description of the average quasi-stationary state of the power system. Therefore, state estimators in today's dispatch centers are limited to steady state monitoring applications.

  When phasors of the direct system voltage measured with synchronized PMUs are used, a real simultaneous measurement of the power system state is obtained. In this case, the estimation of the state vector is not required. From a practical point of view, it is useful to use current phasors that provide redundant information. In this way, a linear estimator of the state of the power system is obtained using both voltage and current measurements. The result of the estimator is the product of the matrix of constants and the measurement vector obtained at the computation rate. Synchronized phasor measurements provide a dynamic state estimator.

Since the usual dynamic phenomena in the power system are in the range of frequencies from 0 Hz to 2 Hz, it is possible to observe dynamic phenomena in real time and in high resolution in the control center. To achieve a satisfactory state estimation, synchronized measurement units must be installed in approximately 30% of the nodes of the system.

- **Voltage angle monitoring** (Fig. 25).

  The data on the difference of the angles between the voltage vectors on the buses is very important to get a dynamic picture of the state of the power system. The difference of the angles between the power system buses increases when the system becomes weaker, i.e. when the connection between the nodes in the system becomes weaker. The load limits of the system derive from its required stability as well as from the settings of the primary and backup protection systems and the settings of the protection against synchronism outages. The real-time EPS image allows its operation closer to maximum transmission capacity without compromising stability. The WAM system makes it possible to take certain actions that can improve the situation before the outages of part or the entire EPS.

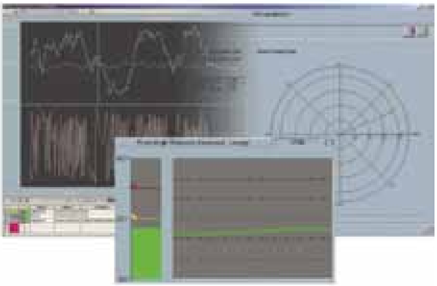

Fig. 25. Monitoring voltage angles
Sl. 25. Praćenje kutova napona

- **Thermal monitoring of the transmission line** (Fig. 26). This function provides the user with information about the actual line temperature, and about the active and reactive power losses on the line. The calculation of the average temperature of the transmission line based on the phasors measured at both ends of the line (impedance of the transmission line by knowing the voltage and current phasors at both ends of the transmission line) is done using the following expression (5):

$$t = t_{20} + \frac{1}{\alpha}\left(\frac{R}{R_{20}} - 1\right) \tag{3}$$

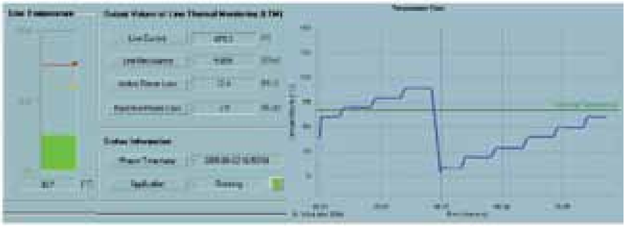

Fig. 26. Thermal monitoring of the transmission line
Sl. 26. Nadzor topline prijenosnog voda

Since in most cases the load on the transmission line is limited more by the thermal limit than by the voltage stability, the operating limit is set very conservatively. Transmission lines are designed for an outside temperature of 40° and an excess temperature of additional 40°. These real-time conductors' temperature measurements allow early alerting of the system operator in case of overload. Furthermore, the transmission capacity of the line is dynamically controlled, and indirect estimation of the sag of the line is possible.

- **Voltage stability control** of transmission lines or corridors (Fig. 27) is the basis for monitoring power transmission. It is possible to display the dynamic PV curve and follow the current operating point, and the operator receives real-time information on the safety distance to the transmission power limit with respect to the voltage stability of the EPS. This ensures optimal dynamic load shedding to maintain voltage stability.

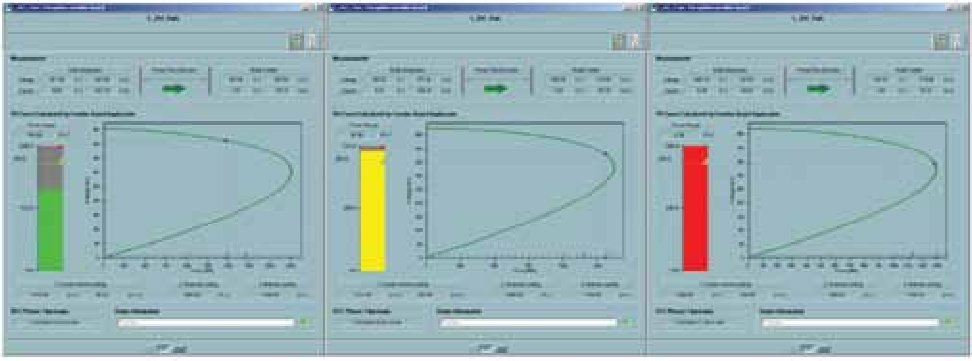

Fig. 27. Voltage stability control
Sl. 27. Kontrola stabilnosti napona

- **Monitoring the frequency of the power system** and prediction of frequency drop or frequency overshoot after load shedding or other disturbances is enabled by the WAMS. In addition to frequency amplitude, the WAMS also allows monitoring the rate of change of frequency (ROCOF) df/dt. It monitors the rates of change of frequency from 0 Hz/s to 10 Hz/s, which basically occur as result of large imbalance [21].
- **Monitoring of power oscillations on lines.** Power oscillations occur due to the interaction of the generator with the power system, caused by different responses of the generator to changes in the load in the system. The development of the WAMS made it possible to study systemic low-frequency oscillations (Fig. 28). These oscillations are

divided into local and inter-area oscillations. Local oscillations range from 0.7 to 2.0 Hz, while inter-area oscillations range from 0.1 to 0.8 Hz. Low-damped power oscillations can cause loss of synchronism on transmission corridors or parts of the system, ultimately leading to non-selective line or generator shutdowns, and possible outages of parts or the entire power system. Very long and heavily loaded transmission lines are one of the causes of low frequency oscillations. The WAMS alerts system operators in real time within 1 second when uncontrolled oscillations occur.

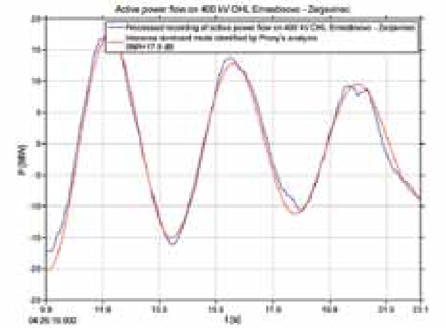

Fig. 28. Monitoring of low frequency oscillations during disturbances in the Croatian power system
Sl. 28. Praćenje niskofrekvencijskih oscilacija tijekom poremećaja u EES-u RH

The WAMS offers the possibility to continuously monitor the system dynamics thanks to the high-resolution measurements of the PMUs. The dynamic characteristics of the power system can be derived from small changes in the measured values resulting from random small disturbances in the loads connected to the system. By comparing the frequency of oscillations to known instances of oscillations, the operator can identify the severity of the disturbance by gaining an instant insight into the amplitude of the frequency oscillations and the dumping of the dominant modes of the power oscillations.

The dumping of oscillations is of great importance as it shows how close the system is to the instability limit. With the WAMS, it is possible to determine the areas where the generators oscillate with the same or opposite phase. It is usually useful to identify a particular generator that has a significant effect on the mode of the oscillations. Reduced oscillation damping (insufficient damping torque) can also be caused by broader system effects such as overload of interconnection lines and poor voltage profile.

- **Power flow control in the power system and congestion management**. The WAMS enables the correction of power flows and the improvement of the transmission capabilities of the entire power system. It further allows real-time monitoring of the PST operation in case of manual regulation, and there is also the possibility of automatic PST regulation, as well as the ability to manage all PST in the region, which has already been implemented in Austria and Germany.

2) Integration of the WAMS into the Energy Management System (EMS)

Since the main function of the EMS is to provide the system operator with an insight into the condition and security of the power system, it is only natural to assume that synchronized phasor measurements and calculations based on them will contribute to the functionality of the EMS.

The EMS system receives data (a very large number of signals) that change relatively slowly (refreshing in tenths of seconds or even minutes) from the Remote Terminal Units (RTU) that are part of the SCADA system, and the network is usually completely covered by such measurements. This ensures an overview of the steady state of the power system. On the other hand, the WAMS receives much higher resolution measurements that give insight into dynamic phenomena, but these measurements usually do not cover the entire network. Since both systems complement each other, it is practical to combine them in order to improve the management of the system dynamics. Measurements from the WAMS should be used as complementary and controlling measurements to the SCADA system.

The basic idea of monitoring system dynamics is to detect emerging problems before they become critical. The integration of the WAMS and the EMS systems can solve this problem. The measurements from the WAMS can form the basis for future more complex applications within the EMS. One of the more complex applications that is being intensively researched is WAMPAC.

Wide Area Monitoring, Protection and Control (WAMPAC) systems include three levels of protection functions [22]. The first level is basic relay protection, the second level is central system protection with wide-area protection functions (WAP), and the final level is power system control. Over the recent years, central protection systems have been intensively developed and innovative methods based on synchrophasor data have been introduced. WAMPAC systems must be tailor-made and adapted for every particular transmission system [23].

3) The WAMS in the Croatian EPS

In 2003, the first two PMU devices were installed in Croatia to monitor the 400 kV Tumbri–Žerjavinec transmission line. A phasor data concentrator was installed at the National Dispatching Center, which collected and processed phasor data [24]. Communication was based on the point-to-point principle using a 19200 bit/s modem with a data transmission delay of less than 100 ms. This system represented the first phase of the development of the WAMS in Croatia. In several phases, the WAMS in Croatia was improved. Today, this system covers all 400 kV and 220 kV lines, as well as 110 kV lines connected to major power plants. Thus, the Croatian EPS is probably the power system with the most PMU devices in Europe, according to the total number of system nodes.

In addition to archiving data, the following functions have been activated in the Croatian WAMS:

- monitoring of voltage phasor angle difference between individual nodes,
- monitoring of power oscillations on the transmission lines,
- thermal monitoring of the transmission lines,
- monitoring of voltage stability of the transmission line or transmission corridor.

B. Real-time line temperature monitoring

Due to the increasingly difficult requirements associated with more economical power system operation, difficulties to obtain corridors for new overhead line construction, and the variability of the RES generation in developed countries, there is a trend toward line uprating using line monitoring. There are two methods to increase the transmission capacity of the line: the first is based on the current load capacity (ampacity based), whilst the second is based on the nominal voltage level (voltage based). The second method involves technologies to increase the voltage level of the selected line, which is not discussed in detail here.

The first method, based on the current capacity of the conductor, refers to the use of the existing conductors by introducing real-time monitoring technology. Real Time Thermal Rating (RTTR) or Dynamic Cable Rating (DCR) continuously calculates the conductor temperature based on real-time measurements and monitoring different parameters of the corridor through which the line passes, such as: current load, load history, tension (tensile force), temperature of the conductor, thermal conditions, differential GPS to monitor sagging, characteristic points of the conductor in the route, vibration, etc. At the same time, it predicts the maximum permissible load for steady state and emergency situations.

A serious problem is the fact that about 60% of the European transmission network is older than 30 years [25]; thus, due to the loss of mechanical properties, there is an expressed problem of increased sagging, which further limits the transmission capacity of the lines. It is known that the current limitations of the lines directly depend on the weather conditions (ambient temperature, solar radiation, wind speed and direction), the measurements of which are relatively rare during the day, which leads to additional limitations on the allowable line loads. In addition, a high current load (from 2 A/mm2) leads to a significant increase in the conductor temperature, which further increases the conductor sag. Therefore, in addition to the amount of current, it is also necessary to continuously monitor conductor temperature [26].

In practice, the dynamic increase of the transmission capacity by controlling the conductor temperature is often used (Fig. 29); the method can also be applied to power cables. This allows to increase the transmission capacity of the line by 10-15%, and the price of the systems in question is acceptable compared to the construction of new lines (about 7% of the cost of building a new line [27]). The price of the system depends on the number of critical parts of the line to be monitored, as well as on the technology used and the cost of the communication system.

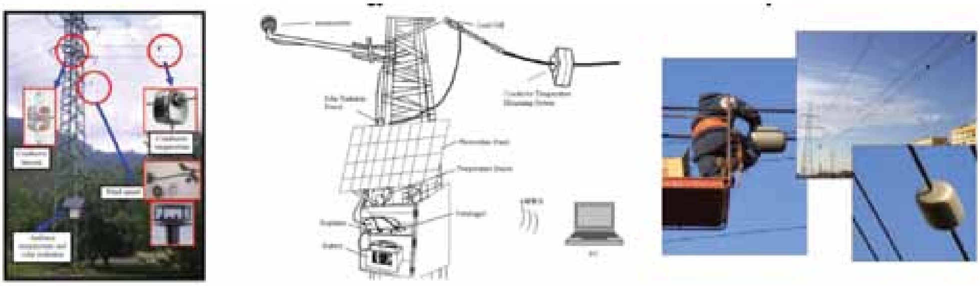

Fig. 29. Sensor system for measuring ambient conditions, current and conductor temperature
Sl. 29. Senzorski sustav za mjerenje stanja okoline, struje i temperature vodiča

Measuring devices for dynamically increasing the transmission line capacity by controlling the conductor temperature are installed directly on the conductors at several points along the route (Fig. 29), and there are several sensors in commercial use (DONUT, Darmstadt University System, RIBE-Ritherm System, SMT, TMT, etc.) [28].

For cables based on real-time temperature and current measurements, the remaining allowable thermal load is calculated according to IEC 60287 and IEC 60853. Cable monitoring accessories include partial discharge monitoring, insulation damage detection and, for newer cables (especially submarine cables), the installation of optical cables in the cable core together with the conductor [29].

7. CONCLUSION

Smart transmission grids of the future will rely on smarter equipment and IoT sensors interconnected to the next generation of communications network infrastructure and propagated by data-derived services. By bringing these innovative digitalization concepts to the power transmission, enormous opportunities to optimize today's energy system can be offered, making it more compact, efficient, smarter, faster, and more profitable.

There are several goals to be achieved by introducing smart grids, the most important of which is the so-called 3D future networks (Decentralized, Decarbonized, Digitalized). Ultimately, the main goal of smart grids development is to build a power system that, together with the transportation system and information technologies, supports and promotes the growth of the global economy, while respecting the principles of sustainable development and environmental protection (Fig. 30). Smart grid technology is largely in place, and while it continues to evolve for its accelerated development, more attention needs to be paid to the development and application of appropriate standards to enable interoperability between assets and devices from different manufacturers.

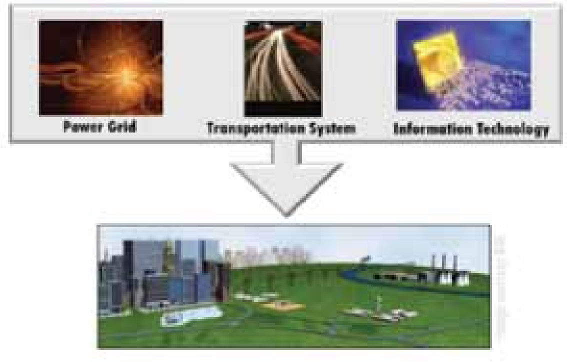

Fig. 30. Integrated smart grid infrastructure
Sl. 30. Integrirana infrastruktura napredne mreže

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PREGLED RAZLIČITIH TEHNOLOGIJA UPRAVLJANJA NAPREDNIM MREŽAMA ZA POVEĆANJE FLEKSIBILNOSTI ELEKTROENERGETSKIH SUSTAVA I OMOGUĆAVANJE MASOVNE INTEGRACIJE OBNOVLJIVIH IZVORA ENERGIJE

Sažetak

U posljednjih 15 godina u elektroenergetskom sektoru dogodile su se velike promjene. Značajno povećanje udjela obnovljivih izvora energije (OIE) s varijabilnom proizvodnjom, praćeno gašenjem konvencionalnih elektrana na fosilna goriva, dramatično je promijenilo način rada elektroenergetskog sustava (EES). Tijekom tog vremena bilo je neodgovarajućih i nepravovremenih ulaganja u prijenosnu infrastrukturu. To se dogodilo dijelom zbog nedostatka financijskih sredstava, a dijelom zbog klimatskih promjena i porasta ekološke svijesti, kao i utjecaja zelenih aktivista koji su otežali dobivanje dozvola za izgradnju energetskih objekata. Osim toga, potrošnja električne energije u stalnom je porastu zbog rasta stanovništva u nerazvijenim zemljama i zemljama u razvoju te zbog povećanja životnog standarda u razvijenim zemljama. Stoga se očekuje da će se globalna potrošnja električne energije utrostručiti do 2050. Kako bi zadovoljili nove zahtjeve, operatori prijenosnih sustava (TSO) uvode napredne tehnologije prijenosa temeljene na sveobuhvatnoj primjeni informacijskih i komunikacijskih rješenja. Ove tehnologije povećavaju kapacitet, učinkovitost i pouzdanost postojećih i novih elemenata prijenosnog sustava. Ova primijenjena rješenja razlikuju se od sustava do sustava i ovise o mnogim utjecajnim čimbenicima. Primjena ovih naprednih tehnologija posebno je važna za upravljanje zagušenjima jer elektroenergetski sustav radi sve bliže i bliže granicama stabilnosti, povećavajući rizik od njegovog sloma. U radu su opisane tehnologije koje transformiraju postojeću mrežu u napredne elektroenergetske mreže, prvenstveno sa stajališta povećanja kapaciteta postojeće infrastrukture kroz različite investicije u napredne tehnologije.

Ključne riječi: obnovljivi izvori energije; napredne mreže; fleksibilnost; prijenosna elektroenergetska mreža.

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