ORIGINAL PAPER

A review of challenges and benefits of integration of CHP plant into the grid: a case study in Serbia

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Abstract

The Republic of Serbia must make significant efforts to promote and exploit renewable energy sources and increase energy efficiency in all energy sectors to ensure energy security and economic competitiveness, reduce the negative impact on the environment from energy production and use, and contribute to global efforts to reduce greenhouse gases. Within the paper several issues of integration of recently realized CHP plant are introduced and discussed. Firstly, the legal and energy policy issues in the Republic of Serbia regarding connecting CHP to the grid are presented. The challenges and technical solutions for CHP connection to the grid, as well as power quality issues and the role of the CHP plant during the restoration of power supply during the maintenance of the substation and unplanned loss of high voltage supply, are presented and discussed. Finally, the impact of prospective massive integration of CHP on the energy balance and CO_2 emission reduction in the province of Vojvodina in Serbia is investigated and discussed. Since it is the first CHP plant realized in Serbia, it is crucial that experience be shared to all potential stakeholders in the future energy efficiency projects.

Keywords Energy efficiency · Energy policy · Combined heat and power · Power quality · Grid code · Restoration of supply · CO_2 emission

1 Introduction

The electric power performance of Republic of Serbia in 2020 can be summarized as follows: The total installed power capacity of the Serbian Electric Power Industry (EPS) is 8054 MW generating 39,405 TWh/a of electricity, where thermal power capacities provide it with 65.7%, large and medium sized hydroelectric power makes up almost 31.6% of total electric power capacity, while the renewable energy sources (mostly wind turbine generation) account for 2,1%. The thermal power capacity of the Serbian EPS consists of eight thermal power plants of total installed power amounting to 5100 MW which rely on lignite, as well as three combined heat and power plants of total installed capacity amounting to 353 MW powered by liquid and gas fuels (0,7% of total electricity generation) [1]. The energy production from efficient small sized cogeneration units is as 98.7 GWh/a.

The share of gaseous fuels equals to 17% in final energy consumption while the industry plays dominant role in Serbian gas consumption (65.6%) [2]. Natural gas is also used in systems for centralized heating, so that overall share of natural gas for domestic heating and other household demands is about 31.6% [2]. However, as much as 30% of the district heating in the cities use the oil or coal as a primary fuel, while the 60% of the household burn wood or coal for heating. Total CO_2 emission in Serbia was 41.1 million tons/a in 2018 according to the website worldometers.info (67% comes from power industry, 11% from transport, 8% from other industry, and 6,9% from buildings). The energy intensity of Serbia is four times higher than that of OECD countries.

In the report of South East European Energy Community Treaty, it is pointed out that the response in SE Europe to implement reforms in the energy and environmental sector in accordance with the European Union's respective policy has been at a low level [3]. Poor energy efficiency and high carbon intensity due to strong dependency on fossil fuels are two of the main challenges in the Serbian energy sector [4].

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For these reasons, the governments of the Republic of Serbia made significant efforts in last 15 years to promote and exploit renewable energy sources and increase energy efficiency in all energy sectors. The Energy Development Strategy of the Republic of Serbia by 2025 defines five priorities, two of which refer to this issue: (1) Selective use of new renewable energy sources, and (2) Rational use of energy and increased energy efficiency [5]. The second priority includes programs targeted by sectors for the rational use of quality energy products within the framework of the program for substitution of electricity for thermal energy services in the building. These programs are based on the use of natural gas, i.e., the increase in the number of users of centralized heat supply in the household and public/communal sectors, increasing energy efficiency, both in energy generation and distribution systems, as well as in the energy consumption sectors (end-users).

The energy transformation of Serbia started in 2004 when the category of privileged power producers in Serbia was defined by the *Energy Law* [6]. Since 2003 several strategic documents regarding development of renewable energy sources and increasing energy efficiency in Serbia were published [7–11].

The combined cycle heat and power (CHP) generation using natural gas is nowadays the cleanest available source of power using hydrocarbon fuels. Since natural gas can be obtained at increasingly reasonable costs the CHP technology is widely used. It is known that burning natural gas generates only about half the CO_2 per MWh that coal does (900 kg). To analyze the fuel and CO_2 emission saving for the CHP system, thermal and electricity output should be calculated separately. It is demonstrated in ref. [12] that the 10 MW CHP natural gas-fired combustion turbine and heat recovery systems (operation hours 7500 per year) can reduce the 67.5 tons of CO2 equivalent, which is equivalent to approximately 12,800 passenger vehicles.

In ref. [13] district heating CHP and distributed generation (DG) CHP have been compared regarding energetic, environmental, and economic criteria. An optimal deployment with respect to capacity sizes and types of DG for CHP system with microgrids was presented in ref. [14]. The objective was to minimize the total net present cost and the CO_2 emission. A parametric model for techno-economic evaluation of cogeneration systems for residential use is presented in ref. [15]. In ref. [16] the integration of the concepts of distributed energy resources and combined production of different energy vectors such as electricity, heat, cooling power, hydrogen, etc. is proposed.

Nowadays cities account for approximately two-thirds of global primary energy consumption and have large heat and power demands [17]. The impact of CHP planning restrictions on the efficiency of urban energy systems is investigated in ref. [17] and is demonstrated that the CHP systems

can offer significant primary energy efficiency improvements and emissions reductions. The role of district heating in the future energy systems in Denmark is investigated in ref. [18] and it is reported that the best solution is to combine gradual expansion of district heating with individual heat pumps in the remaining houses.

In ref. [19] a multi-objective optimization model is proposed to analyze the optimal operating strategy to fulfill electrical and thermal demand, while combining minimization of energy cost with minimization of CO_2 emissions. It is demonstrated that increasing the satisfaction degree of economic objective leads to increased CO_2 emissions. Techno-economic analysis of biogas powered cogeneration with case study in Serbia is presented in ref. [20] showing the full potential of such facilities. The electrical considerations in cogeneration are investigated in ref. [21–24]. A value-based distributed generator placement for service quality improvements is investigated in ref. [25]. Reliability modeling of distributed generation (DG) in medium voltage distribution systems planning and analysis is presented in ref. [26], while a new index of reliability supply in the industrial systems with distributed generation using different technologies and primary energy is proposed in ref. [27].

The steady state performances of distribution systems with embedded generators are investigated in ref. [28] while the performance of low voltage distribution network with high penetration of small-scale household CHP units (up to 5 kW) is investigated in ref. [29]. The improvement of power quality using DG is investigated in ref. [30]. In general, the distributed generators improve voltage profile, decrease losses, contribute to reactive power compensation, increase reliability of supply, but increase fault level and can deteriorate power quality of supply. Distributed generation planning at a local level in Serbia is investigated in ref. [31], and it was demonstrated that DG integration could postpone investments in the network infrastructure and become a cost-effective solution benefiting both, the energy suppliers, and the energy consumers. The significance of development of modern syllabus course in the higher education regarding renewable energy sources and energy efficiency is presented in ref. [32].

From the listed literature it is obvious that the planning, commissioning, and integration of CHP into the grid is a complex multi-disciplinary venture which includes policy and legal aspects, technical and operational problems, economic and business issues and finally the analysis of environmental impact. The aim of this paper is presenting an overview of the challenges and benefits of the CHP integration into the power distribution grid enabling the experience and lessons learned to be shared to potential stakeholders in the future energy efficiency ventures. The main contribution of the paper is the evaluation of technical, operational, and power quality issues in the real project of integration of the

CHP plant into the city's power distribution system. The second contribution of the work is the assessment of the role of the CHP plant in the power supply restoration after the outage of substation. Finally, the third contribution of the paper is the analysis and assessment of multiple impacts of massive application of the CHP plants in district heating and industry on the energy and power balance as well as reduction of carbon emission on the regional level.

The paper is organized as follows. The legal and energy policy issues in the Republic of Serbia regarding connecting CHP to the grid are presented in the second chapter. The electric power and heating system of the city of Novi Sad and CHP data are presented in the third chapter. The technical solutions for CHP connection to the grid as well as power quality issues are explained in the fourth chapter. It is shown how the CHP plant is connected to the power distribution grid and the heating system, and how the CHP plant facilitate the network reconfiguration to restore power supply during the maintenance in the substation 110/20 kV, as well as unplanned loss of 110 kV supply. Power quality monitoring is performed in the 20 kV busbar at the connection point of the CHP plant and the measurements are analyzed and discussed in the fifth chapter. The data are obtained using a Power Quality Measurement unit, the Supervisory Control and Data Acquisition System (SCADA) and the Distribution Management System (DMS). Possible impact of massive integration of CHPs into the district heating in the cities and in industry facilities in Autonomous Province of Vojvodina on the CO_2 emission reduction is also presented in the fifth chapter. The last chapter contains lessons learned from the CHP project, conclusion remarks and the proposals to increase energy efficiency.

2 Energy policy

A key step to begin market development of the renewable energy sources and energy efficiency projects in Serbia was to determine the feed-in-tariff in 2011, for electricity produced from renewable energy sources for 12 years from the start of production [7]. It is worth of noticing that the state took over balance responsibility for the privileged power producers.

The electric energy import of Serbia in 2019 was 18%, but the total energy import including oil and natural gas is around 1/3 of the total demand [1]. It is of the utmost importance to provide safe and reliable supply of energy and reduce the country's energy dependence in the future. In this respect main objectives of the energy policy of the Republic of Serbia were defined, as follows [5]:

- Development of energy infrastructure,

- Diversification of energy sources to ensure security of supply,
- Introduction of modern technologies in the energy sector,
- Reducing the growth of final consumption,
- Increasing energy efficiency, and
- Increasing the use of renewable energy.

According to agreement with the EU since 2009, Serbia took over the obligation to increase the share of renewable energy in total energy consumption from the current 21.2% (including large hydro plants) to 27% in 2020 [5]. The new model of power purchase agreement increased investments slightly and additional wind power projects with a volume of 483 MW are in the pipeline. However, Serbia is not yet on course to achieve its 27% target. The adoption of the above documents was the basis for the realization of the CHP project which is presented in the following.

3 System and CHP data

EPS Distribucija—Novi Sad is the distribution grid operator in province of Vojvodina (North province of Serbia with 1.9 million inhabitants) and is part of the Electric Power Industry of Serbia. The power distribution system of city of Novi Sad (around 0.5 million citizens) delivers 2308 GWh/a of electricity reaching 433 MW peak, through the 15 substations 110/x kV, 23 transformer stations (TS) 35/x kV, and 2648 TS MV/LV. The Novi Sad central heating system has a heat consumption capacity of 902 MW, 690 MW of heat sources, 105 thousand consumers, 223 km of distribution network, and 3832 heating substations.

The "Heating plant West " has the installed capacity of 256,3 MW of heating system, 38 MW of water heating, and 9,98 MW of electrical power, supplying the west part of the city, and is the property of JKP "Novosadska Toplana". The boilers in the plant are over 30 years old while the total emission of CO in period 2010–2015 was 69 tons.

The CHP "Plant West " is powered by natural gas and is connected to the substation TS 110/20 kV/kV "Novi Sad 5" (2×31.5 MVA of rated capacity) by underground cable 20 kV type XHE 49A 3x(1×150) mm^2 (total length 1862 m, rated current 345 A). The rated apparent power of gas-powered cogeneration plant is 12.4 MVA, while the real electric power is 9.98 MW and the reactive power is 7.44 MVAr. The facility consists of three gas power motors, three generator units, 4.13 MVA of apparent power each, 3,3 MW of the real power, with power factor 0.8. Basic data of CHP "Plant West" are presented in Table 1 and the generator unit in CHP plant is shown on Fig. 1. Single-line diagram of the CHP facility in the "Heating Plant West" and connection to TS "Novi Sad 5" is presented on Fig. 2 and the locations of the

Table 1 Basic data of the CHP "Plant West"

Number of co-generation modules	3
Electric power (10 kV)	9,98 MW
Heat capacity (90/70 °C)	10,04 MW
Electric efficiency	45,6%
Heat efficiency	45,8%
Natural gas consumption	769 Nm^3/h
NOx emissions (at 5% O_2)	< 100 mg/Nm^3
CO emissions (at 5% O_2)	< 300 mg/Nm^3
Noise level at the facility	< 85 dB
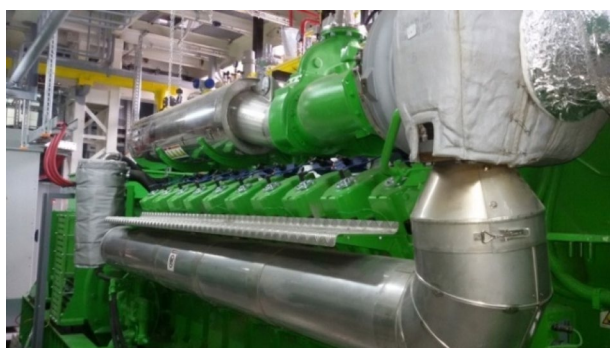
Fig. 1 The generator unit in the CHP "Plant West"
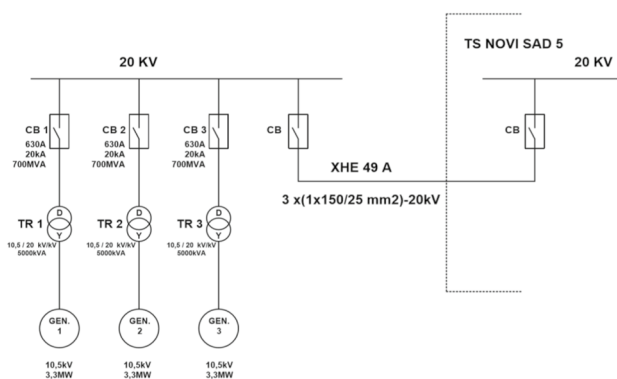
Fig. 2 The single-line diagram of the CHP in the "Heating Plant West" and connection to TS "Novi Sad 5"

CHP, TS "Novi Sad 5" and TS "Novi Sad 7" are presented on Fig. 3.

Upon connecting the CHP "Plant West" to the grid, the loading of transformer no. 3 in TS "Novi Sad 5 "decreased for 275 A, when the CHP operates with full capacity. The main problems in the first year of operation occurred due to the ground-faults on the 20 kV connection cable. During the summer, the CHP plant operates with maximum capacity causing maximum cable loading. The cable 20 kV type XHE 49A 3x (1×150) mm^2, with rated current of 345 A, has

insufficient capacity causing the overheating of insulation. Besides, large voltage drops, and power losses are registered, which suggests that the cable need to be replaced soon.

The CHP plant generated 77.1 MWh of heat and 76.7 MWh of electricity for the first 12 months of operation (equivalent time of maximum power generation $T_{max} = 0,87$), making 6,9 million € of total revenue to the public heating company. The curve of heat and electricity generation duration of the CHP "Plant West" in the first year of operation is shown on Fig. 4 and Fig. 5, respectively.

4 CHP on the grid

4.1 Challenges and operating conflicts of CHP on the grid

Even though synchronous machines use old technology and are common on power systems, there are some concerns when they are applied in grid parallel DG applications. With proper field and governor control, these machines can follow any load within its design capability. It is the source of concern to utility distribution engineers because this technology can easily sustain inadvertent islands that could occur when utility feeder breaker opens. It also can feed faults and possibly interfere with utility overcurrent protection [33]. The DG protective relays will generally perform their function independently of any outside knowledge of the system to which they are connected. The greatest fear of the utility protection engineers is that DG relaying will fail to detect that the utility breaker has switched off and DG will continue to energize a portion of the feeder. Therefore, much attention has been paid to detecting islands. There is also the safety concern of a generator accidently energizing the line resulting in injuries to the public and utility personnel.

Unless the machines are large relative to system capacity, interconnected synchronous generators on distribution systems are usually operated with a constant power factor or constant var exciter control. The engineers in most utilities do not want the DG to attempt to regulate the voltage because that would interfere with utility voltage regulation equipment and increase the chances of supporting an unwanted island. Large DG greater than 30% of the feeder capacity that is set to regulate the voltage will often require special communications and control to work properly with the utility voltage-regulating equipment.

The most common power quality problem is a voltage sag, but the ability of DG to help alleviate sags is very dependent on the type of generation technology and the interconnection location. During the voltage sag, DG might act to counter the sag since large rotating machines can help support the voltage magnitudes and phase relationships. However, the impedance

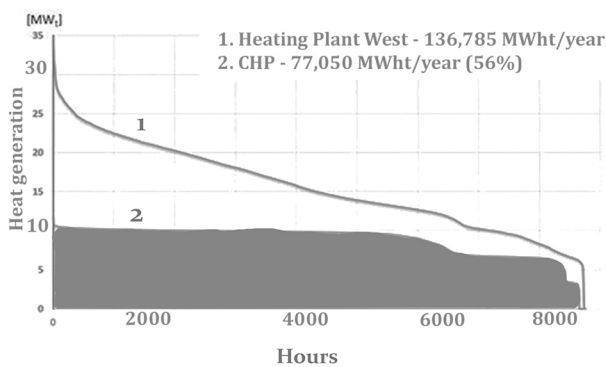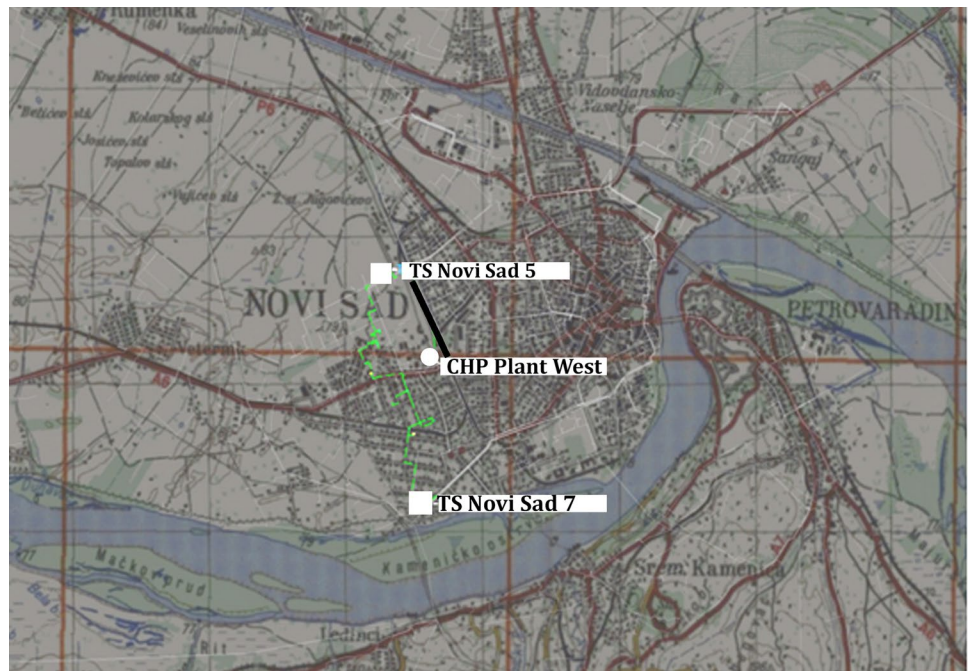**Fig. 3** The locations of TS "Novi Sad 5", CHP "Plant West" and TS "Novi Sad 7"

Fig. 4 Heat generation of the Heating plant West and the CHP unit in the first year of operation
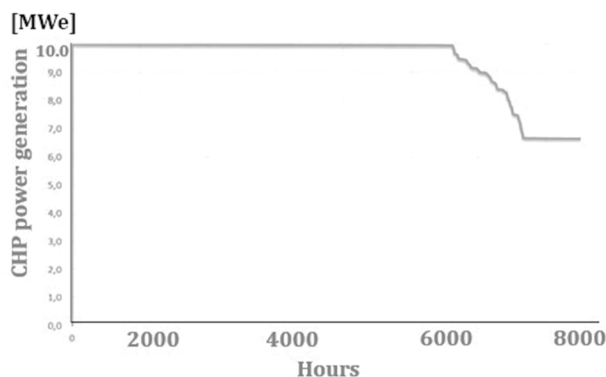

Fig. 5 Electricity generation of the CHP unit in the first year of operation

of service transformers hinders the ability of DG to provide any relief to other loads on the same feeder.

Deploying generation along utility distribution systems naturally creates some conflicts such as utility fault -clearing requirements, reclosing of the breakers, interference with relaying etc. A certain amount of DG can be accommodated without making any changes, but at some point, the conflicts will be too great, and the modification of the distribution system components operation must be made.

4.2 Connecting CHP to the grid

According to Serbian regulation, there are conditions a DG must meet to be connected to a distribution grid and these are as follows [8]: the criterion of allowed power, flickers, harmonics currents, short-circuit power, voltage fluctuations due to the simultaneous connection and disconnection of the generator, and voltage variation in steady state. In case of synchronous generator, the most relevant criteria are the criterion of allowed power, the criterion of voltage fluctuations due to the simultaneous connection and disconnection of the generator, and the criterion of voltage variation in steady state. The most relevant criteria in the considered case of CHP connection to the grid are presented and evaluated in the following.

4.3 The criterion of allowed power

Evaluating the criterion of allowed distributed generator (DG) apparent power at the connection point of the grid is performed according to the expression (1) [8]:

$$S_{\text{ngm}} \leq \frac{S_{\text{KS}}}{50k} \tag{1}$$

where S_{ngm} is the maximum power of generating units that are connected or total power if all generators are simultaneously connected to the network, S_{KS} is three phase short circuit power at the DG connection point, and $k = 1$ for synchronous generators.

The total short-circuit current at the DG connection point is calculated as the sum of the short-circuit current of the system and the short-circuit current of all the generators at the power plant. The resulting short-circuits current (power) at the DG connection point must not exceed the maximum allowable value of the short circuit current (power) of the equipment.

According to the criterion of allowed power the maximum DG power is calculated for various distribution grid voltage levels and presented in Table 2. According to Eq. (1) and Table 2, the maximum DG connected power on the bus-bar 20 kV is 10 MVA meaning that in the considered case (12,4 MVA) the criterion of allowed power is not satisfied. On the other words, the selected generator of CHP unit is oversized, and the maximum unit loading is 80% of the generator rating.

4.4 The criterion of voltage variation in steady state

Voltage increase after connecting DG is calculated using expression (2), [8]:

$$\Delta u = 100 \cdot \frac{S_{\text{DG}}}{S_{\text{KS}}} \cdot \cos(\psi_K + \phi_{\text{DG}}) \leq 2\% \tag{2}$$

where Δu is voltage increase at the DG connection point (%), S_{DG} is indicated apparent power of DG, ψ_K is the argument of the network impedance measured from the connection point, and ϕ_{DG} is the argument of DG loading.

This criterion means that the DG through their actions do not cause the voltage increase at any point exceeding limits for a given voltage level. Since in the considered case $S_{DG} = 12.4$ MVA and $S_{KS} = 500$ MVA, to keep the voltage

Table 2 Maximum DG power on the grid

DG connecting point	Maximum DG power
In the 400 V network	50 k VA
On the bus bar 400 V	200–250 k VA
In the 10 kV network	2–3 MVA
On the bus bar 10 kV	8 MVA
In the 20 kV network	7 MVA
On the bus bar 20 kV	**10 MVA**
In the 35 kV network	12–15 MVA
On the bus bar 35 kV	25–30 MVA

variation up to 2%, the maximum value of $\cos(\Psi_k + \varphi_{\text{DG}})$ should be 0.8.

4.5 The criterion of allowed harmonics currents

Harmonics from rotating machines are not always negligible particularly in grid parallel operation. The utility power system acts as a short circuit to zero-sequence tripled harmonics in the voltage, which can result in surprisingly high currents. For grounded wye-wye or delta-wye service transformers, only synchronous machines with 2/3 pitch can be paralleled without special provisions to limit neutral current [33]. For service transformer connections with a delta-connected winding on the DG side, nearly any type of three-phase alternator can be paralleled without this harmonic problem.

The criterion of allowed current harmonics is evaluated using the following expression [8]:

$$I_{\text{vhd}} = I_{\text{vhs}} \cdot S_{\text{ks}} \tag{3}$$

where I_{vhd} is allowed value of the harmonics current at the voltage level of the generator (A), I_{vhs} is allowed value of the harmonics current that is reduced to the three-phase short-circuits power at the DG connection point in the grid (A/MVA).

If the above criteria have not been met, the owner of the power plant should take specific protective measures, such as installing of filters for the corresponding higher order harmonics current or connecting the DG to the point with the higher value of the short circuit power (higher voltage level).

4.6 The criterion of allowed flickers

The criterion of flickers is evaluated using the flicker disturbance factors of the DG plant, caused by long-term flickers lasting over two hours. The plant with n generators with total installed capacity S_{mel} can be connected to the grid if the following requirements are satisfied [8]:

$$A_{\text{lt}} = \left(C_{\text{fmel}} \cdot \frac{S_{\text{mel}}}{S_{\text{ks}}} \right)^3 = \left(\frac{c_{f1}}{\sqrt{n}} \cdot \frac{S_{\text{mel}}}{S_{\text{ks}}} \right)^3 \leq 0.1 \tag{4}$$

$$P_{lt} = C_{fmel} \cdot \frac{S_{mel}}{S_{ks}} \leq 0.46 \tag{5}$$

where A_{lt} is long-term factor of the flicker noise, P_{lt} is long-term flicker emission factor, S_{mel} is total installed capacity of the power plant, n is number of generators in the power plant, C_{f1} is flicker coefficient of the power plant with a single generator, and. C_{fmel} is flicker coefficient of power plant with n generators ($c_{f1}/\sqrt{n}$).

In the considered case, $c_{f1} = 32$, $n = 3$, $S_{mel} = 12,4$ MVA, the flicker emission factors are $A_{lt} = 0,0966$ and $P_{lt} = 0.4589$,

which means that the criterion of flickers expressed by (4) and (5), is satisfied.

4.7 Restoration of supply

The main objective of the network restoration procedure is to obtain the switching operation plan for supplying the un-served loads by satisfying current and voltage limitations in the network. Besides, the network configuration change should be performed with the least number of switching operations, without any interruptions in the supply minimizing the risk of such operations.

A restoration of supply after the outage of HV/MV transformer is much more complex issue comparing to the outage of MV line since the outage power and number of affected consumers is usually large. Basically, each of the transformers, which supply its portion of distribution grid, has its own availability shown as a current reserve equal to the difference between the continuous maximum allowable load and the actual load (before failure).

The problem of supply restoration in distribution system has attracted significant research interest in last three decades and different approaches have been applied to solve the supply restoration task [34]. Some approaches are based on the multi-objective optimization methods and numerical algorithms, some use heuristic methods, many are based on the AI techniques while others present combination of all previous mentioned. The supply restoration after the fault in the 20 kV grid of the city of Novi Sad is reported in [35]. An algorithm for restoration of supply after the outage of transformer HV/MV based on the mixed integer programming technique applied on the network of Novi Sad is presented in ref. [36]. The objective function minimizes un-served load, the number of switching operations, voltage deviation, and loading unbalance among transformers.

5 Application

5.1 Power quality monitoring

Power quality issues regarding connecting distributed generators to distribution grid in Serbia are presented in Technical recommendation [8]. Power quality monitoring of the CHP "Plant West" was performed in period 15 March—3 April 2018 at the busbar S2 in TS 110/20/10 kV "Novi Sad 5 ". The diagram of real and reactive power injected into the busbar S2 in TS 110/20/10 kV "Novi Sad 5 " is shown in Fig. 6. The range of the real and reactive power was 9,5–9,9 MW and 0,6–1,0 MVAr, respectively. The outage of one of three generators occurred on 22 March and on 3 April 2018, lasting about four hours.
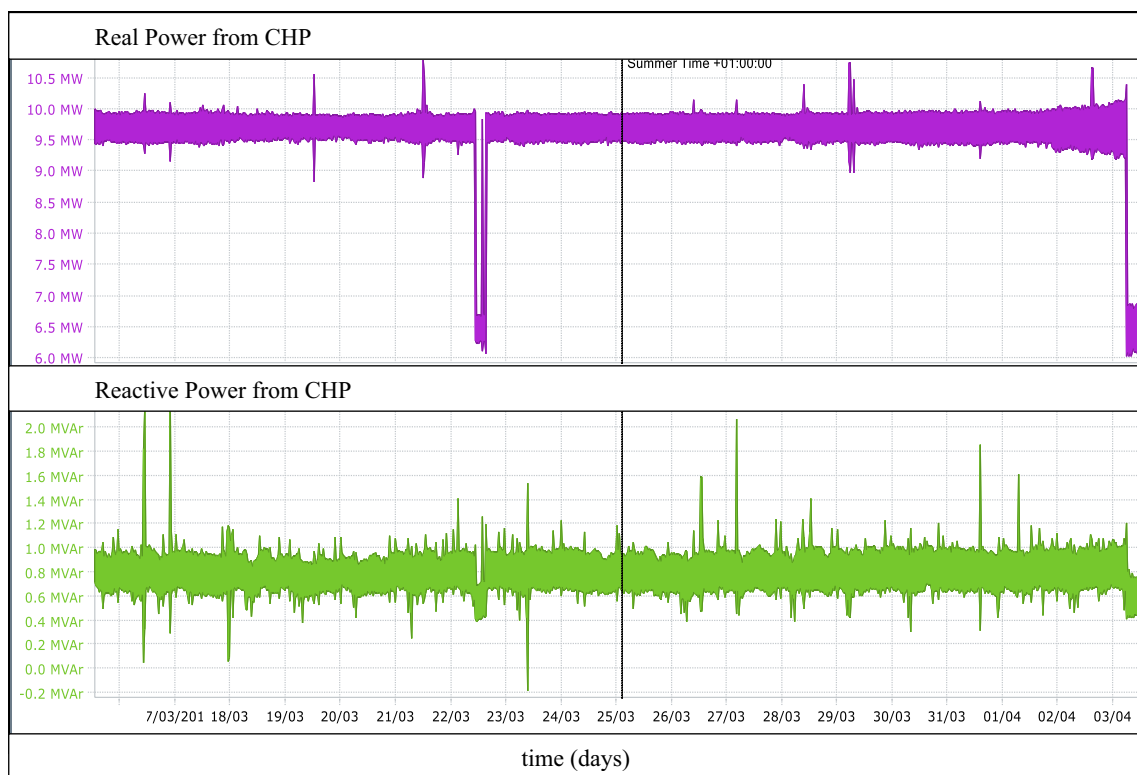

Fig. 6 Real and reactive power injected by CHP into the busbar in TS 110/20 kV "Novi Sad 5"

Figure 7 shows voltage and current profile at the busbar S2; the phase voltage and current are in range of 11,5—12,2 kV, and 260–280 A, respectively. The diagram shows the periods of voltage drop and current peaks; the maximum voltage drop (5,2%) remains within the limits of ($\pm$) 10% of the rated phase voltage ($U_f = 11,56$ kV). At the instant of failure of one of the generators, the injected current is 180A. The voltage waveform is not significantly affected by the disturbance since the DG is connected to an infinite bus (500 MVA of three-phase short circuit power on the 20 kV side).

Voltage sag may be caused by switching operations associated with a temporary disconnection of supply, the flow of inrush currents associated with the starting of motor loads, or the flow of fault currents. These events may emanate from the customers system or from the public network. Besides, lighting strikes can cause momentary voltage sags. For transient stability analysis, a synchronous machine is represented by internal generator internal voltage E' behind the generator reactance X_d' therefore the voltage balance is given by equation, $E' = V_g + j\, X_d'\, I_g$. Since the field winding has small resistance, the flux linkage will tend to remain constant during the initial disturbance, meaning that internal generator voltage E' is assumed constant. During the voltage sag, the DG might act to counter the sag since large synchronous machines can help support the voltage magnitudes and phase relationships [37].

Figure 8 shows the voltage sag in the busbar S2 which occurred on 16 March 2018 at 11:24 h; the voltage drops to 10,93 kV, the depth of voltage sag is 0,77 kV, while the duration of the event is 130 ms. The cause of voltage sags in this case is unknown. However, since electric motors draw more current when they are starting than when they are running at their rated speed, starting an electric motor in the heating plant can be a reason for a voltage sag.

Figure 9 shows the voltage sag in the busbar S2 which occurred on 16 March 2018 at 22:30 h; the voltage drops to 10,93 kV, the depth of voltage sag is 0,97 kV, while the duration of the event is 95 ms. The disturbances might be caused by changes in the network configuration, transient faults, large load application or removal, or any combination of these. It is noticeable that the current waveform and its corresponding voltage waveform (green curve) in phase a have similar patterns in comparison with other phases, which might be explained by switching operations associated with sudden resistive load changes in phase a. The voltage and current waveforms in phase b and c might be caused by switching operations associated with the flow of inrush currents due to the starting of motor loads.

Figure 10 shows the voltage and current waveform in busbar S2 during switching off one of the generators in CHP plant that occurred on 22 March 2018 at 10:55 h. Restarting attempted at 13:56 h, but the outage occurred at 14:02 h. The
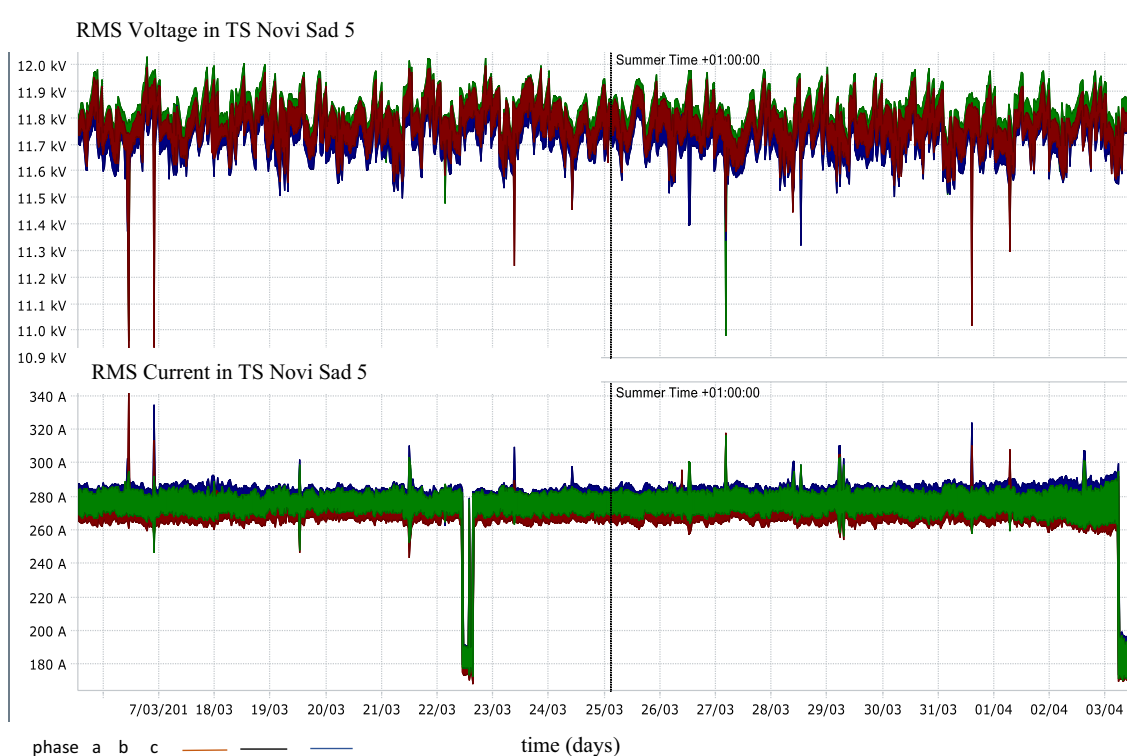

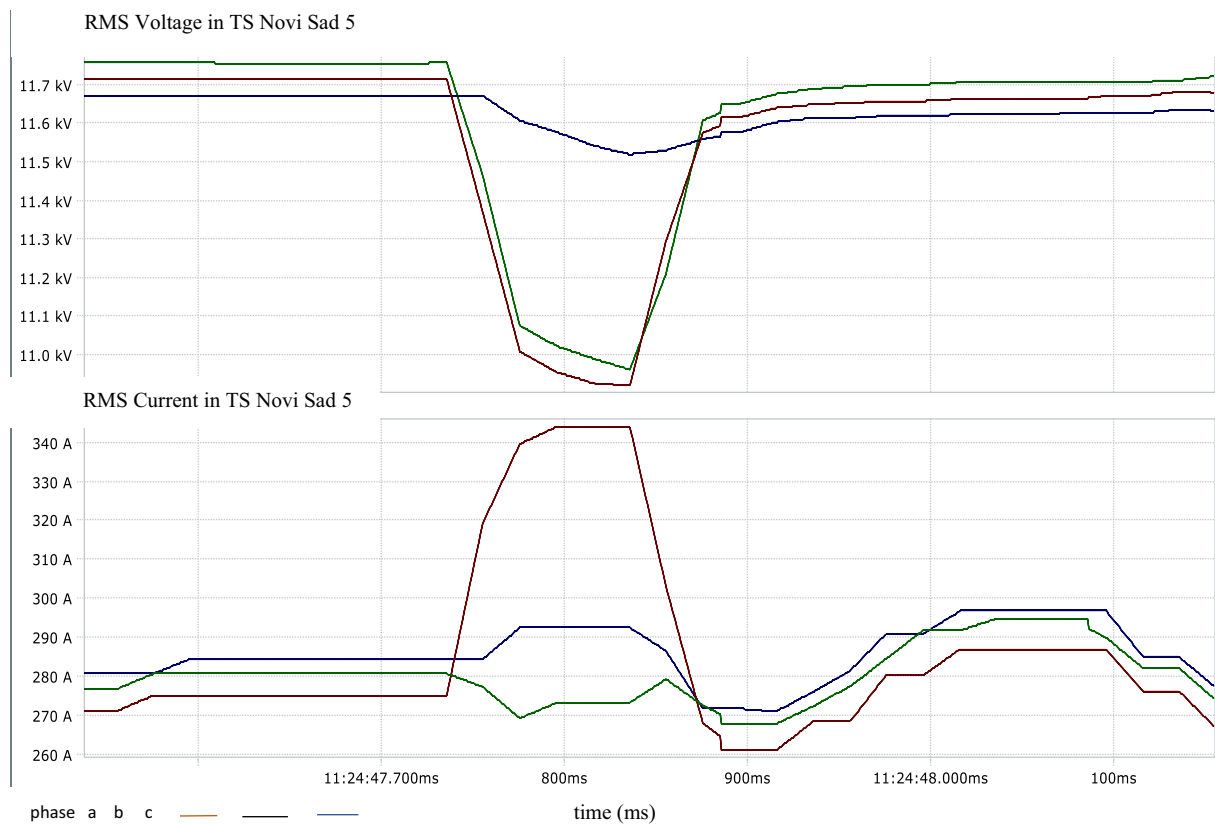**Fig. 7** The voltage and current profile in TS 110/20 kV "Novi Sad 5"

Fig. 8 The voltage sag and current profile in TS 110/20 kV "Novi Sad 5" recorded on 16 March 2018 at 11:24 h

automatic voltage control in the substation TS "Novi Sad 5 "operated at 09:46 h.

Figure 11 shows the voltage and current waveform in busbar S2 during the operation of automatic voltage control which happened four times at 05:37 h, 06:29 h, 06:42 h and 08:09 h. The switching off one of the generators occurred at 06:42 h. It is noticeable in Fig. 10 and Fig. 11 that the DGs do not participate in the voltage control procedure and the current change (decrease) due to switching off one of the generators have not been reflected in the corresponding voltage waveform. Such a voltage waveform can be explained by the fact that the DG is connected to a strong grid (infinite bus) which keeps the voltage stable.

Figure 12 shows the harmonics and flickers level in the CHP plant. The current harmonics level is around 1% confirming that the synchronous generators are clean energy source in terms of power quality. The short-term sensitivity to flickers (PST = 45%) as well as the long-term sensitivity to flickers (PLT = 30%) stay within the allowed range (≤ 46%).

5.2 Restoration of Supply with CHP support

In spite the predicted allowed failure time of the TS 110/20 kV including 5 km long overhead line 110 kV is

around 7 min, according to reported failure experience worldwide the interruption of supply due to failure of TS HV/MV can reach up to three hours in the municipality area and even 6–12 h in the rural areas [23]. The CHP facilities are usually located on-site or close to consumers therefore electricity transmission and distribution losses are reduced, and delivery reliability is enhanced. Compared with large, interconnected grids, a CHP is more resilient when weather or security events interrupt energy supplies.

As an example of the benefits of CHP integration into the grid, the restoration of supply after the outage of substation HV/MV with the CHP support in balancing power is presented in Table 3. Two substations TS 110/20 kV/kV "Novi Sad 5" and TS 110/20 kV/kV "Novi Sad 7" are interconnected by eight 20 kV feeders (11 MW of maximum capacity each). The maximum loading of the substation TS 110/20 kV " Novi Sad 5", 2 × 31,5 MVA and the substation TS 110/20 kV "Novi Sad 7", 2 × 31,5 MVA, is 60% and 50% respectively. The substation TS 110/20 kV/kV " Novi Sad 5" is supplied via two 110 kV transmission lines from the substation TS 400/220/110 kV "Novi Sad 3", which facility is equipped with two transformers. Due to the lack of corridor for the 110 kV overhead transmission lines, the substation
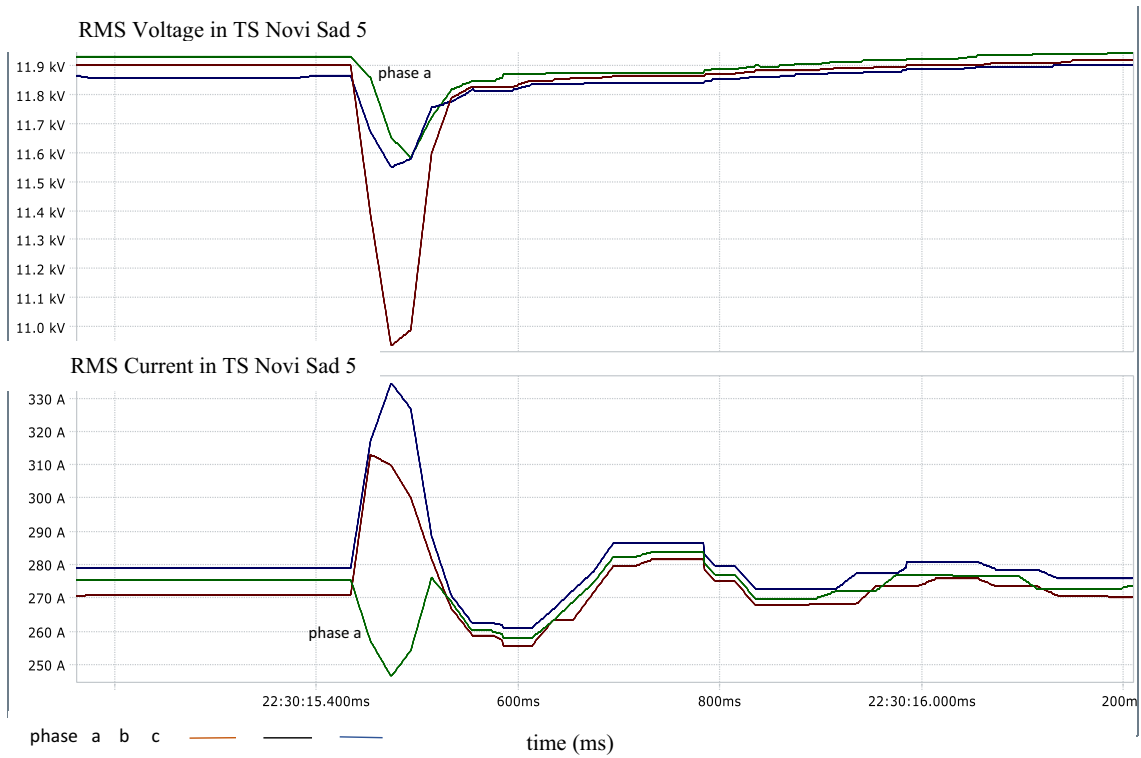
Fig. 9 The voltage sag and current profile in TS 110/20 kV "Novi Sad 5" occurred on 16 March 2018 at 22:30 h
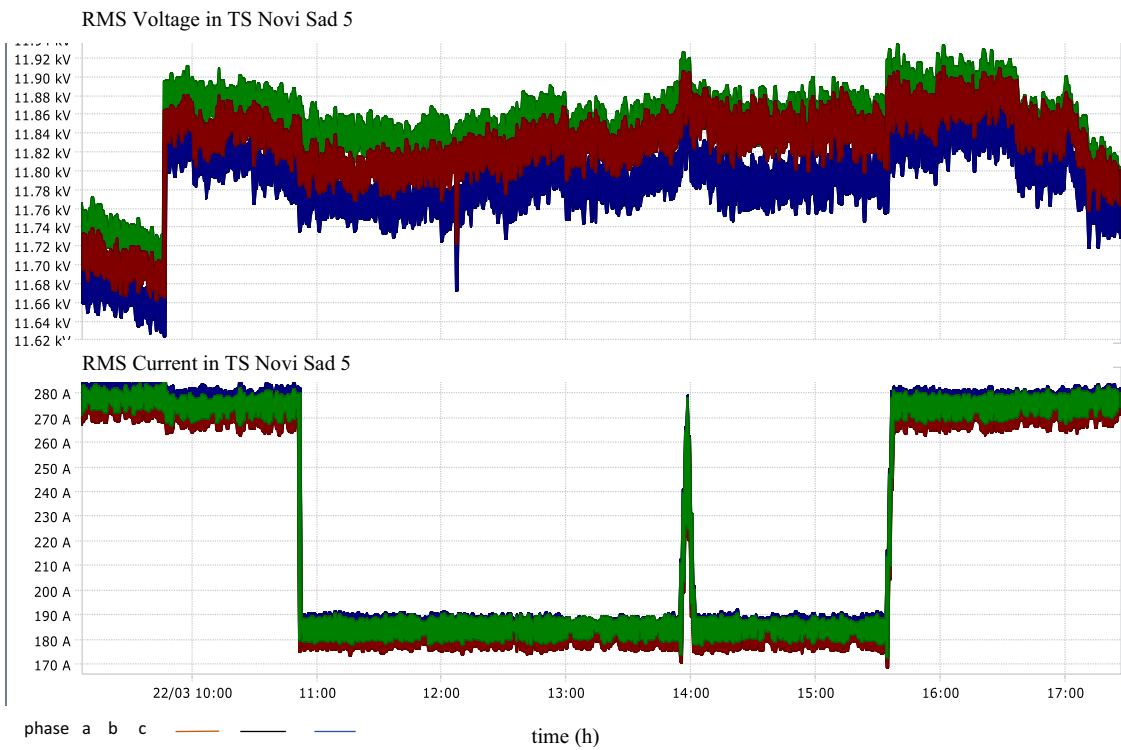

Fig. 10 The voltage and current profile after the switching off one of the generators in CHP on 22 March 2018 at 10:55 h
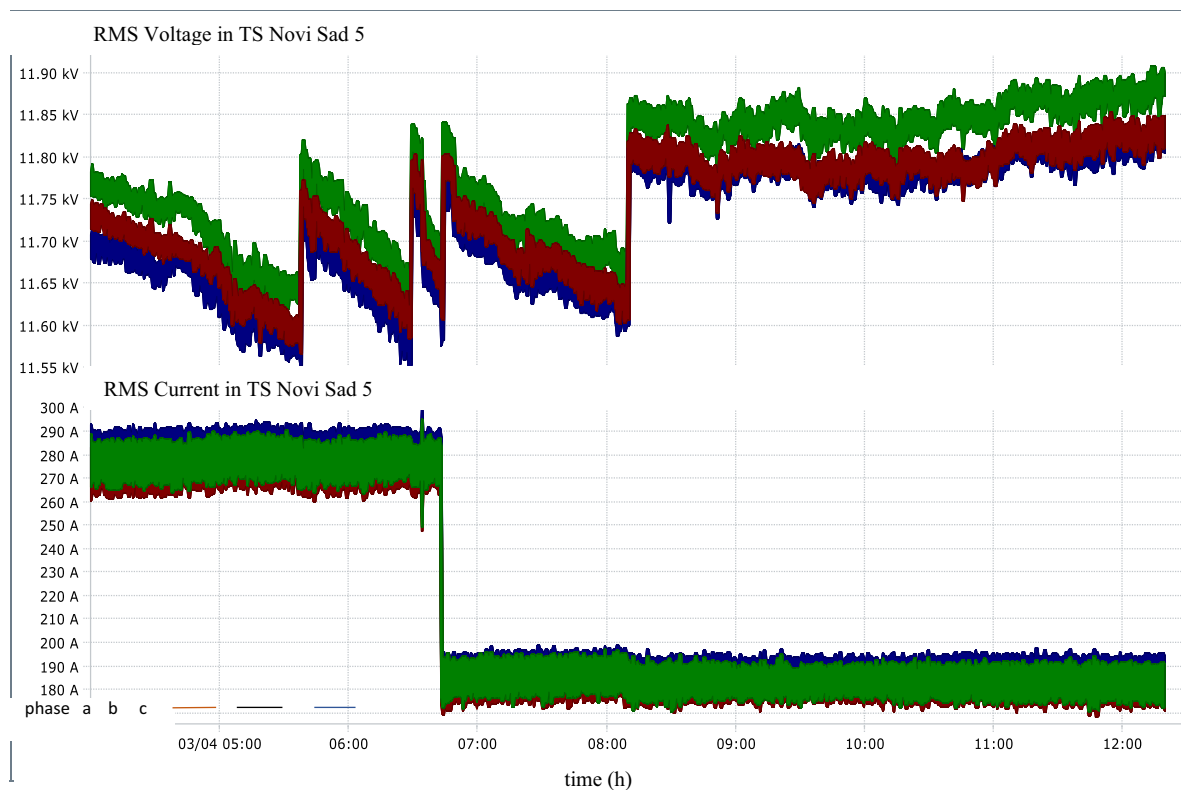
Fig. 11 The voltage and current profile during the operation of automatic voltage control in TS 110/20 kV "Novi Sad 5 "

TS 110/20 kV/kV "Novi Sad 7" is still connected to the 110 kV grid via single transmission line.

5.3 Case study 1- maintenance

During the reconstruction of the 110 kV field in TS 110/20 kV/kV "Novi Sad 5" in 2017, the existing disconnectors were replaced with the motorized ones which were then integrated into the SCADA system. For performing planned activities, the substation TS 110/20 kV/kV "Novi Sad 5" was switched off five times from the 110 kV supply, namely both transformers were switched off. The continuous supply of 53,962 consumers (34,4% of the total city consume), including some very sensitive ones (hospital, maternity hospital, faculty of medicine, fair etc.) depended on the available power in the substation TS 110/20 kV/kV "Novi Sad 7" (2×31,5 MVA). The power supply was provided partly from the CHP "Plant West" (10 MW) and TS "Novi Sad 5", Fig. 2, via 20 kV inter-connection cable feeders, Table 3, case 1.

5.4 Case study 2 – outage

In case of loss of 110 kV voltage in the TS 110/20 kV/kV "Novi Sad 7", the power supply of its consumers can be

fully restored via eight 20 kV inter-connection cables from TS 110/20 kV/kV " Novi Sad 5". The power supply was provided partly from the CHP "Plant West" (10 MW) via 20 kV inter-connection cable feeders, Table 3, case 2.

Therefore, in both cases, the maintenance of TS 110/20 kV/kV "Novi Sad 5" as well as the fault in the 110 kV grids which caused the outage of TS 110/20 kV/kV "Novi Sad 7", the support of the CHP ensured security of supply for large number of consumers. The only precondition for securing continuous power supply in both cases is to keep the 20 kV supply on the busbar of the transformer ET2 in TS "Novi Sad 5" where the CHP is connected.

5.5 Case study 3 – total loss of 110 kV supply

When a local power system or a microgrid switches from islanded to grid-connected operation mode, it needs to be synchronized with the main grid to avoid damage and power quality issues [38]. The main concern in synchronization is the switching transients, while a standard method for synchronization is based on the feedback control to adjust generator voltage and frequency.

In case of loss of 110 kV in both TS, which is not very likely event (heavy storms), theoretically the supply restoration of priority consumers (central hospital, maternity ward,
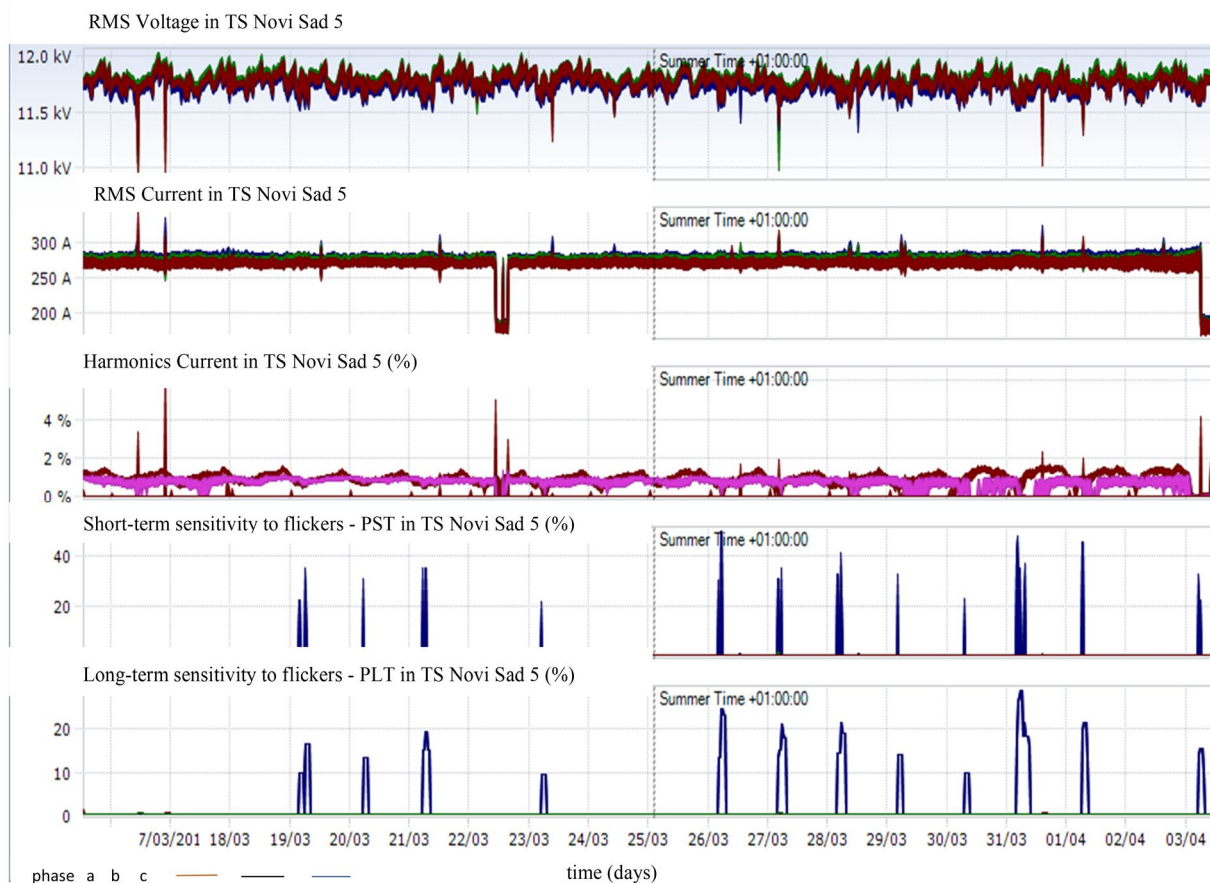
Fig. 12 The rms value of voltage and current, the harmonics current and flickers generated by CHP unit measured in 20 kV busbar in TS "Novi Sad 5 "

Table 3 The supply restoration with CHP support

	Case study	Outage power (MW)	Available power (MW)	Supply restoration completed?
1	Maintenance of TS "Novi Sad 5"	37,8	$P_{NS7} + P_{CHP} = 31 + 10 = 41$	Yes
				$41 > 37,8$
2	Loss of 110 kV supply in TS "Novi Sad 7"	31	$P_{NS5} + P_{CHP} = 25.2 + 10 = 35,2$	Yes
				$35,2 > 31$
3	Loss of 110 kV supply in TS "Novi Sad 5" and TS "Novi Sad 7"	68,8	$P_{CHP} = 10$	No
				(islanded operation of CHP is not allowed)

fair etc.) might be obtained from the CHP using the 20 kV cable connection between the CHP plant and TS "Novi Sad 5", Fig. 2, (case 3, Table 3). However, this scenario is not the option in practice in EPS Distribucija because the islanded operation of the CHP plant connected to the grid is not allowed (according to the regulations [8]). Namely after the unplanned outage of 20 kV supply of the transformer ET2 in TS "Novi Sad 5", the CHP protection will immediately

switch off the generator unit; the CHP operation will be reactivated after the restoration of supply of the transformer ET2.

The operating CHP plants in islanded modes is becoming a new trend nowadays due to increased reliability and economic benefits. To enable islanded operation of CHP, the application of sophisticated equipment for generator synchronization to the grid during the switching transient, based on the feedback control to adjust generator voltage and

frequency as well as upgrading of regulation and operating practice, is needed [38].

5.6 Scenario of massive integration of CHP

There is a huge potential for increasing energy efficiency and decreasing environmental impact in the industrial plants, heating systems as well as in the power sector in Serbia [3]. In the study of development of sustainable bioenergy market in Serbia, the substitution of natural gas by biogas and modernization of the existing systems for district heating in Vojvodina is investigated [39, 40].

To estimate the impact of massive integration of CHP systems on the electrical power and heating demand and the environment, in this research a scenario of installing more CHP natural gas-powered systems in district heating of 12 cities and CHP units in industry facilities **in** the Autonomous Province of Vojvodina is considered. The territory of Vojvodina is a complete socio-political, economic, cultural, health, and educational entity and as such, it is suitable for generalizing results. Energetic performance of the province is as follows: Total installed thermal capacity of the boilers in the 15 public heating plants is 1106 MW, natural gas consumption is 106 558 139 Sm^3/a and the total CO_2 emission is 203 kt/a [40]. Total electricity and district heating demand of the province in 2020 is estimated to 9109 GWh/a (1737 MW peak load) and 2478 GWh/a respectively [1].

The estimation of CHP environmental impact is based on the research in ref. [12] where it is demonstrated that the 10 MW CHP natural gas-fired combustion turbine and heat recovery systems (operation hours 7500 per year) can reduce the 67.5 tons/a of CO2 equivalent, which is equivalent to approximately 12,8 thousand passenger vehicles.

According to the scenario, the 15 new CHP natural gas-fired combustion turbine and heat recovery systems (operation hours 7500 per year) in the 12 cities in Vojvodina, with a capacity of 10 MW electrical and 10 MW thermal each, would be installed in the 15 heating plants and integrated to the existing district heating and power distribution systems. The estimated electricity and heat produced from new cogeneration are 1080 GWh/a, and 1080 GWh/a, respectively.

Apart from the district heating, in the research based on a sample of 44 companies in Vojvodina, the possibility of investments of each of these companies in producing over 90% of its electricity needs by implementing partial cogeneration, is considered [10]. It is found that upon the installation of the 44 plants with a gas engine (0.2—2 MWe) and the 6 plants with a gas turbine (5 – 20 MW), in total 105 MW of installed electricity power, and 130 MW of rated thermal capacity, the amount of 697 GWh/a of electricity would be generated. The heat from prospective industrial cogeneration

usable in technological processes equals 939 GWh/a, while the additional gas consumption is 1139 GWh/a.

Summarizing, the prospective 15 CHP in district heating and 50 CHP in the industry facilities in the province of Vojvodina, could generate 1777 GWh/a of electricity and 2019 GWh/a of heat. The energy from cogeneration would fulfill 1/5 of total electricity consumption and cover 2/5 of the district heating demand of the province. Besides, the new cogeneration would reduce amount of 2,6 kt/a of CO_2 emission, which is equivalent to approximately 480 thousand passenger vehicles.

5.7 Concluding remarks

The CHP "Plant West" operates with full capacity during the summer reducing CO_2 and NO_x emission. Besides, the operation of CHP plant increases security of power supply since in case of the maintenance of TS 110/20 kV/kV, as well as the fault in the 110 kV grid which cause the outage of the TS 110/20 kV/kV, the support of real power from the CHP "Plant West" enables continuous power supply of all consumers including some critical ones.

The CHP plant generates electricity according to the standards since the field measurements showed there were no power quality issues: The current harmonics level is around 1%, the long-term sensitivity to flickers (PLT) is within the allowed range ($\leq 46\%$), while the voltage drops remain within the limits of the rated phase voltage after switching off one of the generators (2%).

The technical power losses in the medium voltage (MV) and low voltage (LV) distribution grid in the city of Novi Sad is around 13%. The city consumes around one million MWh of heat energy a year; the overall measured heat generation system efficiency is 96%, while the heat distribution system's efficiency is somewhat over 90% [41]. In general, the CHP "Plant West" is of great importance for the energy efficiency of the city.

The prospective high penetration of CHP natural gas-powered systems in district heating and in the industry facilities in province of Vojvodina would significantly contribute to energy balance and reduce CO2 emission in the province.

6 Conclusion

The combined heat and power (CHP) generation is a proven solution for meeting growing energy demand efficiently, cleanly, and economically. In this paper the challenges, benefits and lessons learned of the integration of recently realized CHP "Plant West" in the city of Novi Sad are presented and discussed.

The overall operational, energetic, environmental, and economic impact of the presented CHP plant is positive

despite initial technical problems regarding connecting 20 kV cable and issues related to CHP unit sizing and system protection adjustment.

By realization of the CHP plant the three objectives of proclaimed energy policy were achieved: Diversification of energy sources to ensure security of supply, introduction of modern technologies in the energy sector, and increasing energy efficiency.

Since it was the first such CHP plant realized in Serbia, it is crucial that experience and lessons learned be shared to all potential stakeholders in the future energy efficiency projects. To harness the potential for increasing energy efficiency, it is necessary to fully implement adopted strategy and action plan, simplify the procedure of obtaining excessive documentation and shorten the period of connecting new CHP plants to the grid. In addition, it is expected that the government takes active role in the developing market models and provides real incentives (tax and customs reduction, grants) for investment in the energy efficiency projects. It would certainly have positive socio-economic effects such as encouraging foreign investments, promoting employments, as well as developing domestic production of the electro-mechanical equipment and components and increasing the national GDP.

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