ASSURED CAPACITY, TOTAL ASSURED CAPACITY AND DISPATCHABILITY OF SERBIAN POWER SYSTEM AND POWER PLANTS – A CONTRIBUTION TO THE RESEARCH[*]

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Abstract: In electricity generating systems with high penetration of i-RES, the ability of change the power on demand has increasing importance. Following recently published Ulrich’s and Schiffer's approach with assured capacity; in this paper is defined term total assured capacity and is further applied together with dispatchability indicator and possible duration of load change to indicate dispatchability of Serbian power system (EPS). The results of the performed analyses are presented. Total assured capacity appears as very sensitive indicator and its numerical value changes significantly if, in the hypothetical case, one technology e.g., lignite fired power plants have to be substituted with the other technology like wind turbines. An overview of participation different technologies for electricity generation within Serbian power system is presented together with a comparison with German power system. Numerical values of dispatchability factors for EPS’s fossil fueled power plants are presented and discussed. It is underlined the necessity of a specific project study for EPS’s power plants to be performed aimed to define real technology possibilities, limitations that are conditioned by the quality of lignite, as well as the cost increase that arise in satisfying the needs to change the power on demand in conditions determined by hypothetical increase of i-RES electricity generation.

Keywords: Dispatchability, Total assured capacity, Energy technology, Power system

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1. INTRODUCTION

More or less great participation of intermittent electricity sources (i-RES), like wind and photovoltaic (PV) generators, characterize almost all today's electricity generating systems. The target is to reduce as much as it is possible CO_2 emissions during electricity generation. On the other hand, this intermittent electricity sources, although not emitting CO_2, cannot produce electricity when the power system needs it, but when the weather conditions allows it. This fact brings a lot of problems for the operation of such systems, as well as the individual power plants that operate in them. The origin of the problems is strong necessity that dispatchable power plants increase or decrease their output in the amount, as well as with the gradient necessary to maintain the systems stability when weather conditions cause reduction or increase of the intermittent electricity sources power.

The economic principle of the power system's operation technology is to maintain the basic technological parameters of the system (power, frequency and voltage) within the foreseen limits and to preserve the integrity of the system with the tendency to keep the total system costs to a minimum. In practice, this principle is realized by considering all sources in the system as a unique technological structure. A so-called merit order principle is applied to define the order of engagement the plants when consumer's power increase. The merit order is determined by the criterion of the least price of the generated electricity. So, first enters in operation the source with the cheapest electricity, then the next one which has the cheapest electricity from the remaining as yet unplugged sources and so on, to the source with the most expensive electricity in the system, the inclusion of which is delayed for as long as possible, so the last one is switched on.

In the power systems with intermittent renewable energy sources (i-RES) technologies, the priority to feed-in electricity into the system is given to i-RES, regardless of their electricity price, although it is the highest of all sources due to the system of "feed-in tariff".

For this reason, in power systems with i-RES, the load diagram of the system is divided into two parts. The first part – it corresponds to the green area in Fig. 1 – is covered by priority in feed sources that are simultaneously non-dispatchable ones (i-RES). The other, residual part – corresponds to the pink surface in Fig.1, is covered by the dispatchable sources and they switch on according to the merit order principle. In the residual part of the load diagram, there are, by analogy to the system load diagram, three parts i.e. the base part, the intermediate part and the peak part.

In electric power systems with a very large share of i-RES, in certain conditions can arise the surpluses of electricity generation even if all dispatchable sources are switched off. The annual surpluses of i-RES electricity generation correspond to the blue surface in Fig. 1. In order to protect the integrity of the electricity system, this surplus electricity must be either storage, or, if there is insufficient capacity to storage, then they must be exported abroad. This creates additional costs for the system because the foreign buyer of the electricity offered for export will not recognize its price at the power tariff, but accept only the current market price, which is much lower than the price of the electricity at the feed-in tariff. Similarly, storage expensive electricity in order it to be used at a time when i-RES are not working, increases the overall cost of the system. The practice so far always uses the cheapest electricity for storage, since such a total system has the best economic effects.

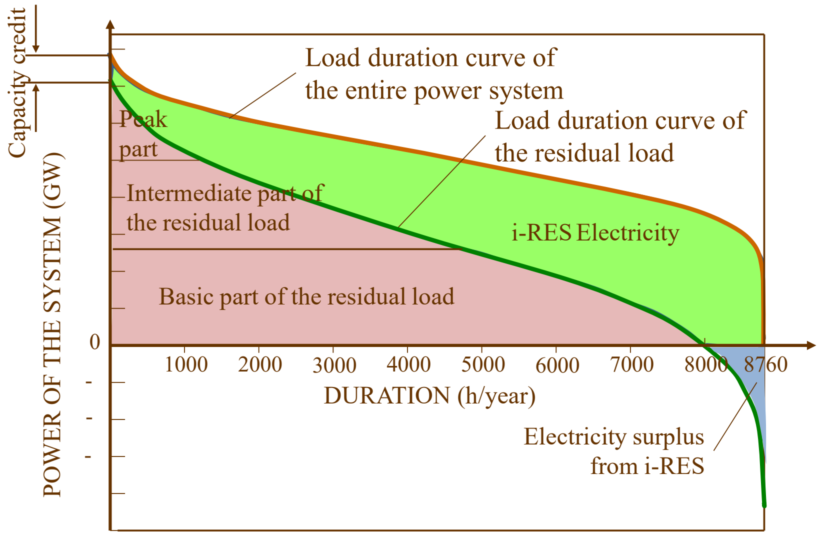

Figure 1. Graphical presentation of the overall load and residual load duration curves

One of the most important requirements for safe operation of a power system is system's stability. The requirement for system's stability is transferred from the system level to individual power plants aimed that the power plants with their individual features ensure necessary stability of the overall system. In order to estimate level of the power system's safety, regarding the stability of its operation a number of indicators are defined and used. In power systems with i-RES the stability issue is additionally sharpened. Therefore, in such systems appears the necessity for some additional, more adequate indicators. Some of them will be either reviewed or proposed in the wording ahead. We should also bore in mind that there are no proven quantitative relations between the power system stability and the numerical values of the indicators. In that respect we have only assumptions about qualitative dependence.

2. INDICATORS

It is rather long time history of using different indicators in energy engineering. In wide use are different groups of indicators like energy efficiency indicators, performance indicators, ecology indicators and others. A general overview of such indicators is presented in literature [1]. A systematic overview of performance indicators is given in literature [2]. Also a systematic overview of energy efficiency indicators in combined heat and power generation is given in [3]. An overview of existing and new ecology indicators is presented in literature [4].

In this paper, we are going to consider existing, as well as the new indicators that indicate the ability of the certain power system with i-RES to change its power on demand, with particular intention to point out their application on Serbian electricity generating system.

There are several indicators that, more or less, can help in description the ability of the power system with i-RES to meet the requirements in the cases when weather conditions cause significant and fast change of the intermittent sources actual power.

In power systems with i-RES it is essential that traditional plants (such as hydro power plants, fossil steam power plants, nuclear power plants, combined gas and steam turbines and open cycle gas turbines natural gas fired) be operationally available to accept an electrical load when weather conditions cause a reduction in power or a complete shutdown of i-RES. This is one of the biggest problems for the design, construction and operation of power systems with i-RES. These "reserve" capacities should have sufficiently low variable costs to prevent an unacceptable increase in the average cost of total electricity generation. The question arises of the necessary size of the total power of these capacities, which must be always available. Theoretical analyzes indicate that a certain part of the total capacity of the i-RES will always be able to function. The part of these capacities that always remains operational and can thus be a substitute for the adequate power of dispatchable plants, provided that there is no reduction in security of supply, is called capacity credit and is a very important indicator in power systems with variable renewable energy sources.

The numerical value of the capacity credit depends on the size of the share of variable renewable energy sources in the total load of the electricity system, on the structure of i-RES (photovoltaic or wind turbines), as well as on the degree of diversification in the spatial distribution of the applied renewable electricity sources. In addition, general climatic conditions, such as the number of windy days or sunny days, as well as their distribution in the year, also affect the amount of capacity credit.

There are different estimates of the capacity credit numerical value. In European engineering practice, according to Fürch et al [5], capacity credit is estimated at 5%. However, Nicilosi et al. [6] cite slightly higher figures for a smaller share of variable renewables, up to 10%. The numerical value of the capacity credit thus defined can also be seen as the difference between the maximum load of the power system and the maximum residual load of the power system (see the graphical representation given in Fig. 1). Schiffer's data, published in [7], on the other hand, indicate that the minimum power of variable renewable electricity plants in Germany in the series from 2010 to 2017 does not exceed 0.5% of the amount of their total installed capacity. However, the percentage given by Schiffer relates to the total i-RES installed capacity, while the capacity credit is defined in relation to the maximum load of the power system.

In the US, more specifically in California, is used Effective Load Carrying Capacity (ELCC) of i-RES. The estimated values for ELCC in California are much higher than those given in the aforementioned European estimates. For example, according to Breeze [8], for solar energy ELCC is in the range of 88.4 to 89.5%, while for wind energy ELCC is from 23 to 31.1%. Although Breeze consider the nature of ELCC the same as the nature of capacity credit, from his further explanation given in [8] can be concluded that that ELCC is connected with probability of carrying the planned load in the daily load diagram, while the capacity credit is defined, as mentioned before, in relation to the maximum load of the power system.

Recently, Ulrich and Schiffer introduced assured capacity as the indicator for electrical power systems [9]. According to Ulrich and Schiffer [9] assured capacity is „the percentage of the nominal capacity of a power plant that, statistically speaking, is reliably available at the time of the annual peak load". Such definition of assured capacity in sense corresponds with definition of capacity credit given by Fürch et al in [5], but is foreseen to indicate capability of all power plants, which belong to the same technology contained in the power system, i.e. at the technology level. Ulrich and Schiffer [9] provided the values of assured capacity for each power generation technology in the German conditions.

The task can be set to define an indicator for indicating assured capacity at the level of entire power system. In solving the task Ulrich and Schiffer's figures for assured capacity was used and individual assured capacity (IAC) of the considered electricity generating technology was defined and calculated using following equation:

$$IAC = RIC \cdot AC \tag{1}$$

Where with AC is denoted assured capacity at the technology level according to Ulrich and Schiffer [9], and with RIC (MW/MW) is denoted relative installed capacity of the considered technology in the power system, which is defined with following equation:

$$RIC = \frac{IC_i}{\sum_{i=1}^{n} IC_i} \tag{2}$$

With ICi is denoted installed capacity of the considered technology in the power system, while index i denotes i-th technology in the considered power system.

The hypothesis is set that individual assured capacities have additive nature. The hypothesis allows defining the total assured capacity for the considered power system by summarizing all individual assured capacities in the considered power system. This approach leads to the following equation:

$$ACT_{PS} = \sum_{i=1}^{n} IAC_i \qquad (3)$$

It is accepted that the stability of a power system depends on the system's ability to change the power on demand. This ability can be observed and analyzed in two dimensions, i.e. possible change of power, and possible duration the load change on demand.

Each technology for electricity generation in the power system has its own technical characteristic regarding its ability to change the power on demand. For that purpose in literature [10] is proposed power factor (PF_t), which is defined with the following equation:

$$PF_t = \left(1 - \frac{P_{t\min}}{P_{t\,nom}}\right) \qquad (4)$$

With P_{tnom} is denoted nominal power of the power technology in the considered power system, while P_{tmin} denotes minimal power of this technology. The case when P_{tmin} equals to P_{tnom}, corresponds to i-RES, since these technologies cannot change their power on demand at all. In contrary, nuclear power plants, hydro power plants, fossil fuel and biomass fired power plants can change power on demand and thus their value of P_{tmin} can be even significantly lower than P_{tnom}.

Minimal power plays an important role in defining the power system's despatchability. The less numerical value of minimal power of all dispatchable plants in the system the better dispatchability of the power system is. Or, in the other words, the greater value of power factor of all dispatchable plants in the system the better dispatchability of the power system is. Therefore, in power systems with high participation of i-RES must be undertaken particular design measures in each power plant in order to reduce minimal power to as low as possible level. In that respect, three different cases can be distinguished. 1) Minimal power with nominal values of the live and reheat steam temperatures – denoted as $P_{tmin/1}$. 2) Minimal power with reduced values of the live and reheat steam temperatures and without supplementary firing – denoted as $P_{tmin/2}$, and 3) Minimal power with values of the live and reheat steam temperatures lower than nominal and with supplementary firing using liquid fuel – denoted as $P_{tmin/3}$. In principle the numerical relation among this minimal powers is $P_{timin/1}$,> $P_{timin/2}$,> $P_{timin/3}$. In last two decades design measures have been undertaken to reduce one or all of these values by appropriate refurbishment of the existing power plants, [11, 12].

Power system's ability to change the power on demand can be indicated by dispatchability indicator (DI) – expressed in MW/MW, which is, according to Grkovic and Doder [10] analytically determined by following equation:

$$DI = \frac{\sum_{i=1}^{n}\left[\left(1-\frac{P_{ti\min}}{P_{tinom}}\right)\cdot P_{tinom}\right]}{\sum_{i=1}^{n} P_{tinom}} \tag{5}$$

With index i is denoted i-th power plant in the considered power system.

In the particular case the minimal power of a dispatchable plant can be considered as equals to zero, since dispatchable plants can be switched off when power system needs this. In that case, the corresponding numerical value of DI=1 represents the maximal value of dispatchability indicator.

Generally, the numerical value of the Dispatchability Indicator depends on the technology configuration of the considered power system. The configuration can be expressed by participation of i-RES in the overall load domain, as well as by participation of all carbon-free sources in residual load domain [10]. Obviously, greater participation of i-RES in the power system leads to smaller value of its dispatchability indicator.

Numerical value of the power factor can be estimated at the certain electricity generating technology level, e.g. for all power plants of the same technology like lignite fired or natural gas fired technology, or a third one. This approach was performed in [10]. However, this approach leads to too general information and not enough precise numerical values of corresponding dispatchability indicator. Therefore, it is more appropriate to determine power factor at the level of individual power plants. This approach enables also more precise analysis with conclusions directed in pointing out possible improvements of the power system's technology structure regarding dispatchability.

It is supposed the existence of the lowest value of dispatchability indicator until which the corresponding electricity generating system is satisfactory dispatchable. This value is designated as DI_{opr} [10]. For lower values of DI, i.e. for $DI<DI_{opr}$, occurs significant difficulties in changing the power on demand in referent power system. The difficulties can be overcome by exporting the surplus electricity or by importing the missing electricity. However such operation is connected with serious economic losses as is explained and exemplified in the case of Germany by Stevanović in [13]. The other possibility is to build appropriate electricity storage equipment. This solution is conditioned with considerably high investments of money, as well as with the time necessary for installing appropriate electricity storage capacities.

The other important aspect of the power systems ability for power change on demand is the time available for the change its power. This period of time depends to power factor and on the speed of the power change of the individual power plants, as well as on the number of all power plants in the considered power system. In defining the time period available for power change there are two extreme options: 1) when the power plants in the system change their power sequentially, i.e. next plant start its power change after previous plant finished the change and 2) when all power plants simultaneously start to change their power. All real possible time periods of power change in the power system are between these two extreme options. Technology of the power change in overall power system with simultaneously keeping grid frequency and voltage within prescribed values is the complex one and out of the scope of our consideration in this paper. Some important aspects of this technology are explained in the literature, for example in [14, 15].

The speed of the power change represents an individual technology characteristic of each power plant. An overview of these technology characteristics for different electricity generating technologies is presented and discussed in literature [16, 17].

In the first case, i.e. when the power plants change their power sequentially, the time of possible feed-in, reduced to the total installed power in the system i.e. the relative possible duration of power change (RDPC1) is defined, according to [10], with the following equation:

$$RDPC_1 = \sum_{i=1}^{n} \frac{\left(1 - \frac{P_{ti\min}}{P_{tinom}}\right) \cdot P_{tinom}}{\dot{P}_{ti}} \cdot \frac{1}{\sum_{i=1}^{n} P_{tinom}} \qquad (6)$$

With $\dot{P}_{ti}$ is denoted the speed of the power change in MW/min of i-th electricity source in the considered power system for electricity generation.

In the second extreme case when all power plants start to change the power simultaneously the overall time will be equal to the longest individual power plants time.

3. ELECTRICITY GENERATING SYSTEM OF SERBIA

Electricity generating system of Serbia consists of several entities; each of them owns certain amount of electricity generating capacities. The biggest one is Electric Power System of Serbia (EPS) electric utility company that owns and operates fossil fueled power plants and hydropower plants. The other entities own and operate small capacities of wind turbines, PV, biomass and CHPs.

Electric power system of Serbia (EPS) has all to gather 4376 MW (at the high voltage terminals) fossil fueled power plants and 2973 MW hydro power plants [18]. Fossil fueled power plants comprise lignite fired power plants total capacity of 3971 MW (at the high voltage terminals), brown coal power plant Morava capacity of 108 MW, as well as 297 MW (at the high voltage terminals) natural gas fired capacities aimed for CHP generation. Hydro power plants comprise run-of-river power plants total capacity of 1989 MW, hydro storage power plants total capacity of 370 MW, and a pumped storage plant capacity of 614 MW [18].

For estimation of capacities capable for electricity generation installed in the other entities in Serbia are used available data from register kept by the Ministry of energy and mining of Serbia [19], as well as the data publicly available. In the register there are two categories of registered capacities, i.e. privileged and temporarily privileged ones. In the estimation are included only those from the list of privileged capacities. In this way for wind turbines is estimated altogether 355 MW. Photovoltaic privileged capacities include those on land total power of 7,53 MW and those on objects total power of 3,48 MW. However it is not clear which part of these capacities are in operation and which part is still under construction. Therefore, for the analysis is used figure of 7,53 MW photovoltaic capacities. In the register there are also listed privileged biogas and biomass fueled electricity generating plants total capacity of 16,9 MW and privileged CHP plants total capacity of 21,9 MW [19].

A plan for more detailed review of the Serbian electricity generating capacities was elaborated and partially executed. The target was for each unit in each power plant to identify three levels of minimal load, i.e. $P_{timin/1}$, $P_{timin/2}$, and $P_{timin/3}$, as well as appropriate specific heat consumption in each of the modes of operation. For that a special questionnaire was developed. However, only the data for $P_{timin/1}$ were collected.

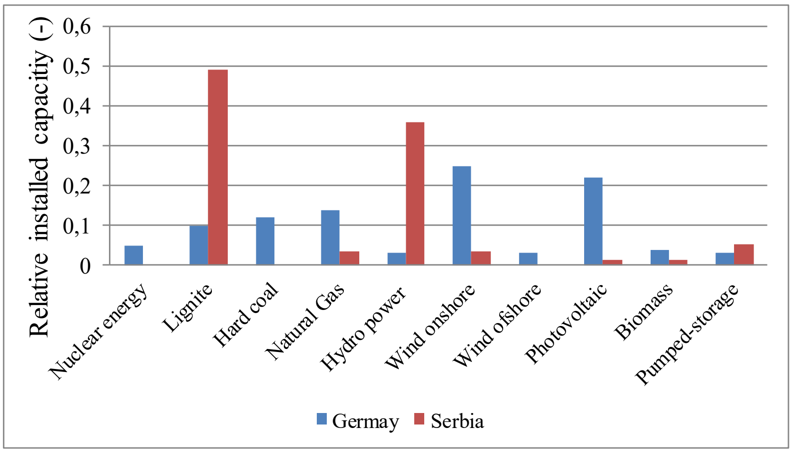

Figure 2. Relative installed capacities of electricity generating technologies in Serbia and Germany

In Fig. 2 are presented comparative data on installed capacities in Germany and in Serbia, according to data given in references [9, 18, 19], and reduced to the total installed capacities. It can be seen that Serbia has much greater share of lignite fired technologies and hydropower including pumped-storage technologies. On the other hand, Germany has much greater share of other technologies like nuclear, hard coal fired, natural gas fired, wind, photovoltaic and biomass. It should be underlined the fact that participation of lignite fired technologies in Serbia exceeds participation of nuclear, lignite, hard coal, and natural gas fired technologies taken together in German power system. This fact indicates the need of a serious care in defining future technology stricture of the

Serbian electricity generating system. On the other hand, participation in German power system of wind, PV and biomass technologies are significantly greater than those in power system of Serbia.

4. ANALYSIS AND THE RESULTS

Numerical value of the individual assured capacity, which is defined by equation 2, obviously depends on the type of technology for electricity generation, as well as on the share of the technology in the total installed capacities of the considered power system. This can be recognized in Fig. 3 where are presented distributions of calculated values of individual assured capacities in the power systems in Serbia and in Germany. Data for Germany are calculated using Ulrich and Schiffer's data presented in [9]. Data for Serbia are calculated using Ulrich and Schiffer's data, as well as available data for electric power system of Serbia [18 and 19] that are presented in the elaborated form in Fig. 2. A general conclusion can be drawn that power system of Serbia relays to the greater extend on technologies with higher values of individual assured capacities than German power system.

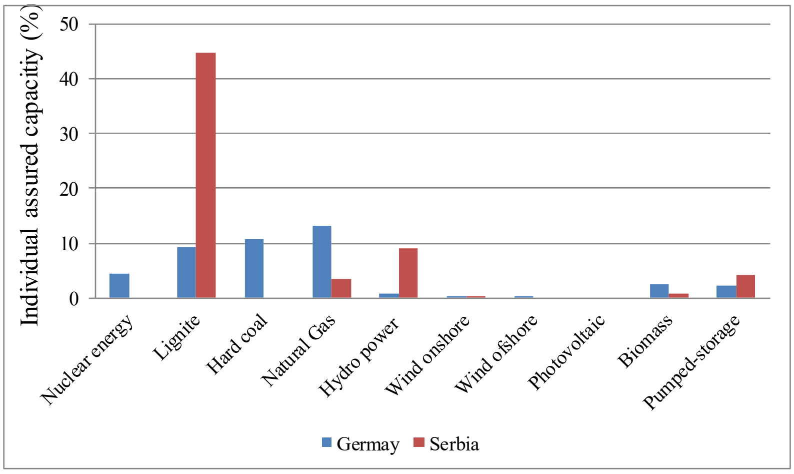

Figure 3. Individual assured capacities in Serbia and Germany

The total assured capacity for the considered power system, which is defined with equation (3), can serve as an important feature of the electricity generating system when it is treated as a complex technology structure. Above examples gives total assured capacity for the power system in Germany of 43,11%, while in Serbia it amounts 62,36%, or slightly over 44% higher.

All alternatively planed future changes in the technology structure of the considered power system can be analyzed regarding the total assured capacities point of view. For example, if Germany substitute nuclear power plants with offshore wind turbines technology, the numerical value of total assured capacity would be decreased from 43,11% to 38,97%, or roughly for about 10%. But in the case that nuclear power plants, lignite fired and hard coal fired power plants, taken together in Germany would be substituted with wind turbines offshore technology only, the value of total assured capacity would drop from 43,11% to 20,01%, i.e. the drop would be more than 50%. Just for the comparison; in the case that lignite fired and brown coal fired power plants, taken together in Serbia will be substituted with onshore wind turbines technology only, the value of total assured capacity would drop from 62,1% to 17,7%, i.e. the drop would be slightly above 70%. However, it is another question what such a reduction of the total assured capacity can mean for technology of the power system operation and its stability. Can frequency and voltage be controlled successfully at all? Next important and unavoidable question is the total price for equipment and for capital necessary for such an adventure. Of course, if natural gas fired technology will be assumed for the substation, in both countries the resulting values of total assured capacities would be slightly increased.

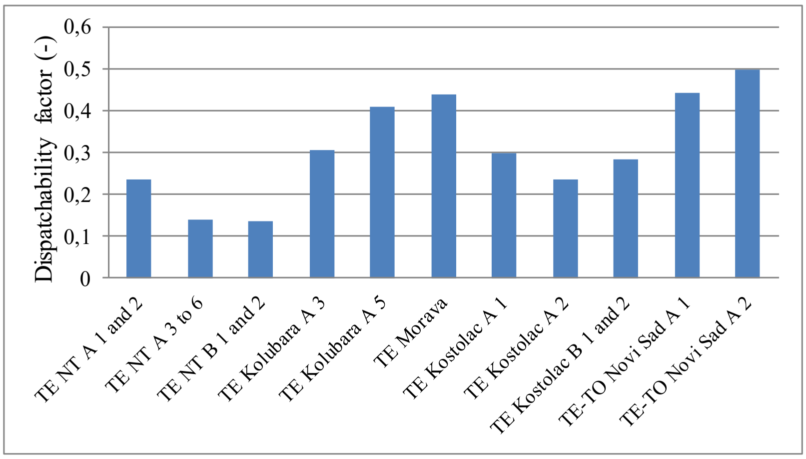

Figure 4. Numerical values of despatchibility factors for fossil fueled power plants in EPS

In Fig. 4 are presented results of established numerical values of dispatchability factors for fossil fueled power plants in EPS. These are a part of the overall results established during the research of dispatchability features of electricity generating plants in Serbia. The values for lignite fired power plants power of 300 MW and larger are considerably lower than those for the units power of 210 MW and lower. This is the consequence of rather high values of minimal powers $P_{timin/1}$, which were observed for these units. Generally, the values of minimal power can be a consequence of the lignite quality used as fuel.

On the other hand bouth natural gas fired CHP power plants have the highest values of dispatchability factors, what could be expected haveing in mind the quality of their fuel.

Dispatchability indicator for the system of fossil fueled power plants in EPS is calculated using above explained procedure, as well as above presented data. As the result is obtained DI_{ffpp} = 0,213. This value is rather low in comparison to the previously estimated values for the European power plants. It can be the consequence of the rather low grade of the domestic lignite.

For the part of EPS's power system that comprise all lignite and brown coal fired power plants only, the calculated value of relative possible duration power change amounts $RDPC_1$ = 28,6 min/GW. This figure is slightly higher than roughly estimated value for lignite and hard coal power plants in Germany, which amounts 20,9 min/GW. In second case when all power plants start simultaneously to change its power, the relative possible duration of power change of EPS's power system $RDPC_2$ equals 4,1 min/GW. We have no available comparable data for individual power plants in European conditions.

An attempt was made to estimate possible improvements of EPS's lignite and brown coal fired power plants regarding their behavior in changing the power on demand and thus to bring closer numerical values of corresponding Serbian indicators to those from EU power systems. The attempt was limited on consideration of the power plants power of 200 MW and higher. Based on the performed estimations it was obtained the numerical value of the dispatchability indicator DI_{ffpp} = 0,298, i.e. for about 40% improved value. Simultaneously was obtained calculated value of relative possible duration power change $RDPC_1$ = 36,25 min/GW, i.e. about 27% better numerical value. These results were obtained on the basis of an estimate of the smallest operable power of each unit and the duration of possible operation on it. However, the capabilities and operating conditions of these units at the lower power levels assumed here should be subsequently thoroughly tested and confirmed by a specifically defined and performed science project study. The project study shall include records of the operation history, technology possibilities, limitations from the quality of lignite, as well as the cost increase arising from such operation (increased fuel consumption and increased maintenance expenses).

Although relative possible duration power change gives certain information on power system capability for change the power on demand, it is not sufficient. The duration of load change is composed of a number of individual power plants durations. In practice this composition is made in accordance with the role of each power plant in the system's power and frequency control and includes some specific analysis of transient states. Therefore this issue have to be addressed separately.

Finally, it is necessary here to underline that a wider and more detailed specific study could give more accurate results together with more precise relations. In the study all three types of hydro power plants i.e., run-off-river, hydro storage and pumped storage also have to be included.

5. CONCLUSIONS

In the power systems with i-RES penetration, the issue of dispatchability becomes highly important. Although Serbian power system still has rather small penetration of i-RES compared to the most European systems, adequate care should be taken in time.

A basic approach in research of Serbian power system's dispatchability is presented and described in the paper. For the research three indicators are proposed and applied. The indicators are: total assured capacity, dispatchability indicator and the relative possible duration of power change.

In the paper is given a brief overview of the technology structure of the capacities installed in Serbian entities for electricity generation. The structure is compared with corresponding data on technology structure of the installed capacities in Germany. From the comparison it follows that participation of lignite fired technologies in Serbia exceeds participation of nuclear, lignite, hard coal, and natural gas fired technologies, taken together, in German power system.

Further are presented distributions of calculated values of individual assured capacities in the power systems in Serbia and in Germany. For the calculation are used Ulrich's and Schiffer's data from reference [9]. A general conclusion can be drawn that power system of Serbia relays to the greater extend on technologies with higher values of individual assured capacities than German power system. As a consequence, total assured capacity for the Serbian power system of 62,36% is considerably greater than for German power system, which amounts 43,11%.

Above figures also point out great sensitivity of the total assured capacity indicator, regarding differences in the power system's technology structure. Therefore, above approach based on the total assured capacity indicator seems very feasible for the impact analyses of different alternatives in planning future changes in the power system's technology structure on the system's dispatchability.

Numerical values of dispatchability factors for fossil fueled power plants in EPS, which were obtained within the research, are presented in the form of an appropriate diagram. On the basis of these data is calculated dispatchability indicator for the system of fossil fueled power plants in EPS. Obtained numerical value of $DI_{ffpp} = 0{,}213$ can be denoted as rather low.

Possible improvements of EPS's lignite fired power plants regarding their behavior in changing the power on demand are estimated. The improvements lead to the possible numerical value of dispatchability indicator of $DI_{ffpp} = 0{,}298$, i.e., for about 40% improved value. However, the capabilities and operating conditions of these units at the lower power levels assumed here should be subsequently thoroughly tested and confirmed by a specifically defined and performed science project study. The study shall include records of the operation history, technology possibilities, limitations from the quality of lignite, as well as the cost increase arising from such operation in terms of increased fuel consumption and increased maintenance expenses.

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