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Study of the technical and economic efficiency and the possibilities for the construction of photovoltaic power plant above the roof structures of transformer power substations 20/0,4 kV and their service areas

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Abstract. This report examines the possibility of constructing photovoltaic systems above concrete complete transformer posts to the medium voltage distribution networks. It has been analysed what capacities could be built depending on the size of the concrete facilities and their service areas, and what would be their economic and electricity efficiency. The main results of the analyses made show that this idea is not devoid of economic and electricity logic.

1. Introduction

In medium voltage electrical distribution networks, transformers housed in concrete cells called concrete complete transformer posts (CCTP) are used to reduce the voltage. These concrete structures have a horizontal roof section without any other structure on it, and in addition they are connected to an adjacent surrounding service area, called service zone, in which no facilities are installed, the entire area being owned by the electricity grid company operating the facility. In view of the size of CCTP and its adjoining areas, horizontal free space above them is available, between 10 – 20 m^2 for CCTP structure and 70 – 100 m^2 for CCTP with the service zone. In this context, it is of interest to study the possibilities of building photovoltaic power systems over these zones and to investigate the effect of the installed capacity.

The study, the results of which are published in this article, was conducted on the basis of the data on the available areas over CCTP and their adjacent areas, owned by an electricity distribution company operating at medium voltage level of 20 kV in the southern part of Republic of Bulgaria. Possibilities for constructing photovoltaic power plants over the CCTP roofs and the area of their service zones are considered, and the connection to the grid should be 0.4 kV in transformer posts.

The power efficiency of the generating capacities has been evaluated in terms of their effect on the loss of voltage in the medium voltage grid and the losses in the transformers when operating in modes close to the real ones. The applied results are for a computer simulated branch of the electricity grid, corresponding in terms of parameters and structure to a real one. The economic estimation has been made on the basis of eligible investment costs for the construction of 1 kWp photovoltaic capacity, adopted by EWRC [1] and on the basis of preferential purchase prices of electricity from producers with total installed capacity of photovoltaic power plants up to 30 kWp.

2. Computing part

The CCTP roof sections are almost horizontal rectangular structures - fig. 1 with the possibility of opening the roof part in order to be able to remove transformers by means of a crane if necessary.

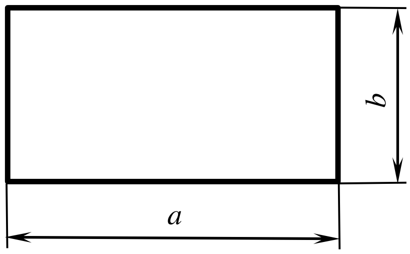

Figure 1. CCTP roof geometry

Two main dimensions of roofs are used a x b - 5.2 x 2.6 m and 5.2 x 5.2 m.

The service zones according to the regulations have the following dimensions, on fig. 2:

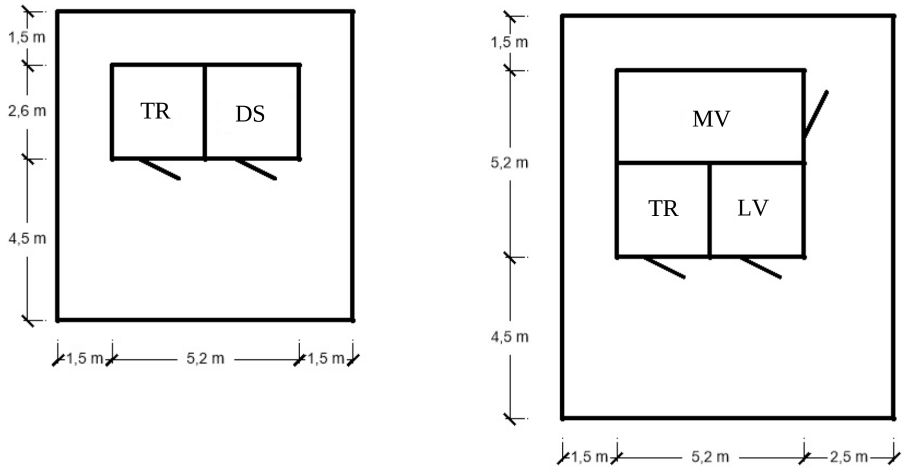

Figure 2. Service zone

The dimensions of one photovoltaic panel with a power of 285Wp and efficiency η = 16.65% are 1.65x0.99m.

According to the mentioned dimensions, it is evident that the square footage of the roof structures is 13.52 m^2 and 27.04 m^2 respectively, and considering the dimensions of the service zones, the available horizontal areas are 70.52 m^2 and 104.04 m^2. Thus, according to the dimensions on fig. 2 of the smaller substation, two rows of photovoltaic panels with 5 panels per row could be assembled - a total of 10 pcs with installed power of 2.85 kWp, and for larger CCTPs the number of panels could reach 20 pcs. with installed power of 5.7 kWp (with additionally added construction, at a slope of 30° in both cases). On the basis of the dimensions of the service zone of the smaller of the two types of Concrete complete transformer posts, above the area by means of a suitable structure there could be placed in 4 rows of 8 a total of 32 photovoltaic panels (of the above-mentioned type) with a total installed capacity of 9.12 kWp without the structure protruding outside the service zone.

The single-line diagram of the electricity grid branch that was used to carry out the electrotechnical and electric power calculations is shown on fig. 3. The diagram shows the numbers of the substations, the rated power of the transformer Sn in each of them, as well as the numbering of the sections with cable power lines at medium voltage level of 20 kV. Table 1 shows data about the cables in the respective sections and their lengths.

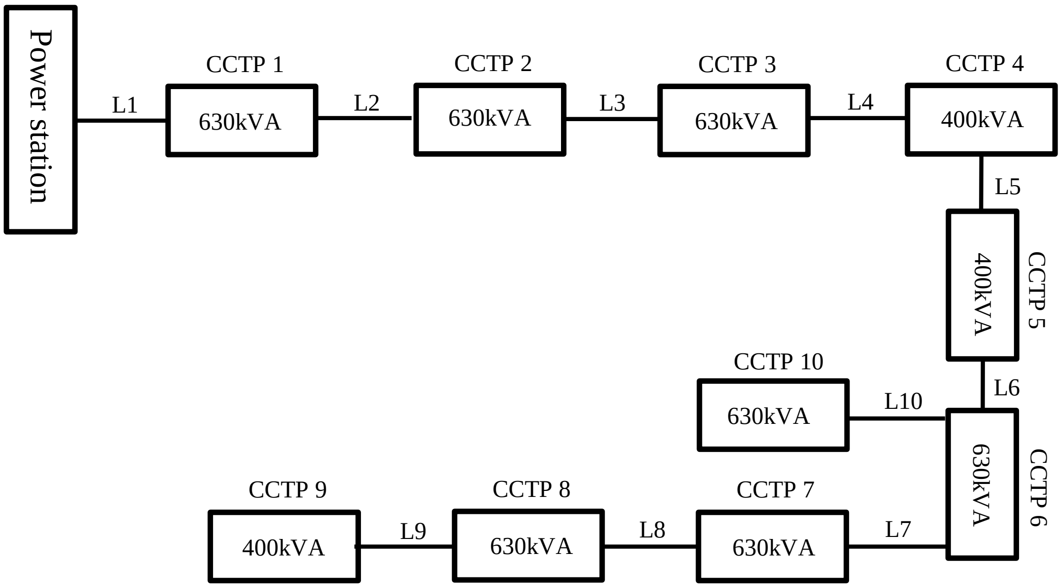

Figure 3. Single-line diagram

Table 1. Power line properties

Power line	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
distance, m	1826	222	186	64	231	165	72	470	208	159
r_0, Ω/km	0.215	0.215	0.215	0.215	0.215	0.215	0.215	0.215	0.215	0.215
x_0, Ω/km	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117
R, Ω	0.39	0.05	0.04	0.01	0.05	0.04	0.02	0.10	0.04	0.03
X, Ω	0.21	0.03	0.02	0.01	0.03	0.02	0.01	0.05	0.02	0.02

The loss of active power at no load run in the transformers are ΔP_{o400kW} = 593 W, ΔP_{o630kW} = 855 W respectively, and the loss of active power in the transformer windings at rated load are $\Delta P_{sc400kW}$ = 4567 W, $\Delta P_{sc630kW}$ = 6659 W respectively, according to their rated power S_n.

In three CCTP the dimensions of their roofs are 5.2x5.2 m, and with the service zone the dimensions are 11.2x9.2 m, while the remaining seven CCTP have dimensions of 2.6x5.2 m, and with the service zone they are 8.6x8.2 m. To CCTP 10, on the side 0,4kV an existing 30 kWp photovoltaic power plant has been connected, the energy generated from which influences one of the parameters for which the study was made.

In accordance with the given sizes and number of CCTPs and their service areas, photovoltaic two variants of power plants could be built above them:

1. Variant 1 - When using roof spaces only above CCTP (of course, assuming that photovoltaic plant structures could be installed above them). In this case, with 3 CCTP sized 5.2x5.2 m and 7 CCTPs sized 2.6x5.2 m in size, and using 285 Wp photovoltaic panels, with size 1.65x0.99 m, we

would have the following total installed capacity of photovoltaic power plants on the roofs of transformer posts from the line in question:

$$P_{pv1} = 3x4x5x285 + 7x2x5x285 = 17.1 + 19.95 = 37.05\,kWp \quad (1)$$

2. Variant 2 - using service zones (assuming, of course, that photovoltaic plant structures could be installed above them). In this case, for 3 service zones with dimensions 11.2x9.2 m and 7 zones with dimensions 8.6x8.2 m, and based on the above-mentioned photovoltaic panels with their capacity and size, we would have the following total installed power of photovoltaic power plants:

$$P_{pv2} = 3x6x9x285 + 7x4x8x285 = 46.17 + 63.84 = 110.01\,kWp \quad (2)$$

If these generating capacities are used to produce and sell electricity, they would have the following characteristics for their owner or operator:

1. Annual electricity production from the photovoltaic power generation in Variant 1, based on an annual solar energy of 1580 kWh/m^2, calculated using the software product [2] e 45978.15 kWh/year. At the price of the systems on the individual substations from 2609 BGN/kWp (according to the investment costs recognized for power plants with total installed capacity up to 5 kWp) and preferential purchase price 242.1 BGN/MWh excluding VAT [1], the payback of the investment of photovoltaic systems is 7 years with a total annual revenue from all power plants 14479,62 BGN.

2. The annual electricity production from the photovoltaic power generation in Variant 2, based on an annual solar energy of 1580 kWh/m^2, calculated by software product [2] is 147743.43 kWh/year. At the price of the systems on the individual substations with service zones of 2284 BGN/kWp (according to the investment costs recognized for power plants with a total installed capacity from 5 kWp to 30 kW) and a preferential purchase price of 205.99 BGN/MWh excluding VAT [1], the payback of the investment of photovoltaic systems is 7 years with a total annual income from all power plants 37083.60 BGN.

The following study was carried out in relation to the effect of the photovoltaic systems under consideration on the voltage loss in the ML 20 kV line, including the existing Photovoltaic power plant connected to CCTP 10. The study was carried out using specialized software (used by the electricity grid operator), in which all the data on the cable lines and transformers in the transformer posts are entered for the line/branch under consideration. Two situations were analysed – transformers operating at 60% of their rated power and transformers operating at a percentage capacity corresponding to that at the time of the study. Characteristic for the load on the LV side of the transformers at the moment of the study is that all transformers work unloaded, with currents of about I_{LV} = (39÷43)A, at U_n = 400V and power factor cosφ = (0.91÷0.93). Based on the simulations made, the following was established:

1.1. When operating in real mode (I_{LV} = (39÷43) A) and without generating photovoltaic power on the substation zones, the loss of voltage at the beginning of the line (20kV buses on CCTP 1) is 0.02%, and at the end it is 0.03% (20 kV buses on CCTP 9).

1.1.1. In Variant 1 of photovoltaic power generators, operating at maximum mode, the loss of voltage at the beginning of the line is 0.01% (CCTP 1) and 0.02% at the end of the line (CCTP 9).

1.1.2. In operation in a real mode, in Variant 2 of photovoltaic power generation, operating at maximum mode, the voltage loss is 0.02% at the beginning of the line (CCTP 1) and 0.02% at the end of the line (CCTP 9), practically not changing anywhere.

1.2. When operating in a mode S = 60%S_{nTR}, at cosφ = 0.92 and without the presence of photovoltaic generating power on the substation areas, the voltage loss along the line sections varies from 0.17% at the beginning of the line (20 kV buses on CCTP 1) to 0.26% at the end of the line (20 kV bus systems on CCTP 9).

1.2.1. In Variant 1 of photovoltaic power generation, operating at maximum mode, the voltage loss is changed from 0.16% at the beginning of the line (CCTP 1) up to 0.25% at the end of the line CCTP 9).

1.2.2. In Variant 2 of photovoltaic power generation, 2 operating at maximum mode, the voltage loss is changed from 0.15% at the beginning of the line (CCTP 1) to 0.24% at the end of the line (CCTP 9).

From the data obtained it is shown that the functioning of the photovoltaic power plants connected to the low voltage side of the transformers would reduce the voltage loss, but this would have a negligible effect.

The next study is about the extent to which photovoltaic systems installed above substations and their service areas could offset the loss of active electricity in transformers. It is made for two transformer loads - at $S = 60\% S_{nTR}$ and at $S = 90\% S_{nTR}$, in $cos\varphi = 0.92$. These two loads have been selected because the operator on which territory the branch in question is located sets such loads on the transformers in their long-running operation schedules. Annual losses of active electricity ΔW in transformers are determined on the basis of the nominal data of transformers for idle losses ΔP_o and the loss at a short circuit ΔP_{sc} by the following formula:

$$\Delta W_{TR} = \Delta P_o . t_{pow.} + \Delta P_{sc} . \left(\frac{S}{S_{nTR}} \right)^2 \tau, \text{kWh} \tag{3}$$

where:

- S is the load on the transformer, kVA;
- S_{nTP} – the rated power of the transformer, kVA;
- $t_{pow.}$ – the time the transformer is connected to the MV network, h. For a period of 1 year it is assumed that, $t_{pow.} = 8760$ h;
- τ – conditional duration of active power loss, h. It is determined based on the hourly usability of the maximum active load on networks MV, at T = 3000 h, and at power factor $cos\varphi = 0.92$ [3] – τ = 1600 h.

The following table shows the comparative results from the calculations for the annual losses of electricity in the transformers and for the electricity produced for one year by the photovoltaic systems in the substation areas, determined respectively by formula 3 and [2].

Table 2. Electricity

Loss in transformers, kWh		Photovoltaic power, kWp			
$S_{nTR,}$ kVA 400	$S_{nTR,}$ kVA 630	without service zone		with service zone	
		$CCTP_{2.6x5.2m}$	$CCTP_{5.2x5.2m}$	$CCTP_{2.6x5.2m}$	$CCTP_{5.2x5.2m}$
$S = 60\% S_{nTR}$		2.85	5.7	9.12	15.39
7825	11325	Generated electricity ΔW_{pv}, kWh			
$S = 90\% S_{nTR}$					
11114	16120	3828	7656	12249	20669

Comparison of results on electricity performance in table 2 shows that the energy produced by photovoltaic systems using only the area above the transformer posts will compensate for about half of the loss in the transformers at maximum load 60% S_{nTP} and about 1/3 of the active energy loss in them at a maximum load of 90% S_{nTP}. But, as it can be seen, if the space above the service zone is also used, these energy losses will be fully offset by the electricity generated by photovoltaic systems. The results in this table raises an interesting case - whether it would be more advantageous for power companies to install such systems above substations and what would be the real economic balance in such a situation with constantly decreasing investment costs of photovoltaic systems, and in the same time rising prices, at which the companies themselves buy electricity. Certainly, one of the effects would be to lower the ambient temperature under the photovoltaic systems due to the shading effect, which would improve the thermal conditions at which transformers operate.

If we compare the preferential prices for the purchase of electricity from photovoltaic systems up to 30 kWp and the prices on the regulated market, it can be seen that there is little difference between them. Also, if we compare the energy production of the photovoltaic systems under consideration with the power consumption of the street lighting systems having medium level of luminous class, having for example LED (30c. x 44 W)/1km = 1.32 kW/km, with an average annual operating time of the lighting system of 2400 h, and an electricity consumption of 3168 kWh/km, we can see that the smallest of the PV systems under consideration can produce energy sufficient to power a one kilometre stretch. Electricity produced and sold at a higher price during the day could be bought at a lower price during the dark part of the day and used for street lighting, in the event of a possible agreement between the municipalities and the electricity grid operators as a form of social service.

3. Conclusion.

The applied calculations and analyses show that the vacant area above the transformer posts, including the service zones, is sufficient to install photovoltaic systems that would produce enough energy to compensate for the energy loss in transformers. It can also be seen that there is some, albeit a slight decrease in the voltage loss values of the studied branch.

It is also evident and should not be neglected the effect of installing photovoltaic systems even only above CCTP, as well as the overall good economic efficiency of such projects, especially in view of the continuously declining investment costs for photovoltaic systems and rising prices of land plots.

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