Determination of an Energy Efficiency Index for Power Systems

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Abstract – The concept of Smart Grid foresees the presence of distributed generation in the distribution level. This generation can be pooled in a virtual power plant (VPP) and balanced within it in the scope of a different generation mix. In the paper the authors introduce a new index for optimizing the generation mix in a VPP. This index is based on the calculation of the general efficiency of the system. First, in the paper the estimation of the efficiencies for different generation technologies is given. Special attention is paid to the CHP technology and the issue of obtaining an objective estimate of the thermodynamic efficiency of cogeneration systems in terms of an index that takes into account the different qualities of the obtained products. These problems can be solved by changing the energy balance of the cogeneration plant. This allows one to determine the value of exergy efficiency of the plant and allocate the fuel consumed among the products. An example of such a calculation will be given in the paper.

Further, some results of calculating the efficiency of a set of generators for different systems will be presented and discussed. Taking into account some sensitivity analyses concerning customer behavior the general usefulness of the proposed index will be confirmed.

Keywords: Insulated power systems, Generation mix, Cogeneration system, Energy balance, Exergy efficiency

I. INTRODUCTION

Currently all developed countries are developing the electric power system for the future named also “intelligent power system” or Smart Grid. The concept of the Smart Gird is related to accomplishing the following goals [1]:

- to offer consumers the possibility to actively manage their demand;
- to widely involve distributed generators using unconventional and renewable kinds of energy;
- to improve the quality of electric power supplied to consumers and the reliability of the electricity supply.

The Smart Grid concept introduces some new construction, in particular the Virtual Power Plant (VPP) [2], [3]. The VPP is taken to mean an integration of distributed generators, load-controlled consumers and different types of energy storages. The structure of the VPP is determined by searching for an optimal combination of conventional and renewable distributed generation sources. The optimization of the VPP structure normally suggests considering the options in which conventional generation sources are represented by cogeneration (multi-generation) plants. This makes sense because combined production at such plants has a number of undisputed advantages as compared to their separate production. So the cogeneration allows one to considerably decrease fuel consumption for production of heat and electricity and, hence, increase the efficiency and reduce its price. A decrease in fuel consumption results in a considerable reduction of harmful emissions into the environment (heat, oxides of sulfur and nitrogen, etc.).

II. MAIN PRINCIPLES OF THE APPROACH

The main generating capacities to be included in the structure of a VPP system are:

- Diesel generators,
- Gas generators,
- Mini-CHP,
- Micro-turbines,
- Cogeneration systems,
- Energy storage systems,
- Biomass-fired plants,
- Wind turbines,
- PV (solar) panels.

Searching for optimal mix of generation different goal functions as costs [4,5], reliability [6] or emission [7] are used. Further there are given some methods to calculate the efficiency of various types of generators e.g. wind generator [8], [9] or CHP [10], [11]. However, those methods do not fully allow for calculating the total efficiency of the system with a different set of generation.

In this paper the authors propose an index which describes the generalized efficiency of virtual power plants and can be represented as follows:

$$\eta_g = \frac{\sum_{i=1}^{n} \eta_i \frac{E_i}{E_W}}{n} \quad , \qquad (1)$$

where: η_i- efficiency of each generator (including energy storage)

E_i – energy produced by each generator within a time period (e.g. week)

E_W – electrical energy delivered to the consumers within a time period (e.g. week),

n - number of generators (including energy storage).

A. Efficiency of renewable generation and energy storage

The efficiency of renewable generation and energy storages depends on the technology and the efficiency of the energy conversion processes included in the technology.

For the wind generator the following conversion processes can be listed:

- from kinetic energy of wind to the rotation energy of turbine (conversion in the turbine => η_{tu}),
- from rotation energy of turbine to electric energy of generator (conversion in electric generator -> η_{ge}),
- from electric energy in generator to electric energy in PCC (conversion in inverter -> η_{in} and transformer -> η_{tr}).

Each of these conversion processes is connected with losses and characterized by an efficiency factor. The total efficiency of the wind energy system η_w is given by Eq. 2:

$$\eta_w = \eta_{tu} \times \eta_{ge} \times \eta_{in} \times \eta_{tr} \tag{2}$$

The total efficiency of modern wind generator is between 35 %– 52 % [3], [8], [9].

In the PV generators two conversion processes can be specified:

- from solar energy to electrical energy (conversion in semi- conductors -> η_{se}),
- from electrical energy in the semi-conductors to electrical energy in PCC(conversion in inverter -> η_{in}).

In the modern industrial produced PV panels the total efficiency is between 11 % - 16 % [3].

Energy Storage Systems (EES) are an important part of the VPP and allow the integration of the produced energy from renewable energy. There are different types of ESS technologies [3], but the most useful for short term (up to 24 hours) storage in the distribution system are batteries. The most commonly used batteries for those application are the lithium ion, NaS and Pb batteries [3].

The conversion processes in the EES are as follows:

- from electrical energy AC into electrical energy DC (DC converter –> η_{DC}),
- from electrical energy into electro-chemical energy (in battery -> η_{ba})
- reverse process from electro-chemical energy into electrical energy.

The modern battery EES are characterized by a total efficiency of 75% to 86% [3].

B. Efficiency CHP generators

A schematic diagram of a steam turbine cogeneration power plant with turbines that have process and cogeneration extraction is presented in Fig.1.

Advantages of cogeneration (tri-generation) systems depend on the criteria and methods applied to their estimation. The use of a well-known index (namely, energy efficiency) for these purposes does not apply to these systems because in this case it is necessary to sum up the forms of energy of different quality. The term “quality” is taken to mean the ability of different forms of energy to be converted to work.

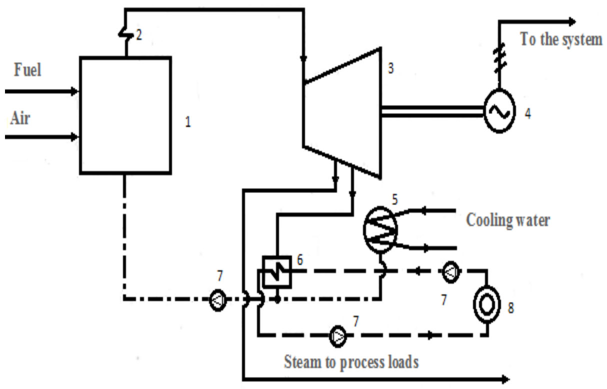

Fig. 1: Schematic diagram and main equipment of a cogeneration plant 1-steam generator; 2- steam superheater; 3- steam turbine; 4 – electric generator; 5- condenser; 6- delivery water heater; 7- pumps; 8- heat consumers.

Therefore, it is inadmissible to determine the efficiency of cogeneration plant or any other cogeneration system by the expression

$$\eta_{CP} = \frac{W_{\mathrm{sup}} + Q_{\mathrm{sup}}}{B_f \times Q_l^{ar}} \quad , \tag{3}$$

where W_{sup} in kWh - amount of electric energy supplied to consumer in a certain period of time;

Q_{sup} in kWh - total amount of heat supplied of all types of heat transfer medium to consumer in the same period of time;

B_f in t - amount of fuel consumed in this period of time;

Q_l^{ar} in kWh/t - the lowest calorific value of the fuel.

It has become possible to solve this problem after the Yugoslavian researcher Z. Rant [12], [13] introduced the notions of "exergy" and "anergy" and suggested that all forms of energy be represented by the sum of the part which is able to perform work E (exergy) and the part which is unable to perform work B (anergy), i.e.

$$I_j = E_j + B_j \ .$$

According to the second law of thermodynamics the applied forms of energy are unequal in terms of this index. They can be divided into three groups:

- energy forms unlimitedly convertible to work I_1 (mechanical – kinetic and potential, all kinds of electric energy);
- energy forms limitedly convertible to work I_2 (chemical, thermal at a temperature above the ambient temperature, $T > T_0$);
- energy forms nonconvertible to work I_3 (energy of systems with a pressure equal to the pressure of the environment, $P = P_0$; heat with a temperature equal to the ambient temperature, $T = T_0$).

In this case the energy forms that are unlimited for conversion to work I_1 can be represented by $I_1 \approx E_1$; the energy forms that are limited for conversion to work I_2 are represented by $I_2 = E_2 + B_2$, and the energy forms that cannot be converted to work I_3 can be represented by $I_3 \approx B_3$. Then, the energy forms included in the different groups can be summed up by summing separately the indicated components. Exergy of heat produced in the cogeneration system is determined by multiplying its amount by the coefficient

$$\tau_e = \frac{T_1 - T_0}{T_1} \text{ , i.e. } E_q = Q_1 \frac{T_1 - T_0}{T_1} \quad , \qquad (4)$$

where: Q_1 – produced heat

T_1 - temperature of produced heat, K;

T_0 - ambient temperature, K

E_q - exergy of heat supplied Then, the index of energy efficiency of any cogeneration system, i.e. exergy efficiency - η_{ex} , can be found by the expression:

$$\eta_{ex} = \frac{W_{el} + E_q}{B_f \times Q_l^{ar}} \quad , \qquad (5)$$

where E_q - exergy of heat supplied in the considered period of time (in this case one hour)

In this case, it was conventionally assumed that the chemical exergy of fuel consumption is numerically the same as the lower heat of combustion, i.e $E_{xt} = Q_l^{ar}$

According to (4) heat at different temperatures has different operational values.

Thus, a power plant that supplies consumers with electricity and heat under different parameters (p and t), i.e. it has turbines of different types (T and PT) is in fact a cogeneration system. In particular, if cogeneration plant has turbines with two types of extraction (process and cogeneration) it produces three products: electricity, heat supplied to the heat supply system (HSS) with hot water and energy (enthalpy) of steam (I_n) supplied to process loads.

In this case the CP efficiency should be determined considering unequal workability (value) of obtained products, i.e.

$$\eta_{CP} = \frac{W_{el} + Q_{ts}\tau_e + I_n \tau_{en}}{B_f \times Q_l^{ar}} \quad , \qquad (6)$$

where τ_{en} - coefficient of energy operability of process steam

According to its definition exergy is the maximum amount of work that can be done as the result of the reversible process of interaction between the technical system and the environment. When the temperature of the technical system is below the environmental temperature, $T_s < T_0$, then during their interaction the environment acts is a heat source. It transfers heat with temperature T_0 in the amount Q_0 to the technical system that acts as a heat compensator in this case. The exergy value that can be obtained as a result of their interaction is equal to

$$E_{q0} = Q_0 \frac{T_0 - T_s}{T_0} \qquad (7)$$

Thus, when estimating the energy efficiency of trigeneration systems, in which one and the same fuel (primary resource) is used to simultaneously produce electricity – W_{el}, heat – Q_h and cold – Q_0, it is also possible to use energy efficiency determined by the formula:

$$\eta^T_{ex} = \frac{W_{el} + E_{qT} + E_{q0}}{B_f \times Q_l^{ar}} \qquad (8)$$

The indicated indices of energy efficiency of the specific cogeneration plant are determined by calculating its energy balance, which is made up according to the first and second laws of thermodynamics, i.e. it takes into account the quality (exergy) of all energy flows [14], [15], [16] We will now consider a steam-turbine CP with the turbine PT-60-90, whose schematic diagram is presented above in Fig. 1, as an example. The initial information necessary to calculate the energy balance is given below:

- Amount of produced steam, D_0 =377.93 t/h;
- Fuel (natural gas) consumption at the boiler plant, B_f = 52.03 tce/h;
- Boiler plant efficiency, $\eta_b = 0.86$;
- Generation, N_g = 60 MW;
- Process steam flow rate, D_s = 125.28 t/h;
- Steam flow rate to condenser, D_C = 41.18 t/h;
- Delivery water flow rate, G_{dw} =2340 t/h;
- Direct delivery water temperature, t_d = 90 ^{0}C.

The balances presented in Tables 1 and 2 make it possible to determine energy efficiency indices for the whole CP and its departments.

TABLE I. MATERIAL AND ENERGY BALANCES [1)] FOR THE BOILER DEPARTMENT OF CP (PER 1 HOUR)

Boiler department						
No	**Balance item**	**Mass, t**	**Energy, GJ**	**Exergy, GJ**	**% of energy**	**% of exergy**
1	2	3	4	5	6	7
			Supply			
1	Fuel	30.53	1524.9	1404.4	100	100.0
2	Supplied air	570.15	0.0	0.0	-	-
3	Air suctions	134.57	0.0	0.0	-	-
	Subtotal:	735.25	1524.9	1404.4	100	100
			Demand			
1	Steam for turbine[*)]	(377.93)	(1311.42)	(658.28)	(86)	(46,87)
2	Losses with exhaust gases	735.25	181.46	52.72	11.9	3,75
3	Environment losses	-	7.62	1.4	0.5	0,1
4	Losses due to incomplete chemical burning	-	24.4	21.0	1.6	1,5
5	Exergy losses due to combustion process irreversibility	-	-	318.8	-	22,7
6	Losses due to heat exchange irreversibility	-	-	352.2	-	25,08
	Total	735.25	1524.9	1404.4	100	100

[1)] Energy balance taking account of workability (exergy) of energy flows.
[*)] Useful (target) energy of boiler.

In accordance with formula (6) and Tables 1 and 2 the exergy efficiency of CP as a whole makes up

$$\eta_{ex} = \frac{216 + 124.68 + 128.47}{1404.4} = 0.334$$

However, the efficiency of generation of any product by the cogeneration (trigeneration) system can be determined by objective distribution of consumed fuel among the obtained products. However, unfortunately it should be noted that there is no scientifically sound method for the distribution of both fuel and all other expenditures of combined production yetr.

TABLE II. MATERIAL AND ENERGY [2)] BALANCES OF THE TURBINE DEPARTMENT OF CP (PER 1 HOUR)

Turbine department						
No	**Balance item**	**Mass, t**	**Energy, GJ**	**Exergy, GJ**	**% of energy**	**% of exergy**
1	2	3	4	5	6	7
			Supply			
1	Live steam for turbine	(377.93)	1311.42	658.28	86.0	46.87
			Demand			
1	Supplied electric energy [*)]	-	216.0	216.0	14.16	15,38
2	Heat energy to HSS [*)]	211.02	391.85	124.68	25.7	8,88
3	Process steam energy [*)]	125.28	367.07	128.47	24.07	9,15
4	Auxiliary power	-	131.4	45.63	8.62	3,25
5	Turbine losses	-	101.88	51.2	6.68	3,64
6	Electric generator losses	-	10.8	10.8	0.71	0,77
7	Condenser losses	41.18	90.60	32.28	5.94	2,30
8	Other losses	0.45	1.82	49.22	0.12	3,50
	Subtotal	(377.93)	1311.42	658.28	86.00	46,87
Total		735.25	1524,9	1404.4	100.0	100.0

[2)] Energy balance taking into account workability (exergy) of energy flows.
[*)] Useful (target) energy of turbine.

We suggest the distribution of fuel consumption in accordance with the exergy share of each product in the total exergy value of all useful products of combined production. [15], [16].

In our case fuel consumption for the i-th product will be determined by the expression:

$$B_i = \left(E_i / \sum_{i=1}^{n} E_i \right) \times B_{boiler}$$

Based on the energy balance data in Tables 1 and 2 we obtain the following distribution of fuel consumed by the CP boiler plant for generation of products:

electricity – $B_{el} = 52{,}03 \frac{216}{469{,}41} = 23{,}15$ tce process steam – $B_s = 52{,}03 \frac{128{,}17}{469{,}15} = 14{,}25$ tce

heat for HSS – $B_q = 52{,}03 \frac{124{,}68}{469{,}15} = 13{,}83$ tce

Fuel distribution among the products of the cogeneration (trigeneration) plant makes it possible to estimate energy efficiency of generation of each product:

- electricity $\eta_{ex}^{el} = \frac{216}{1404{,}4} = 0{,}154$;
- process steam $\eta_{ex}^{s} = \frac{128{,}47}{1404{,}4} = 0{,}091$;
- heat for HSS $\eta_{ex}^{h} = \frac{124{,}68}{1404{,}4} = 0{,}089$.

As is generally assumed, the coefficients of fuel distribution can be applied for distribution of other expenditures (operating costs of CP) which are considered for calculating the cost of products as a result of combined production.

III. EFFICENCY INDEX (STUDY CASE)

A study case has been used for improving the proposed method [17], [18].

A given autonomous power system (VPP) is characterized by the following data [18]:

- Max load – 12 MW

Installed generation:

- CHP – 6 MW
- Wind – 7 to 11 MW
- PV - 8 MW
- Storage 7 to 8 MW – 5,5 to 13 h

The demand and the generation are given as a time series for one week with the accuracy of one hour.

The following efficiencies are used for generation systems:

CHP: 0,42; Wind: 0,49 ; PV: 0,16; EES: 0,80.

Formula (1) was used to calculate the total efficiency of the generation system. Stored energy was multiplied by the efficiency of the applied technology for it generation. A consistent factor (CF) was used for characterizing the consumer behaviors. A small value of their factor e.g. 0,3 informs about a pick character of the load consumption. For the basic load curve the consistent factor is equal to 0,47.

An extensive investigation was done to prove the usefulness of the proposed index. The wind full hours, the CF factor, the wind generation maximal power and the storage power and capacities were changed. Using the simulation program based on the MILP method described in [18] the optimal operation of the mentioned VPP was simulated. The priority of using renewable generated energy was set. The simulation was conducted for one week using the above-mentioned time series for demand and generation (see also Fig. 2). Table 3 summarizes the result of investigation.

With increasing wind generation the total efficiency also increases (see differences between cases a und b). This is because the wind generation has the maximal efficiency in the given system and the storage is only used for covering about 5% of the whole system energy. Also increasing the wind generation (case 2a – 2500 peak load hours) increases the value of the CF index. Furthermore, the use of bigger storage decreases the value e of CF factor. This is caused by storing the wind energy, which is then later used with a worse efficiency (because of additional EES efficiency).

Finally, the systematic investigation to find the dependency of total efficiency from CF index was done. The results of this investigating are presented in Figure 3.

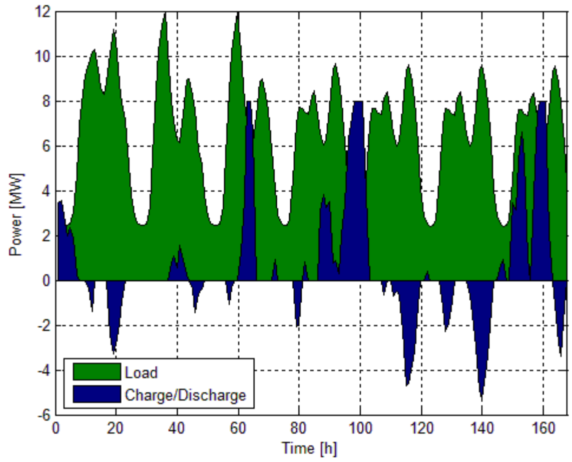

Fig.2: Load curve for the test simulation and corresponding storage operation [18]

TABLE III. TOTAL SYSTEM EFFICIENCY
(T_{PV} = 1000 h/year; P_{PV} max = 8 MW; CF = 0,47; P max =12 MW)

Case	T Wind [h/year]	P Wind [MW]	EES [MW/h]	η_g
1a	2010	7	7/5,5	0,395
1b	2010	11	7/5,5	0,407
2a	2500	7	7/5,5	0,400
2b	2500	11	7/5,5	0,414
3a	1600	7	7/5,5	0,391
3b	1600	11	7/5,5	0,400
4a	2010	7	8/13	0,391
4b	2010	11	8/13	0,402

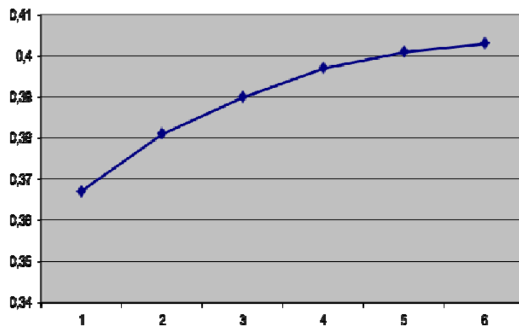

Fig. 3: Total efficiency as a function of CF factor.

In 6 steps the load curve was change from the load curve with a CF factor of 0,2 to 0,7 with the step of 0,1. We can see (Fig. 2) that the total efficiency increases with the smoothing of the demand curve.

IV. CONCLUSIONS

In the scope of this paper a new index for the validation of the generation mix of a VPP is presented. The calculation is based on the values of the needed energy for a certain time period and can be calculated using the expected time series of demand and generation.

The design of intelligent electric power systems (Smart Grids) can be reasonably based on the up-to-date methods for studying energy efficiency of plants in these systems. The most important of these systems are the so-called plants for combined generation of two or more products (cogeneration or multi-generation systems). The method applying the new notions "exergy" and "anergy" that takes into account the different qualities of various energy forms is the most suitable method for the analysis of similar systems.

The results of the study have shown that the index performed well for showing the influence of specific generation and storage on the system and so can be used for choosing the best mix. To do this, a simulation is necessary and the optimization process can performed using dynamic programming or a controlled search in the solution space [18].

The index can be used as an individual optimization criterion or as one of criterion in a multi-criterion procedure. Further investigation should show how the index correlates with other decision functions such as costs or emissions.

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