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Calculation of Losses of Active Power and Energy in Transmission Lines and Transformers, as a Part of the Electrical Distribution Power Network

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Abstract. The paper inhere discusses the impact of renewable distributed generation sources upon the power and energy losses in electrical distribution power networks where these sources are attached. In addition a set of mathematical expressions to calculate these active power and energy losses are presented with the respective examples and implementation.

Keywords: renewable power sources, active power loss, active energy losses, distribution power network.

I. INTRODUCTION

The processes of generation, transmission and distribution of electricity are in no doubt, associated with active power and energy losses. In the conditions of sustainable energy resources, it is especially important the reliable determination of these active power and energy losses, in order to resolve issues related with the planning and optimal distribution of electricity.

In the recent years, the deal of renewable energy sources connected to the distribution power network, as a part of the entire energy production, has a significant increase. The transmission of electricity generated from these sources is associated with additional losses of power and energy that has to be calculated and taken into account in regard with the optimal power flow, and the quality of electricity.

II. CALCULATION OF POWER AND ENERGY LOSSES

In Germany and Austria under the provisions for attachment of generation sources from renewable energy to the distribution power grid, the maximum installed generating capacity that is allowed to be connected to the grid is calculated taking into consideration of the voltage increase in the node of connection according to the following expression:

$$\Delta U_{aV} = \frac{S_{Wmax}}{S_{kV}} \cos\left(\psi_k + \varphi\right) \tag{1}$$

where: S_{kV} - short-circuit power at the connection point; ψ_k - short-circuit impedance phasor angle at the connection point; S_{Wmax} - maximum power capacity of the generating source attached at the connection point; φ - phase difference between voltage and current at the connection point.

The voltage increase, according to (1) doesn't have to exceed 2% in regard to the German regulations [3]

The power factor may be in the range 0.95 (CAP) ... 1 ... 0.95 (IND). In this way, a further increase in the generating capacity could be achieved and the respective source could be involved in the voltage regulation.

Using the above formula, an expression is derived for calculation of the maximum permissible power rating of newly installed generating power sources in the case of limiting the voltage increase within 2% at the point of connection.

$$S_{Wmax} = \frac{0,02\, S_{kV}}{\cos\left(\psi_k + \varphi\right)} \tag{2}$$

Medium voltage distribution power networks (in Bulgaria mainly 20 kV) as a rule are supplied by substations 110kV/20kV. The average subtransient short-circuits power for the 110kV power grid in the country is within 3200MVA. Most often, the substations have two power transformers in operation. The power rating of these transformers may be 6.3, 10, 12.5, 16, 25, 31.5 or 40 MVA.

Under parallel operation, on the low-voltage side, these transformers have bigger values for the short-

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circuit power: 116.02, 180.65, 222.93, 280.35, 419.15, 512.195 and 580.03 MVA.

In separate operation, on the low-voltage side, the transformers subtransient short-circuits power decreases and has the following values: 58.99, 115.13, 146.02, 222.92, 276.315, 316.38 MVA.

The predetermined maximum power rating of renewable generation sources, that can be connected to the grid is also a subject to compliance with the electricity quality requirements for voltage deviation of the Energy and Water Regulatory Commission (EWRC), i.e. the voltage deviation should be within +/- 10% and also the addition condition has to be met that the voltage increase in the point of installation has to be limited up to 2%.

In regard with the German regulations, the maximum allowable capacities of electrical power plants, connected to the busbars 20 kV, depending on the rated power and the number (1 or 2) of power transformers are represented graphically in Figure 1.

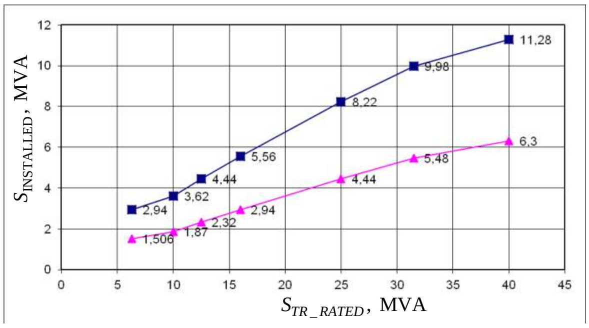

Fig. 1. Maximum allowed generating capacity, installed at the low-voltage buss bar of a substation HV / MV

The calculation of active power and energy losses in medium-voltage power lines and power transformers with attached-in renewable energy generating sources is beneficial in regard with the determination of their efficiency.

In order to calculate the energy losses, it is expected that the source's generated power deviation in time is known. Figure 2 shows the Equivalent diagram of the respective study:

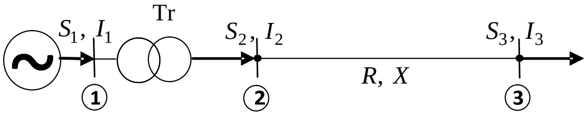

Fig. 2. Equivalent diagram of the system, according to the respective study

Losses of active and reactive power at the end of the line are calculated as:

$$\Delta \dot{S}_W = \Delta P_W + j\Delta Q_W = \frac{P_2^{\,2} + Q_2^{\,2}}{U_2^{\,2}}.\left(R + jX\right) \quad (3)$$

wherein: R and X are the parameters of the line, $\dot{S}_2 = P_2 + jQ_2$ - complex power at the beginning of the line.

The losses of active energy in the line depend on the variation of the generated energy considered for the time interval - T.

In general, the active energy loss is:

$$\Delta A = \int_0^T \Delta P(t).dt = R\int_0^T I_k^2(t).dt = R\int_0^T \frac{S_k^2(t)}{U^2}.dt$$
$$\Delta A = R.\left(\frac{S_{\text{mean.sq}}}{U}\right)^2.T \approx R.\left(\frac{S_{\text{mean.sq}}}{U_n}\right)^2.T \quad (4)$$

where T - period of time for which the energy losses are determined; $I_k(t)$ - alteration of line current in the time domain for the respective period of time; U - operating voltage; $S_k(t)$ - alteration of the apparent power in the time domain for the respective time period; $S_{\text{mean.sq}}$ - mean square apparent power for the period.

The mean square apparent power for the period is obtained by formula (5), where n is the number of power measurements.

$$S_{\text{mean.sq}} = \sqrt{\frac{S_1^{\,2} + S_2^{\,2} + ... + S_n^{\,2}}{n}} \quad (5)$$

Taking into account the deviation of the operating voltage U in relation to the rated voltage U_n, expression (4) is transformed to:

$$\Delta A_l = R.\left(\frac{S_{mean.sq.}}{U}\right)^2.T.\left(\frac{U}{U_n}\right)^2 \quad (6)$$

Transformers passport data in regard with the core and the winding losses are used in order to determine their power and energy losses.

The total active power losses of a transformer are calculated according to:

$$\Delta P_{tr} = \Delta P_0 + \Delta P_\kappa.\left(\frac{S_2}{S_n}\right)^2 \quad (7)$$

where: ΔP_0 - transformer no-load power loss; ΔP_κ - transformer short-circuit power loss; S_2 - apparent power load of the transformer; S_n - rated power capacity of the transformer.

Considering the deviation of the operating voltage U, expression (7) is transformed to:

$$\Delta P_{tr} = \Delta P_0.\left(\frac{U}{U_n}\right)^2 + \Delta P_\kappa.\left(\frac{S_2}{S_n}\right)^2.\left(\frac{U_n}{U}\right)^2 \quad (8)$$

If concrete data is available about the alteration of transformer's load in regard with time, the active energy loss of a power transformer can be calculated taking into account the mean square value of transformer's power load:

$$\Delta A_{tr} = \Delta P_0 .T.\left(\frac{U}{U_n}\right)^2 + \Delta P_{к}.\left(\frac{S_{mean\_sq}}{S_n}\right)^2 .T.\left(\frac{U_n}{U_{av}}\right)^2 \quad (9)$$

where T is the operation time in hours for one year or for a specific period.

III. DEFINING THE MEAN SQUARE APPARENT POWER OF A RENEWABLE ENERGY SOURCE PER ONE YEAR

The software product Microsoft Excel has been used in order to process the generating power load data, collected from a renewable power source. The sequence of work is as follows:

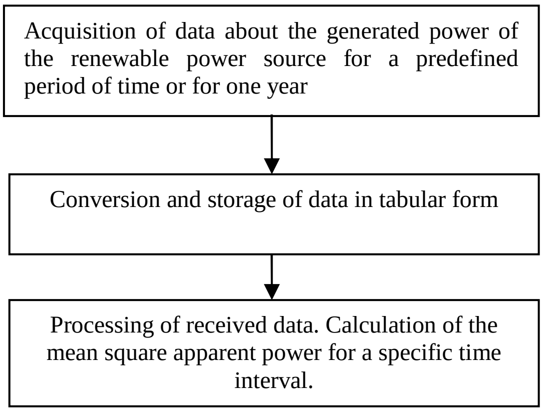

Fig. 3. Algorithm for data processing

A photovoltaic system, connected to the grid is used as an example. The data about the operation of the PV system is collected by the software product PVGIS [4] for a photovoltaic system with rated installed power 1.0 kWp.

Table 1 shows the calculations of the mean square power of a photovoltaic system with a rated output of 1.0 kWp for an operation period of 1 year. The data has been obtained from the software product PVGIS-CMSAF.

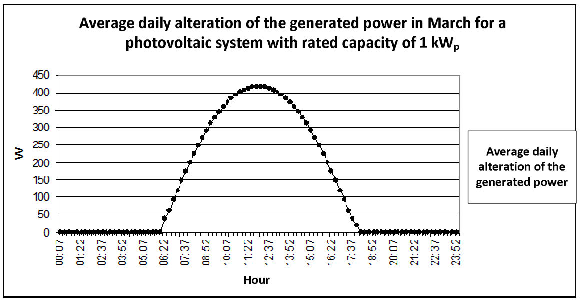

Fig. 4. Average daily power output change in March for a photovoltaic system with a rated power of 1.0 kW_p, obtained by PVGIS-CMSAF

The power output has been taken in every 15min and the total number of indications per year is 35,040.

If a certain photovoltaic system has an installed power rating that is different than 1.0 kWp, the results in Table 1 are multiplied by the square of its installed power capacity in kWp i.e. $(S_{pv})^2$. In this case, expression (5) changes as follow:

$$\Delta A_l = R.\left(\frac{S_{mean.sq\_1kWp}}{U_n}\right)^2 .(S_{PV})^2 .T.\left(\frac{1}{U/U_n}\right)^2 \quad (10)$$

Table I

Day of the year	hour:minutes	Power output	Mean square power
-	**h:min**	**W**	**W^2**
01.01	07:37	56,56	3199,29
01.01	07:52	81,97	6719,78
01.01	08:07	109,03	11886,62
01.01	08:22	130,34	16988,27
-	-	-	-
01.03	06:22	38,85	1509,02
01.03	06:37	62,15	3863,10
01.03	06:52	93,23	8691,98
01.03	07:07	119,65	14315,20
-	-	-	-
31.12	15:37	114,65	13143,93
31.12	15:52	90,25	8145,78
31.12	16:07	25,21	635,35
31.12	16:22	17,89	319,99
		Sum	**1653731868,8**
		S_{mean_sq}	**217,245**

The following example comprises calculations regarding a photovoltaic system with a rated installed capacity of 600 kWp connected to the power system through a power transformer with power rating 630kVA and via an overhead power line with rated voltage of 20 kV. The power line consists of aluminum steel conductors AC-50 with a length of 5 km [8].

Substituting in (10) under nominal operation parameters and $\frac{U_n}{U}$ = 1, the total annual active energy losses are calculated to be 1107 kWh.

Table 2 shows the change of the energy loss in regard with the voltage deviation, as reflected in expression (10). It should be taken in consideration that for the case from fig. 2(Table 2), the voltage of the power line increases from node 3 to node 1, where the generating source is connected. It is obvious that if the voltage in node 3 increases by 10% over the rated voltage U_n the energy losses in the power line ΔA decrease by 17.7%.

Taking into account a photovoltaic system with an installed capacity, different than 1.0 kWp, the values from Table 1 are multiplied by (S_{pv}) and expression (9) regarding the power transformer energy losses will change according to:

$$\Delta A_{tr} = \Delta P_0.T.\left(\frac{U}{U_n}\right)^2 + \Delta P_\kappa.\left(\frac{S_{mean\_sq..}\cdot(S_{pv})}{S_n}\right)^2.T.\left(\frac{U_n}{U}\right)^2 \quad (11)$$

Substituting in (11) with the transformer's passport data ($S_n = 630$ kVA; $\Delta P_0 = 600$ W; $\Delta P_K = 6500$ W) and $S_{PV} = 600$ kWp, $T = 1$ year=8760 h and $\frac{U}{U_n}$ = 1, the obtained annual transformer energy losses will be 7693,5 kWh.

$$\Delta A_{SUM} = \Delta A_l + \Delta A_{tr} = 1107 + 7693{,}5 = \\ = 8800{,}5 \text{ kWh} \quad (12)$$

The annual production of a photovoltaic system with installed capacity of 600kWp under the program PVGIS-CMSAF for the geographic region of Gabrovo is 714360kWh.

According to the above calculations, the resulting total active energy loss in the entire system will be around 1.23% in regard with the annual production.

If the ratio $\frac{U_n}{U}$ changes, this will result in a change of power transformer's energy losses, as shown in Table 2.

Table 2 also reflects the nodes' voltage alteration as a result of the voltage drop along the line.

A voltage increase of 10% over U_n results in an increase of power transformer's energy losses ΔA_{tr} with 8.9 %.

In case the system voltage increases U over the rated value U_n, energy losses in transformer's core increase, while the energy losses in the transformer's windings are reduced.

Table II

$\frac{U}{U_n}$	**Electrical Power line**	**Power transformer**			**Total energy losses**
	ΔA_l kWh	ΔA_0 kWh	ΔA_K kWh	ΔA_{tr} kWh	ΔA_{SUM} kWh
0,9	1366,62	4304,83	2976,03	7280,86	8647,49
0,95	1226,55	4794,47	2672,10	7466,57	8693,13
1	1106,96	5310,59	2412,41	7723,00	8829,96
1,05	1004,05	5853,16	2188,78	8041,95	9046,00
1,1	914,85	6422,21	1994,85	8417,06	9331,90

IV. CONCLUSIONS

The transmission of electricity, produced in photovoltaic systems is associated with the respective active power and energy losses. Calculation of these losses in the power lines and the power transformers, with connected to the electrical distribution power network renewable energy sources allows to determine the efficiency of their use.

The method described inhere allows determination of the active energy losses in electrical power lines and transformers, with connected to them renewable energy sources, by means of preliminary calculation of the mean square apparent power of these generating sources.

The suggested methodology can be used also to determine the energy losses in electrical power networks.

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