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The assessment of energy efficiency of electric machines for domestic appliances drive

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Abstract. In the paper, the division of domestic appliances into categories connected with input power was presented. The authors discussed issues connected with energy efficiency of these devices. An example of such a device power consumption of which affects considerably on overall power consumption from the mains is a vacuum cleaner. Vacuum cleaners are used in almost all households and they were covered by the EU regulations which introduced limitations in power consumption from the mains. In the paper, the assessment of energy efficiency of classic electric motors for vacuum cleaners drive was presented. Results of practical tests of chosen vacuum cleaners were presented. The digital power meter was used to measure electric parameters of tested vacuum cleaners and the PC was used to collect measuring data. The assessment of input power influence on energy consumption and energy efficiency was conducted based on tests results. It was shown in conclusions that the one of development directions of domestic appliances, which can cause improvement of energy efficiency, are alternative technologies of electric machines with much higher efficiency i.e. energy-saving electric machines with electronic commutation.

1 Introduction

Nowadays, domestic appliances are used on a mass scale in households. In Poland, there were over 13 million flats in 2013 according to the statistical data [1]. Domestic appliances in flat equipment include: washing machines, dishwashers, ovens, refrigerators, cookers, hoods, multifunctional food processors or vacuum cleaners. Some of them require one (i.e. a vacuum cleaner) or even several electric motors (i.e. a washing machine). Very small or small power electric motors (i.e. dishwashers) are generally used in most of domestic appliances. Thus, efficiency of energy conversion has negligible influence on energy consumption and in consequence on energy efficiency class. The situation changes when motor which is used in the appliance consumes energy which considerably affects overall power consumption from the mains. An example of such domestic appliance can be a vacuum cleaner which is used in almost all households. In Poland, there are over 13 million vacuum cleaners. The introduction of limitations on power consumption from the mains concerns this device [2]. Working time of a vacuum cleaner depends on a flat area.

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The average usable area of flats equals about 73.1 m^2 [1]. Manufacturers of electric machines for vacuum cleaners assume that these machines operate 50 hours during the year. Additionally, it is assumed that they operate twice a week. Therefore, average working time of the vacuum cleaner equals about 28 minutes. In practice, working time of this device equals about 15-50 minutes during a single vacuuming.

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2 Energy efficiency of domestic appliances

To improve energy efficiency in the EU, many activities were introduced to reduce energy consumption by 20% by 2020. One of these activities is improvement of energy efficiency of the household equipment. Additional information as labelling of most household equipment was introduced to allow the customer to make more conscious choice of a device. The energy label of a device is defined individually for each device, but it describes energy efficiency class of the device and its basic parameters. Energy efficiency classes are marked with letters from A to G, with A being the most efficient. Energy efficiency class is determined based on energy consumption of a given device to standard energy consumption of this type of devices. Separate regulations describe the standard energy consumption of each type of devices which are labelled. Three additional classes A$^+$, A^{++} and A^{+++} have been introduced for several devices i.e. washing machines, refrigerators, dishwashers and TV sets since December 2010. The parameter which must be also placed on the label of each device is average annual energy consumption (kWh per year). Thereby, the consumer is able to compare energy consumptions of different devices of the same type.

The one of the most crucial parameters which influences energy efficiency is input power from mains with its efficiency of conversion. Domestic appliances can be divided into three categories according to their purposes:
- I converting electric energy into thermal energy,
- II converting electric energy into thermal energy and a little bit into mechanical energy,
- III converting electric energy into thermal energy and significantly into mechanical energy,
- IV converting electric energy into mechanical energy.

The first category includes devices such as: a toaster, an electric kettle, etc. These devices are not labelled so far due to minimal possibilities of the energy efficiency improvement. These devices generally contain heating elements. The second category includes devices which contain both heating elements and low-power electric machines e.g. dishwashers. The power consumption of these electric machines has negligible influence on the overall power consumption of the device. The third category of devices are domestic appliances which contain instead of heating elements also electric machines whose power consumption has significant influence on the overall power consumption, e.g. a washing machine. The fourth category contains devices where an electric machine is the only energy receiver and it converts electric energy into mechanical energy, e.g. mixers, blenders, coffee grinders or vacuum cleaners. Most of these devices use electric machines with rated powers which do not exceed several hundred watts, except for vacuum cleaners. Before 01.09.2014, manufacturers of vacuum cleaners were offering, to individual consumers, devices whose power exceeded 2 kW. Therefore, vacuum cleaners were covered by EU regulations [2] which imposed limitations on input power. Since 01.09.2014, every new vacuum cleaner should not consume more than 1600 Watts of power from the mains. After 01.09.2017, power consumed by vacuum cleaners should be less than 900 Watts. In table 1, acceptable values of average energy consumption per year for particular energy classes of vacuum cleaners are presented [2].

Table 1. The average energy consumption for particular classes of vacuum cleaners

Energy efficiency class	Annual energy consumption AE [kWh/annum]	
	After 01.09.2014r.	After 01.09.2017r
A+++	-	$AE \leq 10,0$
A++	-	$10,0 < AE \leq 16,0$
A+	-	$16,0 < AE \leq 22,0$
A	$AE \leq 28,0$	$22,0 < AE \leq 28,0$
B	$28,0 < AE \leq 34,0$	$28,0 < AE \leq 34,0$
C	$34,0 < AE \leq 40,0$	$34,0 < AE \leq 40,0$
D	$40,0 < AE \leq 46,0$	$AE > 40,0$
E	$46,0 < AE \leq 52,0$	-
F	$52,0 < AE \leq 58,0$	-
G	$AE > 58,0$	-

As can be seen in table 1, after 01.09.2017, additional energy classes will be introduced for vacuum cleaners, i.e. A+, A++ and A+++. Other parameters of the device, which are important in terms of device operation, are also placed on the energy label. Fig. 1 shows currently used energy label for vacuum cleaners.

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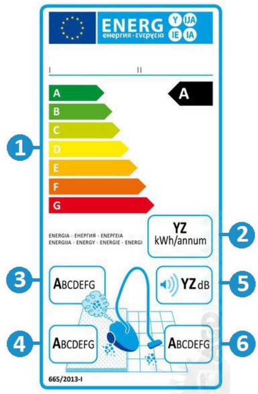

Fig. 1. The energy label used for vacuum cleaners

Besides energy efficiency class of the vacuum cleaner marked with (1) in Fig. 1, the energy label contains also:

- average annual energy consumption (2),
- dust re-emission class (ABCDEFG) (3),
- soft floor cleaning performance class (ABCDEFG) (4),
- sound power level in dB (5),
- hard floor cleaning performance class (ABCDEFG) (6).

The annual energy consumption *AE* in kWh/year does not result directly from input power. It is calculated separately for soft floors (AE_c) and hard floors (AE_{hf}). Equations 1 and 2 allow calculating the annual energy consumption for soft floors and hard floors, respectively [2].

$$AE_c = 4 \times 87 \times 50 \times 0{,}001 \times ASE_c \times \left(\frac{1 - 0{,}20}{dpu_c - 0{,}2} \right) \tag{1}$$

$$AE_{hf} = 4 \times 87 \times 50 \times 0{,}001 \times ASE_{hf} \times \left(\frac{1 - 0{,}20}{dpu_{hf} - 0{,}2} \right) \tag{2}$$

whereby:

ASE_c – is the average specific energy consumption in Wh/m^2 during soft floor test,

ASE_{hf} – is the average specific energy consumption in Wh/m^2 during hard floor test,

dpu_c – is the dust pick-up on model soft floor,

dpu_{hf} – is the dust pick-up on model hard floor.

For general-purpose vacuum cleaners, the average annual energy consumption can be calculated from:

$$AE_{gp} = 0{,}5 \times AE_c + 0{,}5 \times AE_{hf} \tag{3}$$

as a sum of half of energy which is required for hard floor vacuuming and half of energy which is required for soft floor vacuuming – which results from laboratory tests.

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Additionally, it is assumed that the standard surface to be cleaned equals 87 m^2 and this surface is cleaned 50 times per year. In laboratory tests, it is also assumed that the vacuum cleaner passes over each point on the floor four times (two double strokes). Laboratory tests are very often different compared to real conditions, which will be shown in part 3 of the paper.

3 Results of practical tests of chosen domestic appliances

Practical tests of chosen domestic appliances were conducted in real conditions. Yokogawa WT1600 digital power meter was used to measure electric parameters of tested devices (voltage, current, power, energy) and a PC was used to collect measuring data. Fig.2 shows a schematic diagram of a laboratory setup.

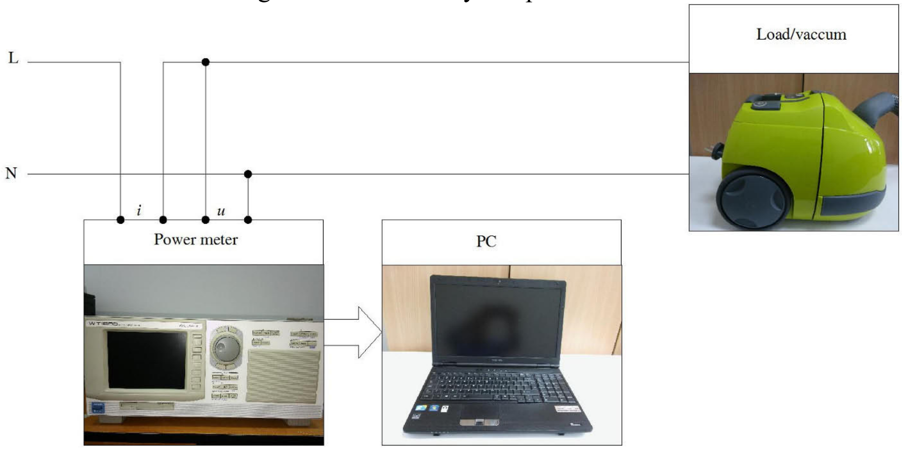

Fig. 2. A schematic diagram of the laboratory setup

Besides input power, power factor was also taken into account during the tests. Waveforms of currents drawn by tested domestic appliances were also registered.

Mixers, blenders, food processors, coffee grinders or vacuum cleaners are typical devices included in the category IV. In vacuum cleaners, electric motors with power exceeding 2 kW were generally used, but introduction of EU's restrictions of power consumption which should not exceed 1.6 kW caused that these motors cannot be used in new devices. At the same time, they are still in a practical use but their contribution in the market will be systematically decreasing and now they constitute over 50% of all vacuum cleaners. Several general-purpose vacuum cleaners with different powers were selected for the tests: 850 W (marked as I), 1000 W (marked as II), 1100 W (marked as III), 1650 W (marked as IV), 2000 W (marked as V) and a central vacuum cleaner with power 1500 W (marked as VI). Practical tests were conducted during vacuuming of a duplex flat with surface to be cleaned of 106 m^2. The flat was equipped with a central vacuum cleaner (the device marked as VI). Both hard floors (75%) and soft floors (25%) were in the tested flat. Practical tests were conducted in conditions which were different from conditions described with equation 3 (larger flat area, more hard floors than soft floors, higher supply voltage). Figs. 3-5 show waveforms of input active power P and power factor $\cos\phi$ of tested devices while vacuuming (I – Fig.3, V – Fig.4 and VI – Fig.5).

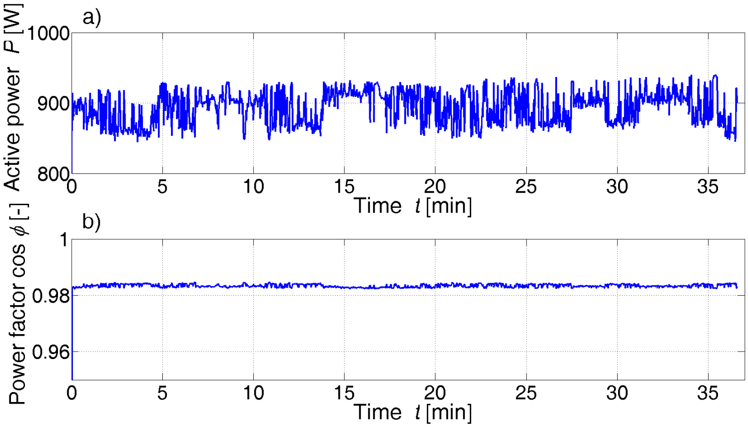

Fig. 3. Waveforms of a) input active power P and b) power factor ϕ for device I

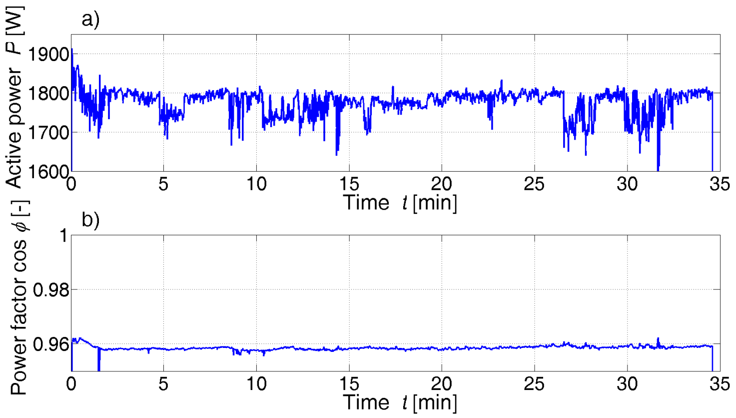

Fig. 4. Waveforms of a) input active power P and b) power factor ϕ for device V

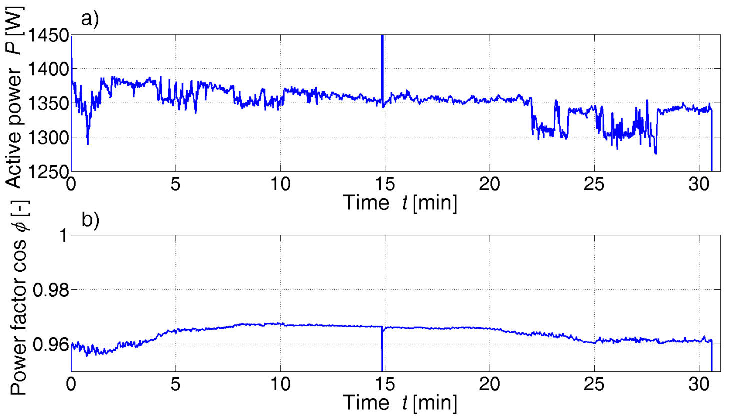

Fig. 5. Waveforms of a) input active power P and b) power factor ϕ for device VI

In table 2, chosen results of the tests are presented.

Table 2. Chosen results of practical tests of vacuum cleaners

Parameter/Vacuum cleaner	**I**	**II**	**III**	**IV**	**V**	**VI**
Input active power P_{inav} [W]	889	1065	1321	1472	1770	1347
RMS voltage U [V]	240,7	241,5	238,2	242,4	239	239,2
Power factor $\cos\phi_{av}$ [-]	0,983	0,991	0,974	0,977	0,96	0,963
Time t [min]	36,5	34,8	35,7	35,9	34,6	30,6
Time $t_{av\ (I\text{-}V)}$ [min]	35,5					30,6
Energy consumption E [kWh]	0,526	0,6301	0,7816	0,8709	1,02	0,688
Estimated annual energy consumption AE [kWh/annum]	26,3	31,51	39,08	43,55	52,36	34,4

The device with the lowest power has had the smallest cleaning head area. In particular, cleaning process with devices III-VI involved much more effort. What can be seen in Fig. 3 are numerous instantaneous changes of input power due to necessity of pulling cleaning head from the surface in order to change point on the floor to be cleaned. Vacuuming of soft floors was dubious, especially on a carpet with long hair. The tested vacuum cleaner with the lowest input power had serious problems with vacuuming such surfaces. It is obviously a subjective opinion which arises from testing of each vacuum cleaner. In the case of the central vacuum cleaner, vacuuming time was noticeably shorter. In this particular case, a significant influence on shorter vacuuming time had vacuuming of stairway which was much more comfortable and less troublesome.

A working point of the motor changes during operation of a vacuum cleaner due to adhesion way of cleaning head to the surface and instantaneous fluctuations of the supply voltage. During tests, the supply voltage was exceeding 230 V. The supply voltage has a significant influence on parameters of a commutator motor. Higher supply voltage about 10 V caused increase in the input power in devices I (about 39 W), II (about 69 W) and III (about 221 W) compared to power given in the data plate. In vacuum cleaners marked as IV, V and VI, which were produced before 01.09.2014, it can be seen that the input power was smaller in tests conditions despite higher supply voltage. These differences were due to the fact that manufacturers give information of power which is consumed only by mere suction unit in a laboratory setup. Older vacuum cleaners have also a little bit lower power factor. The supply voltage in real conditions can vary in the range of $\pm 10\ \%U_N$, so at power voltage of 230 V it means changes in the range of (207 V÷253 V). In laboratory conditions, some vacuum cleaners were supplied with voltages: 207 V, 230 V and 253 V. Tests of vacuum cleaners marked as I, III, IV and V were conducted in two variants. In the first one, input power was measured while vacuuming hard floor and in the second one while vacuuming soft floor. The test was connected with regulation of input power. All tested devices despite central vacuum cleaner allow infinitely, partly infinitely or step regulation of input power. Fig. 6 shows dependencies of active input power P and reactive input power Q in the function of power factor $\cos\phi$ during regulation of suction power at supply voltages: 207 V, 230 V and 253 V (for unit V). In table 3, chosen test results are presented.

The change of supply voltage in the range of ±10 %U_N has great impact on the value of input power and in consequence on suction power. In the case of unit I, a 10 % increase of the supply voltage caused a 15 % increase of the input power and in other units it was a 17 % increase of the input power. When the supply voltage decreased about 10 %, the input power decreased by about 19 % in unit I. The input power in other units decreased by about 18 %. It is not a good situation because suction power decreases noticeably with decreasing of the supply voltage. The supply voltage can equal about 207 V when there is a long feeder or when there are other high-power loads on the same phase (an oven, an induction hob etc.). It is a very problematic situation especially for low-power vacuum cleaners and such devices will be used after September 2017. In general, it should be assumed that when the supply voltage decreases to about 0,9U_N the vacuum cleaner will lose about 17 % of the power output. Results of laboratory tests of an exemplary suction unit with a motor with a classic commutator at various supply voltages confirm this statement (Fig. 7).

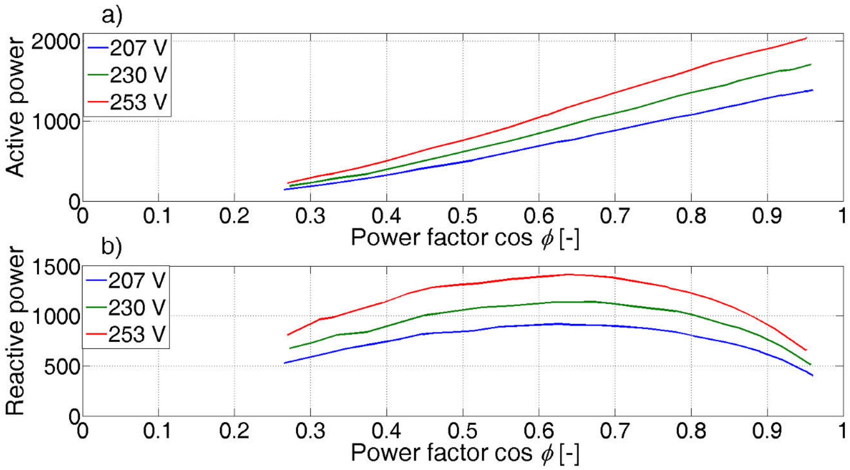

Fig. 6. A dependence of a) active input power P, b) reactive input power Q in the function of power factor cosϕ at U=var

Table 3. Chosen tests results

Voltage	Floor	I	III	IV	V
253 V	Hard	946 W	1507 W	1646 W	2031 W
	Soft	961 W	1418 W	1598 W	1913 W
230 V	Hard	804 W	1256 W	1375 W	1709 W
	Soft	848 W	1187 W	1350 W	1617 W
207 V	Hard	651 W	1077 W	1122 W	1388 W
	Soft	687 W	986 W	1099 W	1310 W

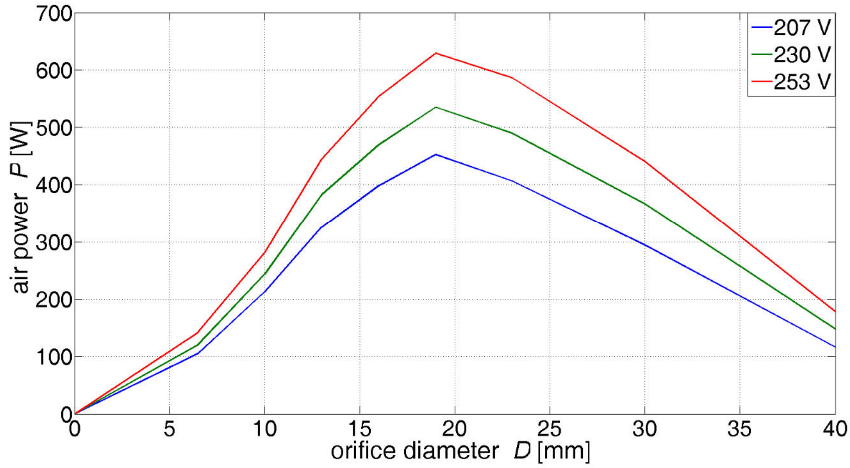

Fig. 7. A dependence of air power *P* of the suction unit in the function of an orifice diameter *D* at *U*=var

The change of the supply voltage has a significant influence on the suction power of the vacuum cleaner. Moreover, the points of maximum air power were obtained at the same orifice diameter regardless of the supply voltage value.

Classic commutator motors were used in all tested units. During operation with decreased supply voltage, there is no possibility to maintain set suction power (performance classes of vacuuming soft and hard floors), as long as manufacturers do not allow such possibility. Among tested vacuum cleaners, only unit III almost disposes declared power at the decreased supply voltage. When new energy efficiency classes appear, used vacuum cleaners should have input power much less than 900 W to satisfy restrictions of highest classes, i.e. A+, A++, A+++. Alternative electric machines with higher efficiency of energy conversion can be one of development directions of improving energy efficiency of vacuum cleaners and also partial compensation of voltage drop by changing control parameters of motor [3-7].

4 Conclusions

The energy efficiency improvement of electric machines used in modern domestic appliances is one of development directions of reducing global energy consumption. It is very important especially in domestic appliances from category IV where electric motor with input power equalling several hundred watts is only one energy receiver. Decreasing of energy consumption by using vacuum cleaners with class A instead of e.g. class D is unnoticeable in terms of one household (it is barely several kilowatts per year). Practice tests show that in real conditions these differences are lower. However, it has significant meaning on a country or world scale because these devices are currently mass-used. Customers will pay all costs which are connected with the introduction of domestic appliances with improved energy efficiency. A purchase of the domestic appliance with A class or higher could be profitable only when lifetime of this device will be extended. Currently, manufacturers of domestic appliances tend to reduce lifetime of their products so the purchase of the energy efficient device is not economically justified. An application of brushless DC motors with electronic commutation on mass-scale in vacuum cleaners is surely one of directions of vacuum cleaners development. However, the purchase of the vacuum cleaner with this kind of motors should guarantee at least over a decade of failurefree operation. The customer should choose the moment of disusing the domestic appliance and not the device itself through limitations introduced by manufacturers which reduce its durability.

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