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Investigation of a pico-hydropower plant performance by combining exergy analysis and global sensitivity analysis: a case study of Andriantseboka Analamanga Madagascar

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***Abstract*— The process of power production with a pico-hydropower plant located in Andriantsemboka Antananarivo was analyzed using the methods of exergy analysis and global sensitivity analysis. The objectives of the present investigation are first, to pinpoint the locations and amounts of exergy losses by identifying and observing the exergy efficiency of the pico hydropower plant, and second, to determine the most important key parameters of the system. For that purpose, the studied power plant was divided into four sub-systems, each with distinct creations and destructions of exergy. Results of exergy analysis showed that some elements of the power plant destroy more exergy than others and significant exergy loss is of importance at the transformer. By contrast, results of the global sensitivity analysis of the system associated model highlighted that the most influential key parameter on the exergy efficiency of the studied power plant is found at the turbine, namely: the diameter of the pulley of the impeller. As the transformer is imported from abroad, the alternative solution for improving the system exergy efficiency can be performed at the level of the turbine geometrical sizes as this component is locally manufactured.**

Keywords— Exergy analysis, Exergy efficiency, Global sensitivity analysis, Pico-hydropower plant

I. INTRODUCTION

In most cases, natural sources are used for energy conversion. Hydropower has a significant place among the renewable energy sources. Indeed, hydropower production accounts for about 2% of the global power production [1]. Changes of the size of dams are expected in this area. Indeed, deployment of small hydropower plants (less than 10 (MW)) is particularly expected in order to comply with environmental advantages.

Terminologically, the United Nations Industrial Development Organization (UNIDO) adopted the term micro-hydraulic to indicate hydropower with a capacity below 10 (MW). More precisely, while P being the installed capacity of the micro-hydraulic, four categories of micro-hydraulic plants arise, namely: pico-hydropower plants with $P < 5$ (kW), micro-hydropower plants with $P < 100$ (kW), mini-hydropower plants with $P < 1000$ (kW), and small-hydropower plants with $P < 10{,}000$ (kW) [2]. Hence, the hydropower plant under consideration in the present investigation is classified in the first category of the abovementioned micro-hydraulic plants.

Exergy is energy with built-in quality measurement. The concern of natural energy resource depletion has led to a rapid increase in interest in describing and understanding the energy conversion process and other resources in society. Availability of relevant concepts enables to understand the process of the conversion process. While the concept of exergy drifting from entropy concept or more precisely from negentropy concept, exergy is defined as the mechanical work that could be obtained from a system in a given environment [3].

As mechanical energy conversion to electrical one dominates this power production process and less thermal and chemical energy transformation takes place in the hydropower plant, applications of exergy analysis on hydropower plants became uncommon. However, considering that exergy analysis provides more insights that are more useful than those provided by energy analysis, Rosen and Bulucea [4] conducted exergy analysis of various electrical devices ranging from simple ones to more complex systems that are included in power production, transmission and distribution. Besides, Doost and Majlessi [5] carried out energy and exergy analyses of the cooling system of hydropower's generator by using NTU method and exergy efficiency analysis respectively.

The purpose of this paper is to study the performance of a pico-hydropower plant by combining exergy analysis and global sensitivity analysis. As case study, the pico-hydropower plant of Andriantsemboka, located in the region of Analamanga in Madagascar was chosen.

II. MATERIALS AND METHODS

A. *Description of the studied system*

The studied pico-hydropower plant is managed by the “Association des Ingénieurs pour le Développement des Energies Renouvelables (AIDER)” or Association of Engineers for Developing Renewable Energies. While its construction has begun in October 2008, this facility started to provide power for lighting in June 2009. At that time, 60 houses spread in an area of approximately 1 (km2) have benefited from this lighting. Up to now, the plant has an average working time of 8,320 hours per year.

As can be seen from Fig. 1, the installation site of the studied hydropower plant is located in the Analamanga Region in the central highlands of Madagascar. It administratively belongs to the District of Antananarivo Atsimondrano and in the Rural Municipality of Andriantsemboka. This site is about 5 (km) from the National Road no.7 from kilometer mark #12 while traveling from Antananarivo city to Toliara, and is situated in an altitude between 1,250 (m) and 1,300 (m) with the Latitude of 19°05'18.5" South and the Longitude of 47°29'00.7" East.

This pico-hydropower plant has the three usual types of works that are found in the construction of a micro-hydraulic plant, namely: 1) civil engineering works such as dam, sand trap, water pipe; 2) electrical equipment such as the generator and the transformer; 3) and finally the hydraulics consisting of the turbine and the speed multiplier [6].

Hence, the characteristics of the main components of the pico-hydropower plant can briefly be described as follows. The dam is a small one that corresponds to run-of-river power plant type. Then, a 12 meters-long concrete supply pipe channels water to the metallic penstock which is 9 (m) long and 0.3 (m) in diameter. The turbine is a Banki-Mitchel (crossflow) type and has 24 blades and two sub-sectors, and its impeller is 0.28 (m) in diameter. The alternator is AC Synchronous Generator brand (TSX Model) and its rotating speed is 25 revolutions per second. While this generator is three-phase, the transformer is single-phase.

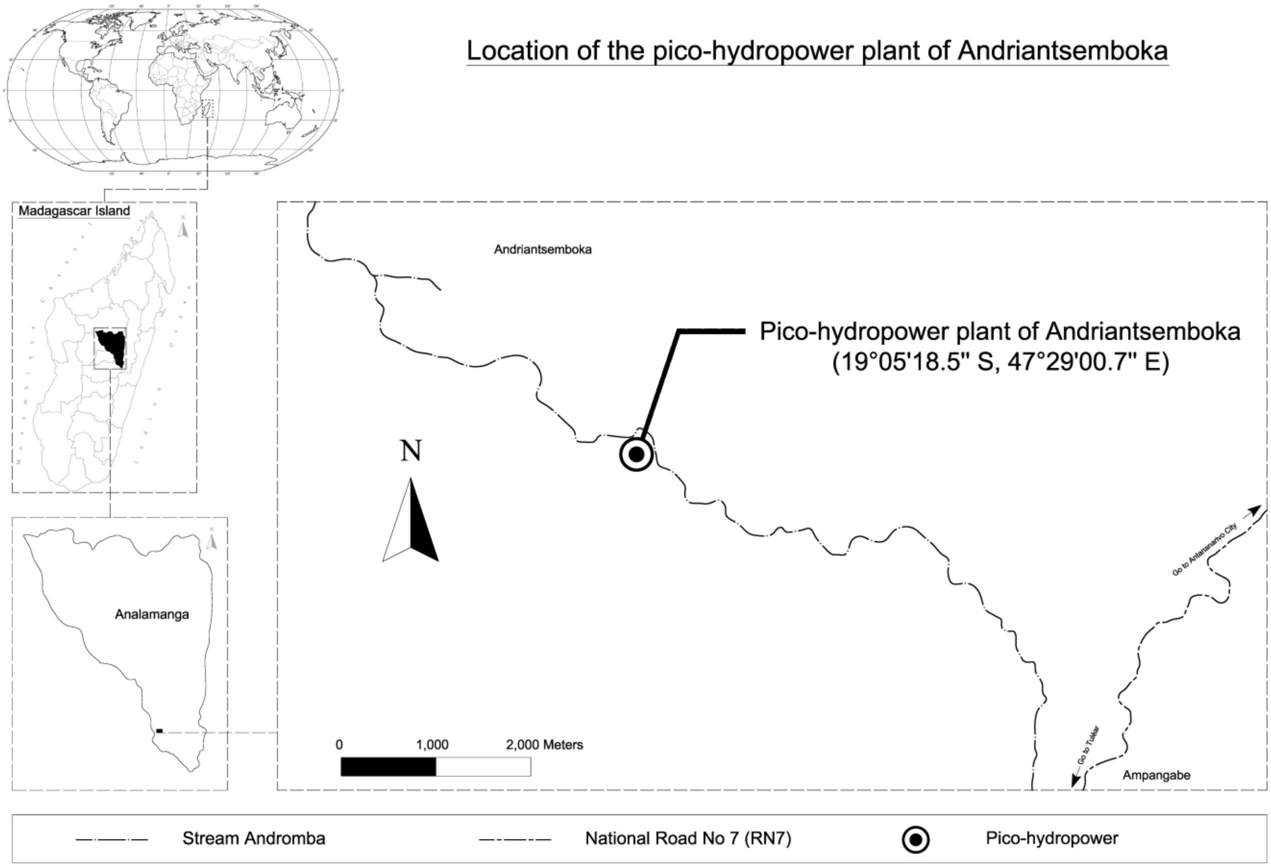

Fig. 1. *Location of the installation site of the considered hydropower plant*

B. Exergy balance of various components of the pico-hydropower plant

B.1. Exergy balance of the penstock

The total exergy at the inlet of the penstock is the amount of potential exergy available in the dam. It is given by [7]:

$$X_p = \dot{m}g(h_2 - h_1) \tag{1}$$

in which X_p denotes the potential exergy (J/s), $\dot{m}$ is the mass flow rate (kg/s), g is the gravity acceleration (9.81 m/s^2), and $(h_2 - h_1)$ represents the difference of elevation between the inlet and the outlet of the penstock (m).

The total exergy outgoing the penstock can be computed by [7]:

$$X_c = \frac{1}{2}mv^2 \tag{2}$$

where X_c , m and v respectively denote the kinetic exergy (J/s), ṁ the mass (kg) and the velocity (m/s) of water.

In the channels, it is the pressure drop that maintains the flow over the free surface. According to [8], it is given by:

$$X_f = \dot{m}\frac{J}{\rho_w} \tag{3}$$

where ρ_w denotes the density of water (kg/m^3), $\dot{m}$ is the water mass flow rate (kg/s), and J represents the pressure drop across the channels (Pa).

The water work developed with the environment is [9]:

$$X_t = Q\left(1 - \frac{T_0}{T}\right) \tag{4}$$

in which X_p represents the exergy loss into the environment (J), T_0 is the environment temperature (K), T designates water temperature (K), and Q denotes the quantity of heat exchanged between water and the environment (J).

B.2. Exergy balance of the turbine

While the turbine inlet corresponding to the penstock outlet, the total exergy at the turbine outlet is represented by the outgoing mechanical exergy X_{mt} (J/s) [10]:

$$X_{mt} = T_{mt}\varpi_t \tag{5}$$

where T_{mt} is the torque (Nm) and ϖ_t denotes the pulsation of revolution of the turbine wheel (rd/s).

The pressure drop due to the machine vibration can be computed by [11]:

$$X_v = z_r\frac{\varpi_t}{2\pi} \tag{6}$$

in which z_r denotes the number of vanes (equal to 24) and ϖ_t has the same nomenclature as in (5).

B.3. Exergy balance of the alternator

The total exergy at the alternator inlet X_{malt} (W) is given by [10]:

$$X_{malt} = T_{malt}\varpi_{alt} \tag{7}$$

in which T_{malt} denotes the torque transmitted by the speed multiplier (Nm) and ϖ_{alt} represents the alternator's pulsation of rotation (rd/s).

The total exergy outgoing the alternator can be calculated by [10]:

$$X_{ealt} = U_{alt}I_{alt} \tag{8}$$

in which X_{ealt} is the electrical exergy (W), U_{alt} is the produced voltage (V), and I_{alt} denotes the produced current (A).

The total exergy that is destroyed by the rotor stator set X_j can be computed by [10]:

$$X_j = R_c I_{alt}^2 \tag{9}$$

where R_c denotes the utilized conductor resistance (Ω) and I_{alt} represents the intensity of the alternator (A).

B.4. Exergy balance of the transformer

While the total exergy at the transformer inlet corresponding to the total exergy at the alternator outlet, the total exergy outgoing the transformer is given by [10]:

$$X_{etrs} = U_{trs}I_{trs} \tag{10}$$

in which X_{etrs} is the exergy coming out of transformer (W), U_{trs} and I_{trs} respectively denotes the voltage (V) and the current intensity (A) outgoing the transformer.

Exergy losses due to the transformer's oils X_h can be computed by [3]:

$$X_h = m_h c_h \left[(T_h - T_0) - T_0 ln\left({}^{T_h}/_{T_0}\right)\right] \tag{11}$$

in which T_0 represents the environment temperature (K) whereas c_h, T_h, and m_h respectively denote the specific heat (kJ/kg.K), the initial temperature (K) and the mass (kg) of the transformer oil.

Exergy losses occurring in the coil X_b may be decomposed into Joule losses which are due to the load current passing [10]:

$$X_b = \sum R_b I^2 \tag{12}$$

where I is the effective charge current in a conductor strand (A) and R_b denotes the coil resistance (Ω).

C. Method of global sensitivity analysis of the model associated with the studied system

C.1. Utilized global sensitivity analysis tool

While the model associated with the studied system being coded in Matlab [12], a tool named as GoSAT (or Global Sensitivity Analysis Tool) [13], which uses a derived FAST (Fourier Amplitude Sensitivity Test) method, was used for carrying out the global sensitivity analysis of this model. It is worth noting that GoSAT [13] was successfully utilized in [14-16].

C.2. Parameter values for simulations

TABLE I. PARAMETER NOMINAL VALUES AND THEIR VARIATION RANGES

No.	Symbol	Description	Variation range	Value	Unit
1	c_h	Specific heat of the transformer oil	[1.692 ; 2.068]	1.88	(kJ/kg.K)
2	d	Diameter of the penstock	[0.25 ; 0.35]	0.30	(m)
3	d_t	Diameter of the turbine pulley	[0.35; 0.45]	0.40	(m)
4	d_{alt}	Diameter of the alternator pulley	[0.14 ; 0.16]	0.15	(m)
5	H_n	Net height of the water fall	[4.5 ; 5.5]	5	(m)
6	I_{alt}	Intensity of the alternator	[20 ; 22]	21	(A)
7	K	Penstock roughness coefficient	[60 ; 90]	75	($m^{1/3}/s$)
8	L_1	Length of copper in the stator	[14 ; 16]	15	(m)
9	L_2	Length of copper in the primary	[15 ; 19]	17	(m)
10	L_3	Length of copper in the secondary	[28 ; 32]	30	(m)
11	m_h	Mass of the transformer oil	[18 ; 22]	20	(kg)
12	r_c	Resistivity of copper	[1.4E-8 ; 2 E-8]	1.7E-8	(Ωm)
13	s_c	Right section of the copper	[0.045 ; 0.055]	0.050	(m^2)
14	T_h	Initial temperature of the transformer oil	[313.5 ; 322.5]	318	(K)
15	T_o	Temperature of the environment	[291 ; 295]	293	(K)

For running the necessary simulations for this sensitivity analysis, parameter nominal values and their respective ranges of variation are listed in Table I.

III. RESULTS AND DISCUSSION

A. *Exergy analysis*

The exergy balance in the penstock is shown in Fig. 2.a in which it can be seen clearly that the potential and kinetic exergies increase both with the volumetric flow rate of the water passing through the penstock.

As can be noticed also from Fig. 2.b, the total exergy loss through the penstock, which was computed by adding irreversibilities respectively due to heat loss (with water temperature mean value of 17.5 (°C)) and pressure drop, appeared significantly smaller than both the potential and kinetic exergies.

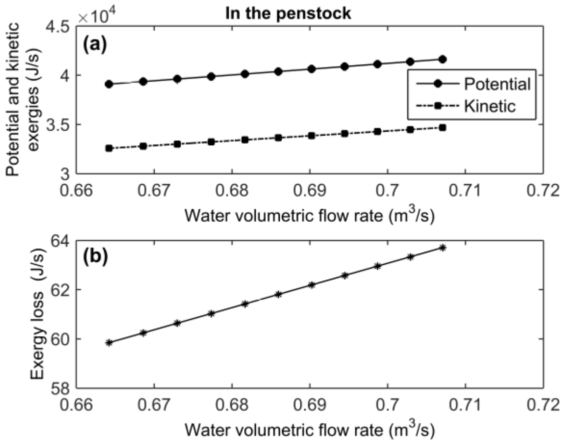

Fig. 2. *Exergy balance in the penstock*

The qualification of these two latter forms of exergy as noble energies is then highlighted. However, there is a wide difference between the values of both exergies. Indeed, from the definition of exergy, potential exergy develops more works than kinetic one.

Fig. 3 shows the exergy balance in the turbine. The kinetic exergy at the penstock outlet is transformed by the turbine into mechanical exergy which also increases with the water volumetric flow rate.

It can be noted from Fig. 3.a that as long as the turbine receives a certain amount of water, irreversibility due to vibrations increases. These vibrations consume exergy as they are momentarily transformed into mechanical exergy. However, we can assert that exergy loss in the turbine is very low (Fig.3.b); the reason can be explained as follows: the turbine is fixed to the ground by its cover and therefore can take all the shocks caused by vibrations.

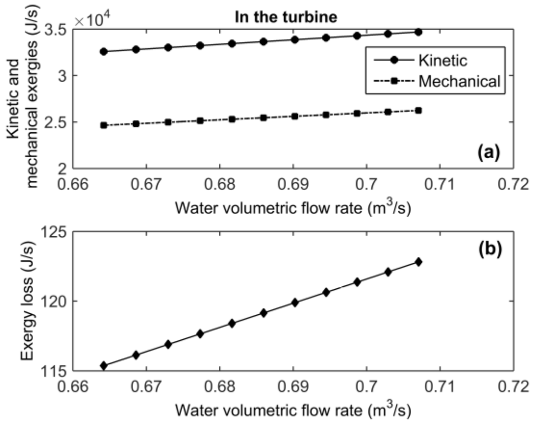

Fig. 3. *Exergy balance in the turbine*

Fig. 4.a shows the changes of the mechanical and electrical exergies that respectively enters into and outgoes the alternator as functions of the water volumetric flow rate. The raise of the mechanical exergy is due to the increase of the engine torque that is developed by the turbine as the water volumetric flow rate rises. Besides, even though the speed multiplier loses some exergy due to the turbine's engine torque, the increase of the revolution speed that is received by the alternator shaft generates at the same time an increase in mechanical exergy. Moreover, it can also be observed from Fig. 4.b that, similarly to the increasing change of the mechanical exergy outgoing the turbine, the electrical exergy outgoing the alternator and the produced current voltage are increasing functions of the water volumetric flow rate.

Irreversibility released as heat is due to heating of the conductors by the passage of current in the rotor-stator winding set. As can be seen from Fig. 4.c, the irreversibility which changes with the intensity of current produced by the alternator remains lower and nearly constant.

Comparison of exergy destructions due to every component of the studied system is illustrated in Fig. 5, which highlights that the transformer is the component that causes most of irreversibility.

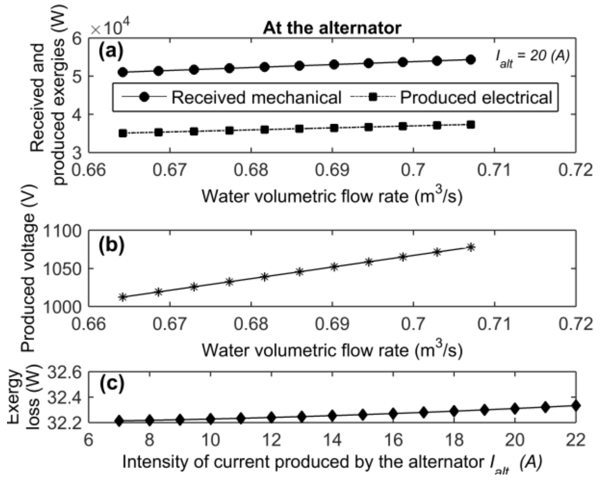

Fig. 4. *Exergy balance in the alternator*

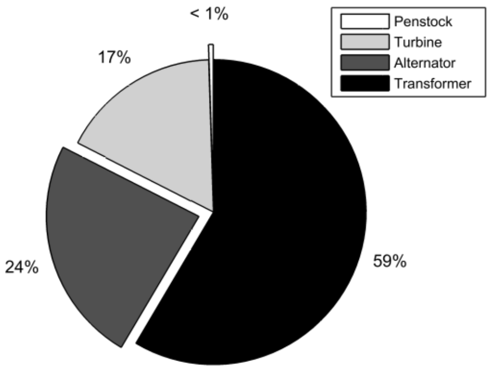

Fig. 5. *Percentage of exergy destruction*

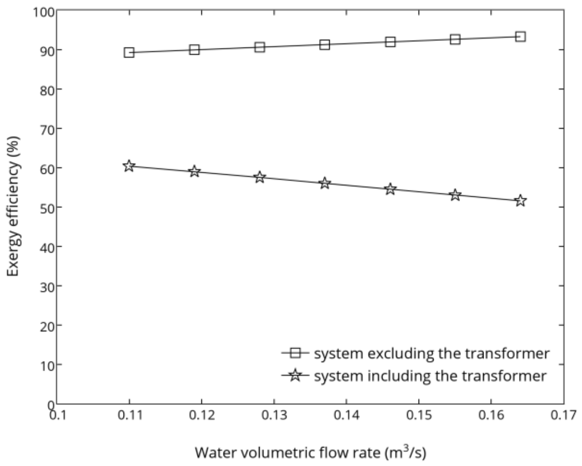

Fig. 6. *Exergy efficiency of the whole system excluding and including the transformer*

After a component-by-component exergy analysis, all the system components were combined for observing the whole system exergy efficiency changes. As can be seen from Fig. 6, if the transformer is excluded and the system is limited to the alternator, the entire conversion process has an exergy efficiency around 90%, which implies good profitability. By contrast, when including the transformer, the efficiency drops to about 60%, implying that an increase in the destruction of exergy occurred in the transformer.

The following results and recommendations can be inferred from exergy analysis of the whole system. First, it is necessary to have a three-phase transformer. In addition, it is important to improve the coupling of the generator to the transformer, as the transmission of exergy between these two system constituents depends on the efficiency of the whole system. Next, the greatest heat losses that cause low exergy efficiency are localized at the level the transformer coolant. Exergy released as heat is due to heating of the conductors by the current passage in the stator winding.

B. *Global sensitivity analysis*

While using GoSAT [13], a global sensitivity analysis of the model that was associated with the studied pico-hydropower plant was carried out. In order to avoid frequency interference, GoSAT [13] automatically selected a set of distinct prime numbers to assign as frequencies of the fifteen input parameters of the abovementioned model. As 953 was the highest selected frequency value, 7625 simulations were run according to the Shannon criterion [17] while observing exergy efficiency of the considered system.

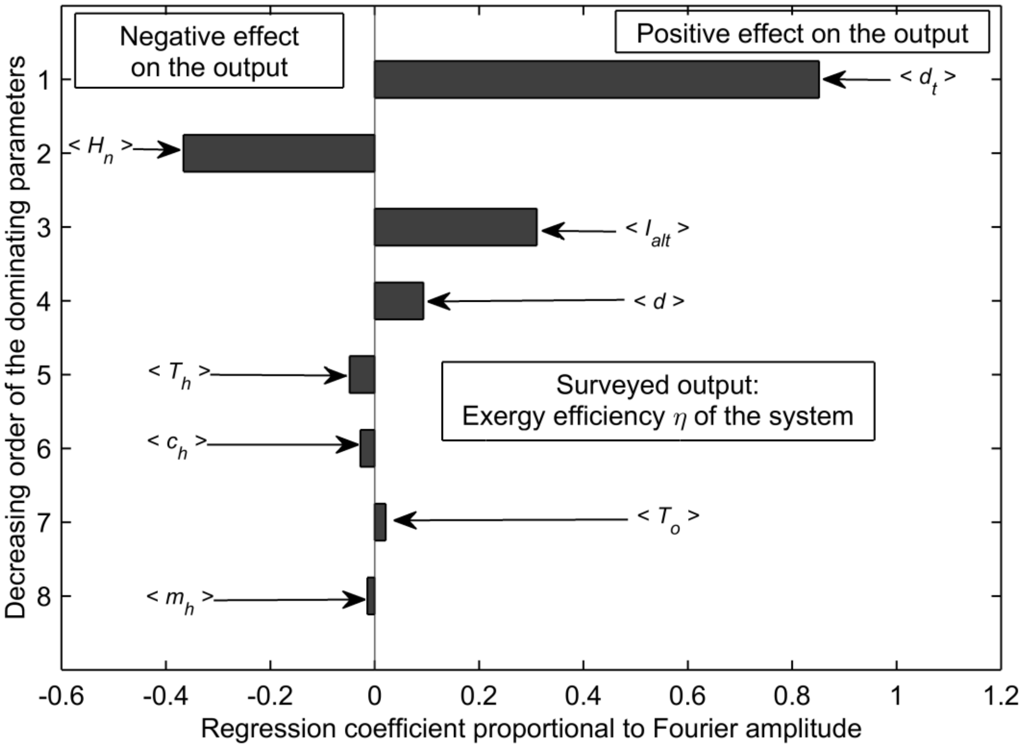

Fig. 7. *Comparison of parameters regression coefficients*

As can be seen from Fig. 7, the diameter of the turbine's pulley d_t, the net height H_n, the intensity of the alternator I_{alt} and the diameter of the penstock d are the most influential parameters while the initial temperature of the transformer's cooling oil T_h, its specific heat c_h and mass m_h as well as the ambient temperature T_0 are influential but in lower degrees compared to those of the above four; other parameters having an insignificant contribution.

The fact that the turbine's pulley diameter d_t is the most influential parameter on the exergy efficiency of the pico-hydropower plant can be explained as follows: first, the transmission speed ratio to the alternator increases with the pulley diameter of the impeller, therefore the alternator works with a maximum rotational speed, which implies an increase in produced current, and consequently, an increase in produced electrical exergy. Hence, that improves the exergy efficiency of the considered pico-hydropower plant.

In addition, it can also be observed from Fig. 7 that the diameter of the penstock d, the amperage of the alternator I_{alt} and the pulley diameter of the turbine d_t have positive effects on the exergy efficiency of the studied pico-hydropower plant. While exergy efficiency η being defined as the ratio between the useful exergy and the provided exergy, an increase in net height H_n implies a decrease in exergy efficiency. Increasing values of the parameters related to the transformer's cooling oil, such as its mass m_h, specific heat c_h and initial temperature T_h, also results in a decrease of the exergy efficiency of the system. As for the ambient temperature T_0, its increase results in a reduction of exergy destruction, and thus increases the exergy efficiency.

IV. CONCLUSION

On the one hand, results from exergy analysis of the studied system highlights that the transformer is the component that causes most of irreversibility, that is, the highest exergy destruction. On the other hand, the global sensitivity analysis of the system associated model outcomes that the most influential key parameter on the exergy efficiency of the studied pico-hydropower plant is the pulley diameter of the turbine while parameters related to the transformer are relegated to the fifth, sixth and eighth ranks in terms of degree of influence on the system exergy efficiency. Therefore, if there is less choice for controlling the technological characteristics of the transformer which is imported from abroad, the alternative solution for improving the system exergy efficiency can be performed at the level of the turbine geometrical sizes as this component is manufactured in a local metallic workshop. An optimization of the system components would be an interesting extension of this investigation.

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