Unconventional Energy from an Electric Impulse Heater Combined with a Wind Turbine

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Abstract: The widespread use of wind power plants can provide full or partial energy supply to the consumer, taking into account certain investments and the instability of energy production. Modern wind energy technology involves the conversion of mechanical energy of the wind flow into electrical energy with subsequent conversion, at the request of the consumer, into thermal energy. In addition, the unprocessed use of the low-potential part of the wind flow, characterized by non-uniformity and randomness of its reception for the purpose of supplying heat to the recipient, requires new approaches to solving this problem. Bench experimental studies of this heater confirmed the adequacy of the mathematical model: within an hour, the temperature increase of the heater core changed from 22 °C to 36 °C at a voltage of 66 V and the number of pulses entering the heater coil was (15–17) discharges, which corresponds to the values of the mathematical expectation of the wind speed of (4–5.2) m·s⁻¹ in the range of wind speed (4–8) m·s⁻¹. The scientific novelty of this work consists in the development of a mathematical model for the operation of an electric pulse heater, which made it possible to develop methodological provisions for determining its mode parameters and to estimate the temperature change of its elements at random wind speed.

Keywords: wind energy; wind power plant; electric pulse heater; capacitive storage

1. Introduction

The energy strategy of any country is aimed at increasing the level of provision of inexpensive and affordable energy for production and the population [1,2]. It should also be noted that the cost of heat and electricity coming from traditional sources is constantly increasing compared to renewable energy sources [3–5]. Therefore, the use of wind turbines is effective [6,7]. The use of wind turbines can have a positive impact on the energy supply of the country [8,9]. However, the implementation of wind turbines requires significant financial costs [9,10]. Analysis of scientific publications shows that modern technologies for the use of wind energy involve the conversion of mechanical energy of the wind flow into electrical energy with further conversion into mechanical or thermal energy [11,12]. However, the stability of wind conditions has a significant impact on the quality of energy production by wind turbines [13,14]. In addition, the unprocessed use of the low-potential...
part of the wind flow, characterized by unevenness and randomness of its receipt for the needs of heat supply to the consumer, requires the search for new approaches to solving this problem [15,16]. In particular, it is proposed to use energy storage systems in compressed air to compensate for the instability of the wind situation [16], but such systems are of considerable complexity and size. Systems for converting the mechanical energy of the wind flow into thermal energy have become widespread [17,18]. However, such systems have a rather low overall coefficient of energy utilization in the wind, up to 30% [19].

The use of renewable energy is a promising solution to the environmental problems caused by the use of fossil fuels. The fact that these types of energy are sporadic can be overcome by using energy storage systems. The authors of [20] studied the integration of a system with a combined cooling, heating, and power cycle consisting of a gas turbine, an organic Rankine cycle, and an absorption cooling system. The results show that under design conditions, the system can generate 33.67 kW of electricity, 2.56 kW of cooling and 1.82 tons of hot water per day, with a round-trip energy efficiency of 53.94%. Sensitivity analysis showed that the parameters related to the gas turbine are the most important system parameters that can significantly change the system’s performance [20].

In recent years, there has been a growing interest in renewable energy sources, in particular wind energy for electricity generation. Scientists [21] have made several attempts to find a solution for the efficient use of wind energy. As a result of comprehensive research and extensive research on the subject, wind energy is now a widely exploited renewable energy source for electricity production. The main challenge for converting wind energy is to deal with the irregular nature of the wind. An overview of the wind energy conversion system was presented, highlighting its electrical and control aspects, including brief notes on aerodynamics and mechanical properties. The capacity of wind farms in the world, including India, was shown and discussed. The article analyzes the latest technology related to the wind power system and future research directions [21].

Significant progress has been made around the world in the transition to a sustainable society. Since 2007, annual investment in renewable energy has exceeded the combined investment in fossil and nuclear energy. However, in many developing countries, the balance is still in favor of conventional energy. An understanding of the barriers and drivers of this global imbalance in wind energy deployment in developing countries is presented through a systematic literature review and meta-analysis. In addition, different perspectives are identified to understand wind energy development from the original equipment manufacturer’s point of view. This is important because the sale of wind turbines is a practical component of the transition to a sustainable society. Factors affecting wind energy diffusion were identified and grouped into the following categories: economic, environmental, technical, technological, social, regulatory, political. A novel closed-loop feedback system was proposed as a conceptual framework for categorizing factors affecting wind energy diffusion into two types: factors related to wind energy demand and factors related to the mechanism of this change [22].

The use of wind energy is currently one of the priority directions of the world energy development, which allows to achieve: elimination of the energy instability of countries associated with energy crises; reducing the amount of harmful emissions generated in the process of using traditional energy carriers; preservation of energy reserves for future generations; increase in consumption of organic raw materials for non-energy needs.

One of the solutions is the use of electric pulse heaters. To create short pulses, it is advisable to use capacitive drives, the energy output time from which is \((10^{-3}−10^{-6})\) s [23].

Pulse electric heaters are not widely distributed today, but examples of their use in soldering devices are known [24]. Pulse power sources are widely used in various fields [25], but they are practically not used to power impulse electric heaters.

One of the reasons that hinder the use of electric pulse heating installations is the lack of appropriate mathematical models, which makes it impossible to estimate the currents that occur in the components of the heater. In addition, without understanding the discharge process in electric pulse installations, it is often impossible to select the parameters of
The aim of the work is to develop a mathematical model of operation of a pulsed electric heater as part of an autonomous wind turbine was carried out by modeling using the Mathcad software package.

The structural diagram of the electric pulse heater with capacitive storage as part of an autonomous wind turbine is shown in Figure 1. The electric energy coming from the wind power plant is fed into the capacitive storage and upon reaching the specified voltage level, it is converted into a pulse and fed to the winding of the electric heater. Additionally, it is induced in the ferromagnetic core and the screen where it is converted into thermal energy.

Structurally, the heater consists of three elements: a ferromagnetic core in the form of a tube, on which a single-layer winding is wound, and this structure is placed in a tubular cylindrical screen connected to the core.

The operating mode of the system is as follows: the wind turbine charges the capacitive storage device to a predetermined voltage level. After that, the converter is activated and creates a pulse in the electric heater winding. The heater is structurally made in the form of a tubular ferromagnetic core, on which a single-layer winding (copper busbar) is wound and the whole structure is covered by a closed ferromagnetic tubular screen.

The used wind turbine has a classic structure: rotor, multiplier, synchronous generator. The operation process of the “wind power plant-electric pulse heater” system takes place in two stages: charging the storage tank through a three-phase rectifier to a given voltage level and discharge to the heater coil, and simultaneously disconnecting the capacity from the wind turbine in order to reduce the influence of the braking mode of the heater operation on the turbine.

The substitute scheme for the study of the operation mode of the electric pulse heater with capacitive storage is shown in Figure 2.
The initial system of differential equations has the form Equation (1):

\[
\begin{align*}
L_1 \frac{di_1}{dt} - M_1 \frac{di_1}{dt} - M_2 \frac{di_2}{dt} + i_1 (R_1 + R_k) - U_c &= 0; \\
L_2 \frac{di_2}{dt} + M_1 \frac{di_1}{dt} + i_2 R_2 &= 0; \\
L_3 \frac{di_3}{dt} + M_2 \frac{di_1}{dt} + i_3 R_3 &= 0
\end{align*}
\]

Rewrite the system of Equation (1) in the following form Equation (2):

\[
\begin{align*}
\frac{di_1}{dt} &= M_2 \frac{di_2}{dt} + \frac{M_2}{L_1} \frac{di_3}{dt} - i_1 \frac{R_1 + R_k}{L_1} + \frac{U_c}{L_1}; \\
\frac{di_2}{dt} &= -i_1 \frac{1}{L_2}; \\
\frac{di_3}{dt} &= -i_2 \frac{R_3}{L_3}; \\
\frac{di_4}{dt} &= -i_3 \frac{R_3}{L_3}
\end{align*}
\]

Replace the first row in the system of Equations in (2) with the last row in the system of Equation (2). Then, replace the fourth row in the system of Equation (2) in the first row of the system of Equation (2). After restoring the normal form and simplification, we will obtain a system of differential equations with the following form Equation (3):

\[
\begin{align*}
\frac{di_1}{dt} &= \frac{L_2 L_3}{L_2 L_3 + M_1 L_3 + M_2 L_2} U_c - \frac{(R_1 + R_2)L_2 L_3}{M_2 M_1 L_3 + M_2 L_2} i_1 - \frac{L_1 L_3}{L_1 L_3 + M_1 L_3 + M_2 L_2} i_2 - \frac{L_1 L_3}{M_2 M_1 L_3 + M_2 L_2} i_3; \\
\frac{di_2}{dt} &= -U_c \left( \frac{M_1 L_3}{L_1 L_3 + M_1 L_3 + M_2 L_2} \right) i_1 + \frac{L_1 M_2}{L_1 L_3 + M_1 L_3 + M_2 L_2} i_2 - \frac{R_2 M_1}{M_2 L_3} - \frac{R_3 (L_1 L_2 L_3 + M_1 L_3 + M_2 L_2)}{M_2 L_2} i_2 - \frac{R_3 M_1 M_2}{M_2 L_3} + \frac{R_3 M_1 M_2}{L_1 L_3 + M_1 L_3 + M_2 L_2} i_3; \\
\frac{di_3}{dt} &= -U_c \left( \frac{M_1 L_3}{L_1 L_3 + M_1 L_3 + M_2 L_2} \right) i_1 + \frac{L_1 M_2}{L_1 L_3 + M_1 L_3 + M_2 L_2} i_2 - \frac{R_2 M_1}{M_2 L_3} + \frac{R_3 (L_1 L_2 L_3 + M_1 L_3 + M_2 L_2)}{M_2 L_2} i_2 - \frac{R_3 M_1 M_2}{M_2 L_3} - \frac{R_3 M_1 M_2}{L_1 L_3 + M_1 L_3 + M_2 L_2} i_3; \\
\frac{di_4}{dt} &= - \frac{L_1 L_3}{L_2 L_3 + M_1 L_3 + M_2 L_2} i_2 + \frac{R_3 M_1 M_2}{M_2 L_3} - \frac{R_3 (L_1 L_2 L_3 + M_1 L_3 + M_2 L_2)}{L_1 L_3 L_3 + M_1 L_3 + M_2 L_2} i_3;
\end{align*}
\]

In vector form, system (4)–(7) is written as:

\[
\dot{x}(t) = A \cdot x(t),
\]

for:

\[
x(t) = (i_1(t), \ i_2(t), \ i_3(t), \ U_c(t))^T
\]
\[ A = \begin{bmatrix} A_{1,1} & A_{1,2} & A_{1,3} & A_{1,4} \\ A_{2,1} & A_{2,2} & A_{2,3} & A_{2,4} \\ A_{3,1} & A_{3,2} & A_{3,3} & A_{3,4} \\ A_{4,1} & A_{4,2} & A_{4,3} & A_{4,4} \end{bmatrix} \] (6)

for:

\[
A_{1,1} = -\frac{(R_1+R_k)L_2-L_3}{L_1L_2L_3+M_1^2L_3+M_2^2L_2}, \quad A_{1,2} = -\frac{R_2M_1L_3}{L_1L_2L_3+M_1^2L_3+M_2^2L_2}, \\
A_{1,3} = -\frac{L_1L_2L_3+M_1^2L_3+M_2^2L_2}{R_kM_0M_1}, \quad A_{1,4} = \frac{L_1L_2L_3+M_1^2L_3+M_2^2L_2}{M_1^2L_3+M_2^2L_2} - \frac{R_2}{L_2}(L_1L_2L_3+M_1^2L_3+M_2^2L_2), \\
A_{2,1} = -\frac{L_1L_2L_3+M_1^2L_3+M_2^2L_2}{R_kM_0M_1}, \quad A_{2,2} = -\frac{L_1L_2L_3+M_1^2L_3+M_2^2L_2}{M_1^2L_3+M_2^2L_2} - \frac{R_2}{L_2}(L_1L_2L_3+M_1^2L_3+M_2^2L_2), \\
A_{3,1} = -\frac{L_1L_2L_3+M_1^2L_3+M_2^2L_2}{R_kM_0M_1}, \quad A_{3,2} = -\frac{L_1L_2L_3+M_1^2L_3+M_2^2L_2}{M_1^2L_3+M_2^2L_2} - \frac{R_2}{L_2}(L_1L_2L_3+M_1^2L_3+M_2^2L_2), \\
A_{3,3} = -\frac{L_1L_2L_3+M_1^2L_3+M_2^2L_2}{R_kM_0M_1}, \quad A_{3,4} = -\frac{L_1L_2L_3+M_1^2L_3+M_2^2L_2}{M_1^2L_3+M_2^2L_2} - \frac{R_2}{L_2}(L_1L_2L_3+M_1^2L_3+M_2^2L_2), \\
A_{4,1} = -\frac{1}{\epsilon}, \quad A_{4,2} = 0, \quad A_{4,3} = 0, \quad A_{4,4} = 0. 
\] (7)

The initial conditions are as follows Equation (8):

\[
\begin{pmatrix}
  i_1(t = 0) \\
i_2(t = 0) \\
i_3(t = 0) \\
i_U(t = 0)
\end{pmatrix} = \begin{pmatrix}
  0 \\
  0 \\
  0 \\
  66
\end{pmatrix} \] (8)

To solve the system, it is necessary to determine the values of inductance and resistance in accordance with the technological conditions.

The coil of the electric pulse heater is structurally made in the form of a solenoid, for the calculation of \( L_1 \) Equation (9), the inductance of which the dependence [26] is adopted:

\[
L_1 = \frac{\mu_0\pi a^2 d_e}{4\alpha} \left[ 1 - \frac{4}{3\pi} \frac{1}{\alpha^2} + \frac{1}{8\alpha^2} \right] \] (9)

where:

\[
\mu_0 = 4\pi 10^7 \] (10)

\[
\alpha = \frac{a}{d} \] (11)

The inductance of the internal ferromagnetic core \( L_2 \) and the external ferromagnetic shield \( L_3 \) is determined by the expression [26] (12):

\[
L = \frac{\mu_0 l}{2\pi} \left[ \ln \frac{2l}{cr} - 1 \right] \] (12)

where:

\[
c = \frac{r}{R} \] (13)

The value \( M_1 \) and \( M_2 \) is determined Equation (14) by the expression [26]:

\[
M = \frac{\mu_0 \omega^2}{a^2} \left[ \frac{\pi}{8} q_2^2 q_3 + \frac{\gamma^4}{64} q_5 \cdots \right] \] (14)

where:

\[
q_1 = -1 + \frac{1}{\gamma} \] (15)

\[
q_3 = 1 - \gamma^3 \] (16)

\[
q_5 = 1 + 4\gamma^5 - 5\gamma^7 \] (17)
\[ \gamma = \frac{D}{\sqrt{D^2 + 4a^2}} \]  

(18)

\[ \delta = \frac{d}{D} \]  

(19)

A comparison of other materials is planned in further studies.

3. Results and Discussions

The result of solving system Equation (6) is shown in Figure 3.

Figure 3. Cont.
The thermal effect of the impulse Equation (20) on the heating process consists of several elements: the temperature from the winding $\theta_1$, which is transferred to the core by thermal conductivity, from the temperature of the impulse of the current induced in the core $\theta_2$ and the temperature on the screen $\theta_3$ of the heater:

$$\Theta = f(\theta_1, \theta_2, \theta_3)$$  \hspace{1cm} (20)

The heat flux from the action of the impulse can be estimated using the Joule–Lenz law Equation (21):

$$Q = I^2Rt$$  \hspace{1cm} (21)
with the assumption that the pulse has a rectangular shape with an area equal to the area of the actual pulse shape. At the obtained values of currents, the estimation of thermal effect without taking into account the heating losses was Equation (22):

\[
\begin{align*}
P_1 &= 4.34 J \\
P_2 &= 0.48 J \\
P_3 &= 0.76 J
\end{align*}
\]  

for one pulse of the heater operation, i.e., the heating is mainly due to the heat transfer from the winding to the core. The influence of the other two components is to counteract the decrease in heater temperature during the pause between pulses.

The temperature increase Equation (23) on the inner surface of the core is obtained from the Fourier equation and will be for a cylindrical surface [27]:

\[
\Delta \theta = \frac{Q_m}{2\pi l} \sum_{i=1}^{n} \frac{1}{\lambda_i} \ln \frac{d_2}{d_1}
\]  

The results of modeling and calculations have been verified in a full-scale bench experiment. Figure 4 shows the scheme of the pulse converter of the electric heater. The operation of the circuit is as follows: The input of the amplifying unit TV receives a signal from the wind turbine, rectifies the matrix VD1-4 and charges the capacitor C4. When the level sufficient for the breakdown of the dinistor VD7 opens the thyristor VS2, the current flows through the inductor L1 (heater winding).

**Figure 4.** Diagram of the pulse converter of the electric pulse heater: TV—amplification unit, VD1—rectifier matrix, C4—capacitive storage, VD7—dinistor, VS2—thyristor, L1—heater winding, [own elaboration].

By changing the voltage, it is possible to determine the time of reaching the limit of operation of the keys responsible for the start of discharging the capacitive storage device. The charging time of the capacitive storage tank of a stand-alone wind turbine up to certain technological limits using simulation modeling under stochastic changes in wind speed level is described in detail in [28]. Figure 5 shows graphs of the time taken to reach the limits of different thresholds of operation depending on the values of the mathematical expectation of wind speed when it changes in the range (4–8) m·s\(^{-1}\).
Figure 5. Dependence of the change in time of reaching the limit of different thresholds of operation of the keys responsible for the start of discharge of the capacitive storage device, depending on the values of the mathematical expectation of wind speed [own elaboration], graph that visually show the dependence of the corresponding functions on the arguments.

The graphs have a linear character of change, which makes it possible to predict the value of operation even at higher wind speeds.

The pulse shape $i_1$ in the experiment had the configuration shown in Figure 6. The amplitude value was 860 A, which corresponds to the calculated value with an error within 3%. The result of 3% is an acceptable result of research as it does not exceed the permissible limit in engineering calculations of 5–10%.

Figure 6. Pulse shape $i_1$ at bench experiment [own elaboration], graph that visually show the dependence of the corresponding functions on the arguments.

With the current value obtained from the model, the thermal effect was estimated $\Delta \theta = 0.79 ^\circ C$ for one minute of operation of the heater without taking into account the
heating losses and the number of (15–17) discharges of pulses entering the coil (operating limit 66 V).

The thermal effect of core temperature during the bench experiment is shown in Figure 7.

Figure 7. The thermal effect of the pulse electric heater core [own elaboration], graph that visually show the dependence of the corresponding functions on the arguments.

The thermal effect of core during the experiment was approximately 1 °C per min, which is adequate to the calculated values.

The paper presents the results of research investigating the possibility of the technological process of electric pulse heating of a mock-up sample, not the final sample of the product.

In addition, a key role in improving the efficiency of energy harvesting in an unconventional way is played by triboelectric nanogenerators (MC-TENGs) to harvest energy in undesirable mechanical excitations. Copper MC-TENG devices proved to be the most effective design generating a maximum mode in the closed-circuit 4 V voltage range with a resistance of 10 GΩ. The proposed MC-TENG concept provides an effective method of obtaining electricity from low-frequency and low-amplitude oscillations, such as ocean waves, which is worth pointing out as a curiosity of scientific research [29].

4. Conclusions

(1) A mathematical model of the operation of an electric pulse heater was developed, which made it possible to determine the pulse currents in the coil (i\text{max1} = 850A), the core (i\text{max2} = 380A), and in the screen (i\text{max3} = 530A), as well as to develop methodological provisions for evaluating the temperature change of its elements at a random wind speed.

(2) Bench experimental studies of the operation of the electric pulse heater were carried out, which confirmed the adequacy of the mathematical model for determining the currents in its constituent elements. It was established that, within an hour, the increase in the temperature of the heater core changed from 22 °C to 36 °C at a voltage of 66V and number of pulses entering the heater coil of (15–17) discharges, which corresponds to the values of the mathematical expectation of the wind speed of (4–5) m·s\(^{-1}\) in the speed range wind (4–8) m·s\(^{-1}\). The results were in satisfactory agreement with the calculated values. This model can be applied to other construction materials of the heater, which is expected in further research.

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Nomenclature

- $A$—core wall area $\text{m}^2$
- $D$—outer diameter of the core or screen $\text{m}$
- $L_1$—coil inductance $\text{H}$
- $L_2$—inductance of the inner ferromagnetic core $\text{H}$
- $L_3$—inductance of the outer ferromagnetic shield $\text{H}$
- $M_1$—inductance between the coil and the inner ferromagnetic core $\text{H}$
- $M_2$—inductance between the coil and the outer ferromagnetic shield $\text{H}$
- $P$—heat effect without taking into account heating losses $\text{J}$
- $Q$—heat flux $\text{W}$
- $Q_w$—heat flux to the core wall $\text{W}$
- $R$—outer radius of the core or screen $\text{m}$
- $R_1$—coil resistance $\text{Ω}$
- $R_2$—resistance of the internal ferromagnetic core $\text{Ω}$
- $R_3$—resistance of the outer ferromagnetic screen $\text{Ω}$
- $R_k$—key resistance $\text{Ω}$
- $U$—voltage $\text{V}$
- $a$—length of the solenoid valve $\text{m}$
- $d$—inner diameter of the core or screen $\text{m}$
- $d_e$—solenoid valve diameter $\text{m}$
- $d_1$—inner core diameter $\text{m}$
- $d_2$—outer core diameter $\text{m}$
- $i$—electric current $\text{A}$
- $l$—core or screen length $\text{m}$
- $r$—inner radius of the core or screen $\text{m}$
- $\Delta$—increment
- $\Theta$—thermal effect impulse $\text{°C}$
- $\theta$—temperature $\text{°C}$
- $\lambda_i$—thermal conductivity of the layers forming the core walls $\text{W} \cdot (\text{m} \cdot \text{K})^{-1}$
- $\omega$—number of turns of the solenoid valve

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