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Comparative Simulation Study of Pump System Efficiency Driven by Induction and Synchronous Reluctance Motors

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Abstract: Grid-powered pumping plants are widespread electromechanical systems commonly set in motion by electrical machines. The productivity of these electromechanical systems varies substantially according to the shift of the location of the working point on the *H-Q* plane, which is determined with the help of mutual positions of the characteristics of the pump unit itself and the hydraulic parameters of the pipeline. The topic of the proposed article is mainly focused on the investigation of pumping plant productivity equipped with two various types of electrical machines known as induction and synchronous reluctance motors. A simulation method of efficiency prediction of a centrifugal pumping plant for flow regulation is proposed. The described Simulink/Matlab simulation approach is quite valuable for validating efficiency in the case of pumping plants supplied with various types of electrical machines. The data relating to the electrical machines' efficiency estimation were obtained during a series of experimental tests with the real experimental setup. Thus, the calculation results of the model are accurate and based on confirmed experimental measurements.

Keywords: pumps; water pumps; hydraulic equipment; modeling; energy efficiency; induction motors; electric machine

Citation: Gevorkov, L.; Domínguez-García, J.L.; Rassõlkin, A.; Vaimann, T. Comparative Simulation Study of Pump System Efficiency Driven by Induction and Synchronous Reluctance Motors. *Energies* **2022**, *15*, 4068. https://doi.org/10.3390/en15114068

Academic Editor: Alban Kuriqi

Received: 10 May 2022
Accepted: 28 May 2022
Published: 1 June 2022

1. Introduction

According to the up-to-date EU regulations, there are ongoing trends of improving standards and requirements for energy efficiency demanded by regulations for CO_2 emission shortening and general increment in energy worth [1]. At the same time, there is a need to implement more sophisticated technical characteristics for pumping units for optimization of operational rates.

Centrifugal pumping systems represent sophisticated electromechanical units, including primarily the mechanical pump unit, adjustable speed drive (ASD or VSD), hydraulic equipment, and diverse transducers [2,3]. Pumping systems are amidst the significant energy utilizers. Generally, pumping systems operate with alternating hydraulic capacities. The characteristics of hydraulic loads are determined by different parameters, for instance, geometrical characteristics of the pipeline (including pipe diameter, wall thickness, wall roughness, etc.) [4–6]. Pumping units globally consume up to 22 percent of the total electricity used by electrical machines worldwide [7], despite the fact that pumping systems are generally driven by electrical machines without VSDs [8]. Recently, approximately 20–30 percent of pumping units have been equipped with VSDs, because of the high productivity [9]. These systems intensify the mechanical energy of the liquid flowing through the pumping unit and amplify its pressure at the system output. In the process of investigating the pumping unit, the main interest lies in the possibility of enhancing its control from the energy consumption point of view.

There are different methods described and offered to examine the enhancement of centrifugal pumping units. According to the literature, the objective function of a pumping unit, which is denoted by J, is given in the following form [10]:

$$J = \sum_{e} \int_{t_i}^{t_f} [c_e Q_e(t) + b_e H_e(t) Q_e(t) / \eta(Q_e(t))] dt, \quad (1)$$

where:

e—a particular pump of a multi-pump system;
t_i—initial time of operation;
t_f—final time of operation;
c_e—unit cost of water production;
b_e—unit price of energy;
$Q_e(t)$—flow of the pump;
H_e—energy head;
$\eta(Q_e(t))$—efficiency as a function of flow.

The above-mentioned equation depicts the dependency amidst flow and the energy heads that are connected by nonlinear dependences. The quantity of fluid stream can be obtained by a discrete variable for a certain speed and framework state or as a continuous variable that depends on the throttling rate of a pumping unit. The above equation depicts a dynamic, nonlinear system. In spite of persistent efforts to discover a common solution, there is still no advancement. Since the general solution is not yet set up, it is required to create approaches that are more versatile. This objective can be settled by an examination of the specific characteristics of the pumping unit [11,12].

One of the major issues in pumping systems is the significant energy loss that occurs inside the pumps. These types of losses are mainly caused by the mechanical, hydraulic losses inside the pumping system and VSD losses in the adjustable speed drives that are connected and rotating the centrifugal pumps. The adjustable drive energy waste is comprised of the energy dissipation in the semiconductor devices and in the electrical machine itself. Losses in electrical machines consist of eddy currents and copper losses. As far as the valuable hydraulic power created by the pumping unit, it could be a portion of the entire input power attached to the adjustable speed drive from the grid; it is necessary to estimate and boost the pump unit's productivity. It was illustrated in the literature that the main goal for minimizing pumping lifecycle costs is to manage the pump control as near to the best efficiency point of a particular pumping unit as is conceivable.

The effect of the adjustable speed drive equipped with the induction motor (IM) and Synchronous Reluctance Motors (SynRM) on the pumping plant's productivity is one of the major objectives of this article. In [13], the authors study the role of the indicators of electricity consumption and CO_2 emissions for four-pole induction motors (IMs) with a rated power of 2.2–200 kW in a variable speed pump unit. Research with similar goals was introduced in [14], where the influence of the energy waste of the IM with nominal power of 2.2 kW, and torque on the shaft of 14 Nm, equipped with the power converter, was explored. As a result, they presented that the peak efficiency relies on the electric machine and VSD's parameters. Generally, the value is close to 92–98% for 1–400 kW variable speed drives. An effect of the variable speed drive efficiency when the system operates at low rotational speed was also shown in [15]. In the literature, there are different approaches described for the design and control strategies of SynRMs. For instance, in [16], the authors propose a design that was later validated by comparison against experimental measurements on a 5 kW–50 krpm SyR prototype. In [17], the authors focused on the design, optimization, and control of a permanent magnet-assisted synchronous reluctance machine (PMaSynRel). A modulated predictive control to improve the steady-state performance of nine-switch inverter-based electrification systems was proposed by the author in [18]. In [19], the authors proposed a method to use the mathematical model of the system to predict control objectives and solve a multi-objective cost function to determine the optimal control actuation.

As was stated previously, there are two main types of electrical machines that are used as a driving force for pumping systems. The necessity to be equipped with the squirrel cage and other technical characteristics were major obstacles for synchronous reluctance motors in comparison with induction motors. Thanks to the advancements within the semiconductor electronics and field-oriented theory during the last few years, the synchronous reluctance machines started to be used in various fields, including pumping technologies [20].

To evaluate the energy productivity of the pumping plants supplied with induction and synchronous reluctance machines, a complex Simulink/Matlab model is proposed. The model represents several benefits valuable for pumping technology. With the help of the developed model, the efficiency of the pumping system with two different types of electric motors is assessed. The sections of the article are separated in the following manner. The following section accounts for the flow adjustment of a pumping plant. It describes the structure of the pumping unit and the influence of the adjustable speed drive. At that point, the design of the model and its subsystems are clarified. Within the last part, the simulation results are analyzed.

2. Efficiency-Oriented Control of a Pump

The general topology of a pumping plant with an adjustable speed drive is presented in Figure 1. The system is composed of a centrifugal pump unit that is fed by a VSD, liquid tank, or reservoir. The liquid flow rate is regulated with the help of a programmable logic controller (PLC). The PLC receives a reference signal and a signal from the installed transducer. The signal from the transducer is then compared with the reference one.

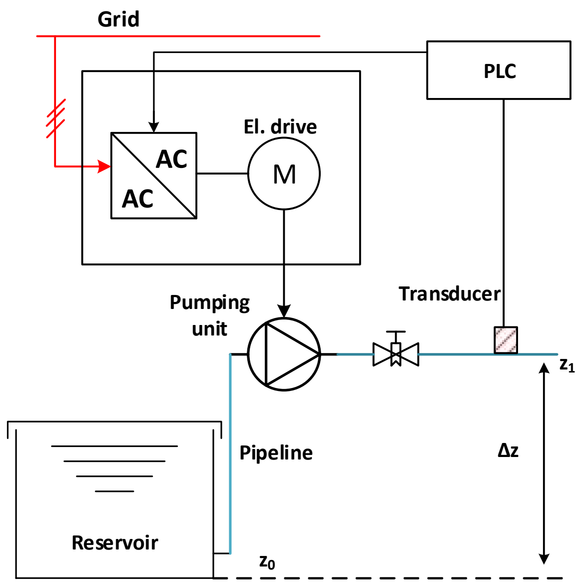

Figure 1. The general structure of the pumping system. Pipeline is presented by blue color and grid connection by red line.

To calculate the efficiency of a pumping plant [21] for a specific operational region on the *Q*-*H* plane, the following equation can be applied:

$$\eta_{pump} = \frac{g\rho h q}{P} = \frac{pq}{P}, \tag{2}$$

where:

h—total head, m;
q—flowrate, m^3/h;

ρ—liquid density, kg/m^3;
g—acceleration due to gravity, m/s^2;
p—liquid pressure at the pump intake, Pa;
P—brake power on the pump shaft, W.

Equation (2) represents the efficiency of a centrifugal pump as a ratio between the hydraulic energy and the input power of the pumping system.

The total input power of a pumping system is calculated based on the torque and rotational speed [22]:

$$P_{shaft} = T \times \omega = \frac{\pi n T}{30}, \quad (3)$$

where:
P_{shaft}—mechanical power, W;
ω—angular velocity, rad/s;
T—pump torque, Nm;
n—pump velocity, rpm.

For each particular component of the pumping plant that composes the application drive chain, it is necessary to evaluate the energy efficiency for a given working point selected from the operation profile [23]. The application drive chain usually consists of a gearbox, electrical motor, power converter, and the centrifugal pump itself. The total efficiency of a system is given by [24]:

$$\eta_{Total} = \eta_{pump} \cdot \eta_{gearbox} \cdot \eta_{el.motor} \cdot \eta_{pow.converter}, \quad (4)$$

Figure 2 represents the major hydraulic and energy characteristics of the pumping unit. The dots shown in the figure, W_a, W_b, W_c, W_d, located on the crossing of the vertical and horizontal lines, are called operational points of the pump system. W_c corresponds to the operation of the pumping unit at the rated speed. W_a, W_b, and W_d correspond to the operation of the pumping unit during mechanical regulation by the throttle and adjustable velocity, respectively. These dots on the Q-H plane denote the main parameters of the pumping unit, including flow rate, energy head, pressure, and efficiency. The other point, Q_{BEP}, represents the flow rate close to the point with high efficiency. The point p_{BEP} represents the liquid pressure in the same area.

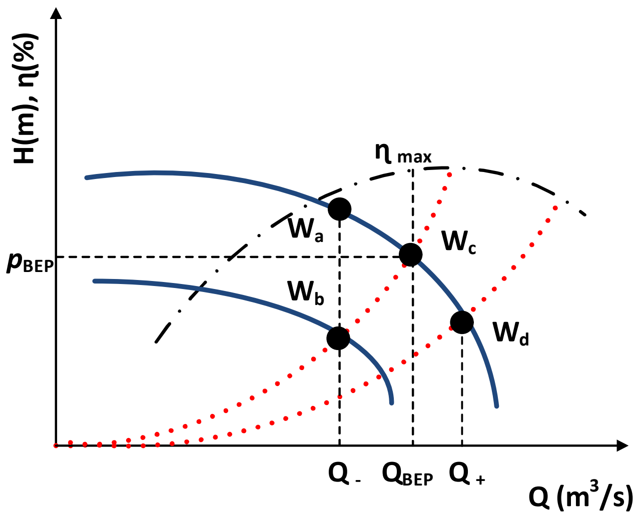

Figure 2. *H-Q* plane of pumping unit's operation.

The blue lines shown in Figure 2 are displayed in the pumping unit's manuals provided by the producer of the equipment and are only for the rated velocity of the pumping plant. The set of equations below offers the possibility to obtain the main pumping characteristics for a desired rotational velocity:

$$\frac{q_{is}}{q_{rs}} = \frac{n_i}{n_r}, \; \frac{h_{is}}{h_{rs}} = \left(\frac{n_i}{n_r}\right)^2, \; \frac{P_{is}}{P_{rs}} = \left(\frac{n_i}{n_r}\right)^3, \tag{5}$$

where the subscript index s indicates the location of the specific operational point on one of the vertical red lines shown in the figure. The index r indicates the location of operational points for the blue horizontal line corresponding to the rated velocity. The index i indicates the operational points for the other horizontal blue lines corresponding to the rotational velocity different from the rated one.

3. Simulation Approach for Pumping Plant's Efficiency Calculation

Two electrical machine types were simulated for the centrifugal pumping system. The first one was an induction and the second one was a synchronous reluctance [25–27]. In general, voltage equilibrium conditions in the case of a two-phase d-q plane are expressed in the following form:

$$V_d = I_d R_s + \frac{d\Phi_d}{dt} - \omega_e \Phi_q, \tag{6}$$

$$V_q = I_q R_s + \frac{d\Phi_q}{dt} - \omega_e \Phi_d, \tag{7}$$

where V_d is the d-axis voltage part, V_q is the q-axis voltage part. I_d is the d-axis current part, I_q is the q-axis current part. R_s denotes stator resistance. Φ_d is the d-axis flux part, Φ_q is the q-axis flux part. ω_e is the electrical velocity. Characteristics of the motors have been transferred into the model with the help of lookup tables.

The entire input power for the pumping unit is presented in the following mathematical expression:

$$P_{in} = P_{loss} + P_{shaft}, \tag{8}$$

The analytical representation of the hydraulic line connected to the pumping units' outlet ought to permit the accurate assessment of the flow rate in the hydraulic line; it is presented in the following mathematical expression [28]:

$$h_f = \lambda \frac{8LQ^2}{d^5 g \pi^2}, \tag{9}$$

where h_f is a specific friction loss, λ is the so-called Darcy friction index. L and d are geometrical characteristics of the hydraulic line. Q is flow rate and g is the acceleration due to gravity.

The structure of the proposed simulation model for the efficiency estimation is made up of several major modules, Figure 3.

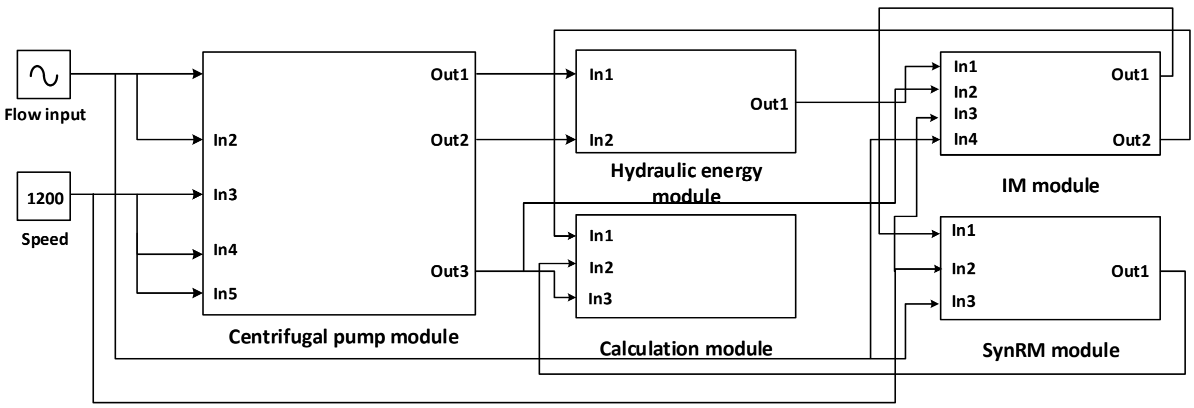

Figure 3. Structure of Simulink model.

The first module supports every fundamental part for the estimation of hydraulic characteristics for the centrifugal pump SE series from Grundfos company, Table 1. The main hydraulic characteristics are described by the so-called affinity equations. The module has several inputs:

- In1, In2—the reference speed input for flow and head calculation of a system curve;
- In3, In4, In4—the reference flow input that determines the position of a system curve;
- Out1—the reference value of total head corresponding to the reference flow;
- Out2—the flow value corresponding to the reference speed and system curve position;
- Out3—the mechanical power of the pumping unit, which is estimated in line with mathematical expression (3).

Table 1. Parameters of the centrifugal pump.

Parameter	Value
Pump type	SE
Impeller type	S-tube impeller
Pump free passage, mm	85
Housing type	Cast iron
Pump discharge, mm	150
Output power, kW	9
Pressure range type	High
Application	Water/wastewater

The second module is designed to calculate the hydraulic energy at the outlet. Based on pressure, flow signals from the first module, and Equation (2), we obtain a value of the hydraulic energy based on the values of reference speed and flow. The next two modules incorporate the data from the efficiency map. In the “IM module” and “SynRM module” blocks from Figure 3, we use lookup tables based on the previously obtained experimental data, which includes torque (rms) and motor-drive efficiency (rms) at different speeds starting from 300 rpm and up to 1800 rpm with a resolution of 300 rpm until 1500 rpm and with the resolution of 150 rpm after 1500 rpm. The output values of the motor-drive efficiency are based on parameters of the rotational speed and torque. The final calculation module is used to compute the overall productivity of the pumping system, taking into consideration both hydraulic losses inside the pump casing and losses caused by the power converter and electric motor.

4. Simulation and Experimental Results

To more easily manipulate the parameters during the simulation, an interface was designed with the help of the App Designer tool from the Matlab/Simulink environment [29], Figure 4.

Then, the operational characteristics were calculated. The hydraulic characteristics of the centrifugal pump consist of the composition of numerical values calculated according to (5). They define a composition of invariable velocities helpful for estimating parameters according to the values, which are already known for another rotational speed. Based on mathematical expression (5), several operational characteristics of the pumping unit can be estimated. The example of the operational characteristics composition estimated according to (5) for Grundfos SE 1.85.150 [30] is shown in Figure 5.

For the comparison of drive performance, the synchronous reluctance machine was designed and assembled [31]. For the construction purpose, the IM 132 MA size frame was utilized, and the stator windings were rewound to achieve the 10.5 kW power of the designed machine. The laminations for the SynRM were developed and manufactured so that the machine’s calculated nominal values were as in [32]. Then, the laminations were assembled, and the SynRM’s rotor was developed (Figure 6).

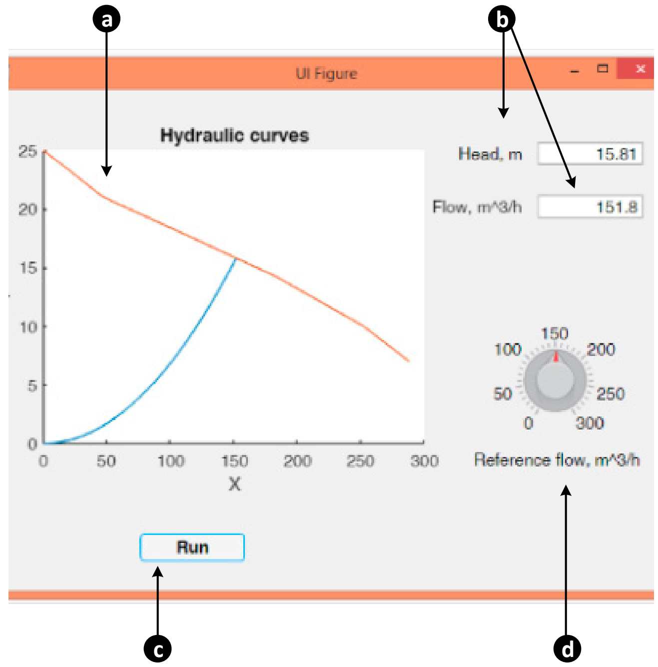

Figure 4. The graphical user interface, (**a**) hydraulic curve diagram, (**b**) pump flow and total head position, (**c**) Start/Stop button, (**d**) reference flow.

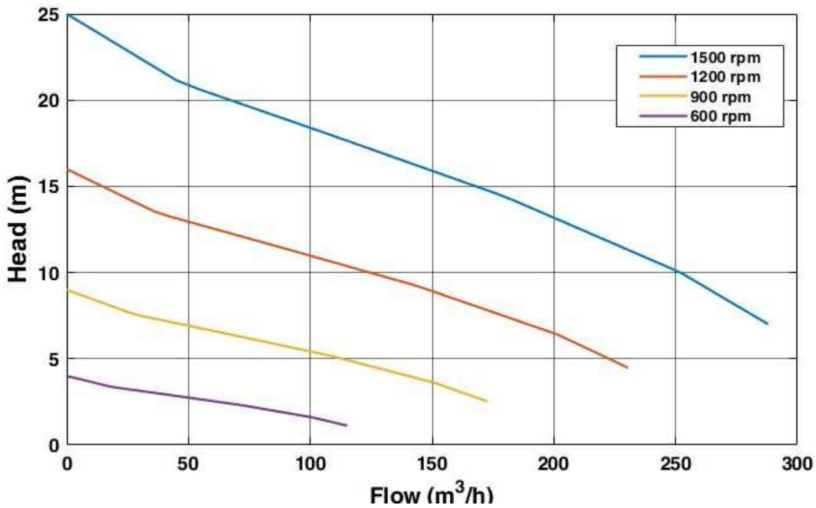

Figure 5. Family of performance curves of Grundfos SE 1.85.150 for a set of various rotational speeds.

Figure 6. The rotor structure of the designed SynRM. Characteristics of the motor are given in Table 2.

Table 2. Motor data.

Parameter	IM	SynRM
Frame size	132 MA	132 MA
Nominal power, kW	9.5	10.5
Nominal current, A	19.3	25.3
Nominal speed, rpm	1460	1500
cosϕ	0.7	0.6
Moment of inertia, kgm^2	0.02	0.02

To calculate motor-drive losses, an experimental setup was employed (Figure 7). The technical specifications of IM and SynRM are shown in Table 2. The frame size of both motors was 132 MA according to ABB company specifications.

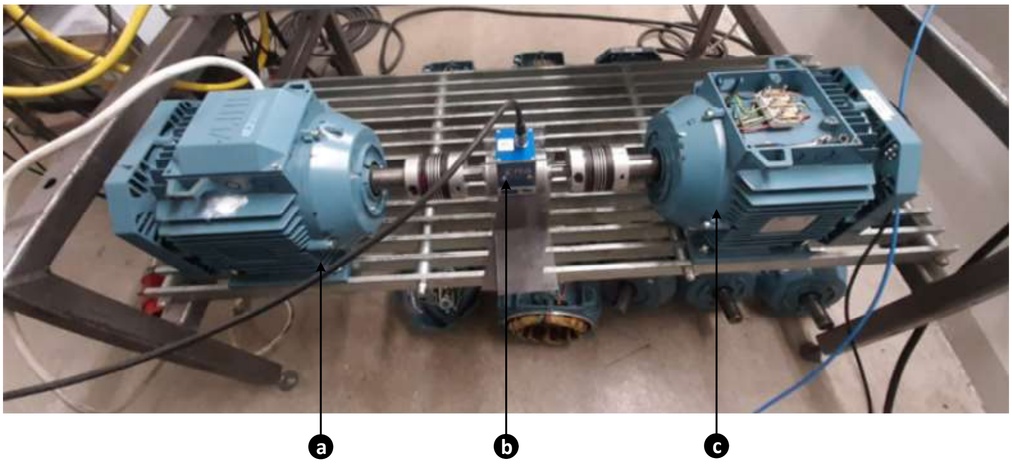

Figure 7. Experimental setup. (**a**) IM, (**b**) torque sensor, (**c**) SynRM.

Based on the experimental data, the set of efficiency curves for both electrical machines was obtained, Figures 8 and 9.

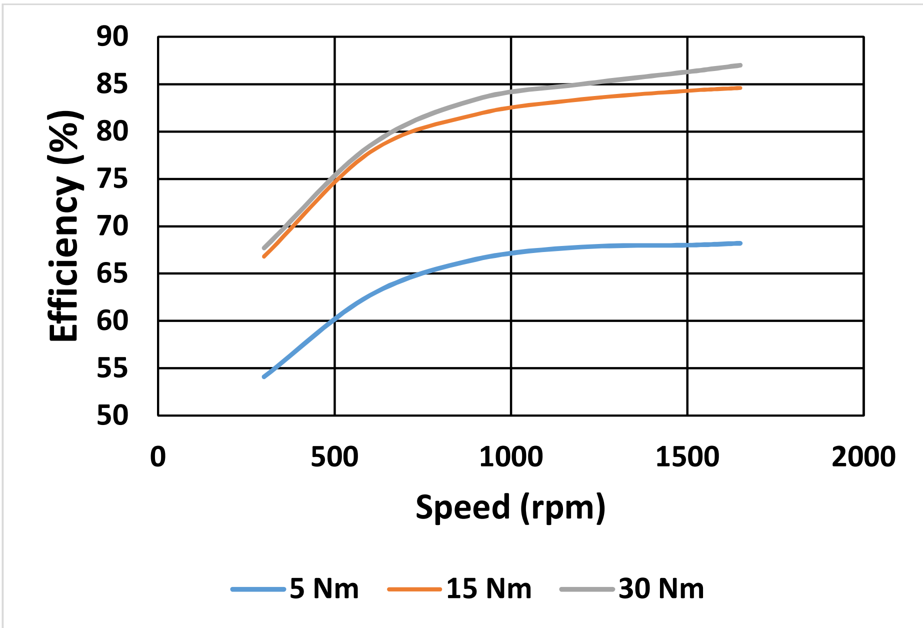

Figure 8. Family of efficiency curves for IM.

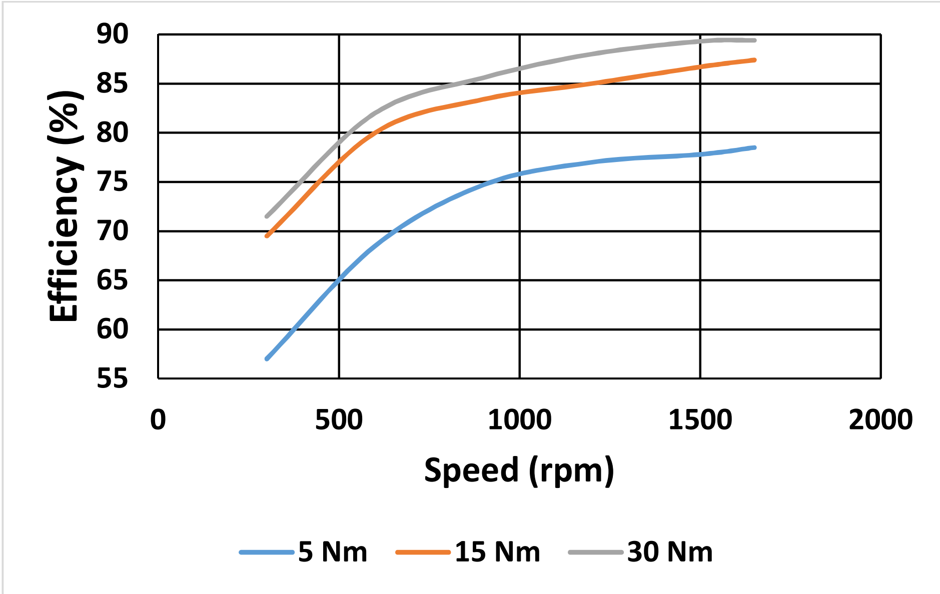

Figure 9. Family of efficiency curves for SynRM.

The data from the efficiency maps were later transferred into the simulation environment. Then, based on the data for speed and torque reference signals, the total efficiency of the system was estimated (Figure 10).

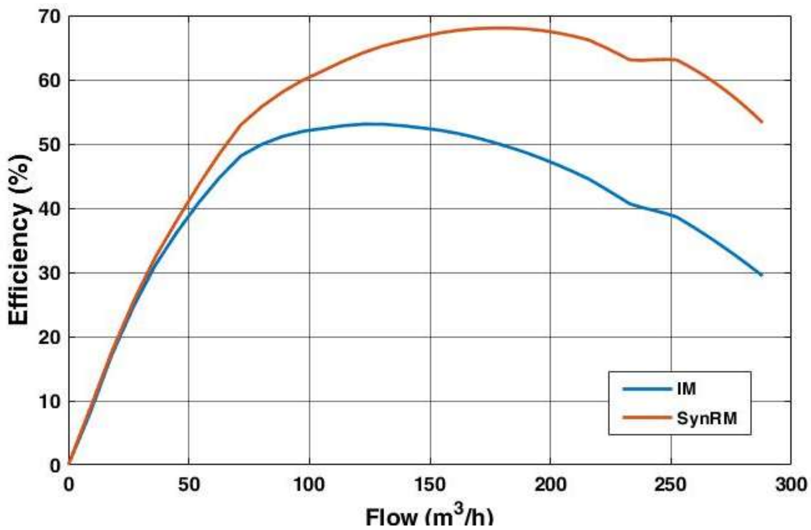

Figure 10. Comparison of IM and SynRM motor drives in pumping application.

To compare the energy efficiency of two pumping units supplied with a single drive induction motor and synchronous reluctance motor, these systems were investigated. The analysis shows that in the instance of a synchronous reluctance motor-based pump system, energy efficiency in the nominal operation point corresponding to 180 m^3/h is much higher. For instance, the application of a synchronous reluctance motor in that operational point can increase energy efficiency by 18%. The energy efficiency and thus savings can be attained thanks to the application of pumping units supplied with the adjustable speed drives based on SynRM.

Despite the rather low difference in the energy efficiency of the IM-based pump system and SynRM-based pump system, flow rates were about 2–3% at 50 m^3/h. The gain of efficiency at the most frequent flowrates corresponding to nominal working point or at high flowrates increases the overall efficiency and energy saving, which can achieve its maximum of 25% at a 280 m^3/h flowrate.

It can be stated that according to the obtained simulation results in the case of operation in the so-called high flow pumping (HFP) region on the given *H-Q* plane, the application of the SynRM-driven pumping system is more beneficial from the efficiency point of view than the application of the IM-driven pumping system. This can be very important in the case of stand-alone photovoltaic (PV) pumping systems because PV-powered pumps usually operate in HFP mode. The model allows the adoption of various technical characteristics of different pumping systems, thus allowing much flexibility.

5. Conclusions

The model for the efficiency estimation of the centrifugal pump system supplied with two types of electric motors has been proposed and designed in the Matlab/Simulink environment. The designed model is composed of several major blocks. Each of the blocks is developed for particular tasks of a calculation procedure. For instance, for performance and system curve characteristics design, centrifugal pump characteristics examination, and various parameters estimations.

Simulations that are carried out with the developed model can be helpful at the design stage of the development of centrifugal pump systems. The model shows quite a high precision at different simulation conditions. In addition, it is flexible during the operational modes that take place in conventional pumping units. The main benefits of the simulation approach are its capability to combine hydraulic and electrical characteristics and predict the productivity of a centrifugal pumping unit supplied with either induction or synchronous reluctance motor drives. In the process of flow regulation utilizing either the hydraulic valves or the adjustable velocity, the system with a synchronous reluctance motor showed better performance from the efficiency point of view.

The comparison for both pump system configurations equipped with SynRM and IM indicates that in the case of electrical drive based on SynRM, the efficiency gain can reach up to 2–25% at the operational point depending on the position of that point which is located on the operational curve of a pumping plant. Simulation results show that the operation in the HFP area is more beneficial from an efficiency point of view when the pumping system is equipped with SynRM. This is quite a significant benefit when operating a PV pumping system because these types of pumps usually operate within the HFP region. The PV pumps deliver the maximum amount of water into the storage reservoir during a relatively short period of time when the irradiation is sufficient to produce enough energy for the pumping process. The proposed novel model can be interesting both from a practical and theoretical point of view. It brings new approaches to the efficiency estimation of pumping systems that were not covered previously in the literature.

Author Contributions: Conceptualization, L.G.; methodology, J.L.D.-G.; investigation, L.G.; data curation, T.V. and A.R.; writing—review and editing, L.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded from the postdoctoral fellowship programme Beatriu de Pinós, funded by the Secretary of University and Research, from the Department of Enterprise and Knowledge (Government of Cata-lonia), with the grant N° Ref. 2020 BP 00134.

Acknowledgments: This project has received funding from the postdoctoral fellowship programme Beatriu de Pinós, funded by the Secretary of University and Research, from the Department of Enterprise and Knowledge (Government of Catalonia), with the grant N° Ref. 2020 BP 00134.

Conflicts of Interest: The authors declare no conflict of interest.

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