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Towards Optimum Energy Utilization by Using the Inverters for Industrial Production

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Abstract

Industrial machines usually experience considerable energy consumption and alternate production rates, as function of the market demand. These machines are typically equipped with electrical motors used to power the tools required for the manufacturing processes. Large mismatches between the changing production rates and the effective motor speeds can have a significant impact on the energy utilization. In order to variate the electrical motor speed, as function of the market requirements, inverters can be incorporated in industrial systems, increasing flexibility as well as the energy savings. In this study, inverters are employed for converting DC to AC mode in a simulated industrial system. The production rates are modeled using different distribution functions comparing the cases with and without the inverter technology. The investment analysis is developed considering the retrofitting costs of the production systems versus the energy saving. The results of the study demonstrate a comparison model which aims to aid the practitioners and industrial experts during the decision-making process, by considering different production patterns, as input, and returning the system economic feasibility, as output.

Keywords: Industrial machines; inverter; energy consumption; manufacturing; distribution functions.

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1. Introduction

In industry, the energy consumption has a substantial effect on the overall efficiency and performance of production and manufacturing machines. On the other hand, development and the integration of renewable energy (RE) sources within industrial machines is an important goal to achieve. Such machines usually consist of electric motors, which are utilized in a broad power range, from mW to MW, and they also have various applications including industrial electromechanical systems, RE systems, electric vehicles, biomedical equipment and the auxiliaries. Tuning the motor speed is a focal factor to enhance the energy efficiency of the machines. Power converters are used to regulate the motor speed. They make a continuous speed control by changing the frequency of the energy source, varying the impedance or by producing an electromotive force. A class of power converters are inverters, which convert DC to AC mode. They are widely used in several applications to adjust the motor speed, optimizing the energy consumption and the overall efficiency of the systems. Lavi and Polge [1] investigated induction motor speed control in conjunction with a static synchronous inverter. They concluded that the new designed system, which employs this type of inverter, has a linear current relation independent on the speed. It also operates as a separately excited DC motor. Faccio and Gamberi [2] investigated energy saving for intermittent production by using inverter technology. Their feasibility analysis estimated the reduction of the energy consumption as a function of the production variables such as the number of daily stops, the average working time and other operative parameters. Gieras and Gieras [3] studied recent developments in electrical motors and drives. Decision parameters for each motor including power density, maximum shear stress, efficiency, torque ripple, overload capacity factor and cost are compared. Calhoun et al. [4] investigated sizing for minimum energy operation in subthreshold circuits using inverter technology. The Authors concluded that the minimum energy point relies on the technology type, the design features and operating conditions such as temperature, duty cycle and workload. Dehghan et al. [5] presented a new variable-speed wind energy conversion system by using a Z-source inverter. It was suggested that by using a DC-link voltage control method total switching device power is increased by only 6% in comparison to the conventional system. Dali et al. [6] employed a single-phase inverter with a lead acid accumulator for designing a hybrid solar-wind system under grid connected and standalone situations. The grid power inverter was sufficiently controlled to allow the operation of the system either in grid connected mode or in standalone status by considering a seamless transfer from one mode to the other. Tolbert and Peng [7] studied multilevel converters as a utility interface for renewable energy systems. It was suggested that such converters are suitable for medium to high power applications. They also have a low electromagnetic interference and switching interface. Keller and Kroposki [8] studied fault characteristics of inverter-based distributed energy resources. Barros et al. [9] investigated the MPPT and integrated energy storage system for photovoltaic applications. Simulation results consisted of variations of power including input power, charging power and injected power. Furthermore, the influence of the temperature and radiation on the produced energy, together with other related parameters, are studied. A novel standalone inverter was designed by Zhang et al. [10] for utilization in Google Little Box Challenge (LBC). The new designed model was able to achieve a peak efficiency of 99.3% and CEC efficiency of 99.26%. Kashani et al. [11] presented a new approach for voltage correlation for distributed PV micro inverters. Their approach decreases the avoidable PV micro inverter tripping and energy reduction while supporting voltage control at the point of common coupling (PCC).

Overall, several Authors stated the use of inverters for a wide range of industrial applications. However, the literature review still lacks an in-depth analysis outlining an effective strategy for using the inverter in production machines, incorporating the energy systems, with the purpose of decreasing the energy consumption and considering different distribution functions of the inverter power output. The current research aims to investigate production rates of an industrial machine by considering different distributions of the energy output. The energy efficiency of the system is evaluated with and without the system variable speed drive, comparing the performances.

This paper continues in Section 2 with the problem statement, while the methodology is in Section 3. In Section 4, the results of the analysis are obtained. In the final Section 5, the conclusions are drawn together with future recommendations for the next research steps.

2. Problem statement

There is a growing awareness towards the environmental concerns, which encourages scientists devising energy-efficient solutions. A significant part of the energy consumption of machines is as a result of the electrical motor power systems. Considerable differences between the production rate and the motor speed can lead to higher energy consumption. Such a discrepancy decreases, also, the overall performance and reliability of the industrial machines. By looking through the past studies, it can become clear that, the aforementioned problem in the industrial machines has not been investigated in depth. We have therefore adopted a new strategy by introducing the inverters as a way to regulate the motor speed as function of the market requirements. Additionally, different distribution functions are considered to assess the performances of the system. This study compares the case of continuous energy use versus its modulation by the inverter. Such comparison is made considering on one side a direct utilization, on the other a modulation according to alternative production patterns. Fig. 1 depicts the schematic of the proposed micro-energy system incorporating the inverter. It is assumed that the DC power output from the considered energy source varies from a minimum of 0 to a maximum of 200 W. Furthermore, two cases of variable speed drive (VSD) and no VSD are considered. The variable speed drive follows the energy demand. The operation process for the current system includes three stages of the market demand, the production system with and without VSD and, then, the final stage which is the energy output for the service plant system. The following assumptions are, also, considered in the system: (1) the average hourly cost of energy is assumed to be 0.4 €/kWh, (2) the DC power output from the energy source varies from minimum of 0 to maximum of 0.2 kW, (3) the number of operating days for the production system is considered to be 220 per year.

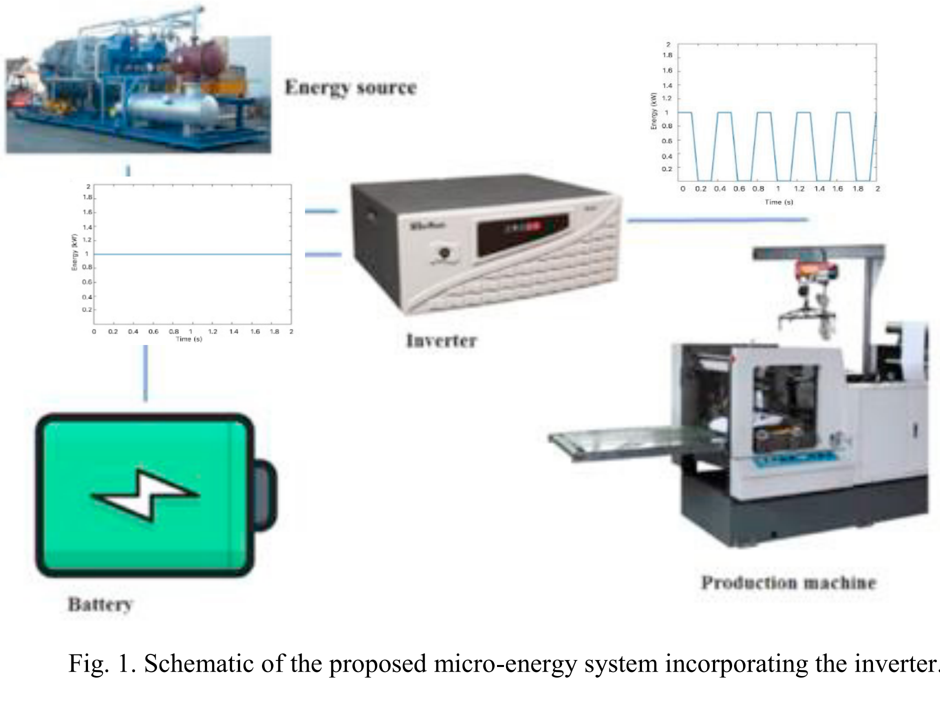


Fig. 1. Schematic of the proposed micro-energy system incorporating the inverter.

3. Methodology

3.1. Analysis of the production system and economic evaluation

The design of the production system can be performed in such a way that it would operate with or without the inverter. In each case, the energy consumption is taken into consideration to put into effect this parameter as a main criterion during the analysis process.

Basically, the energy consumption of the system is also defined according to Eq. (1), as follows [12]:

$$P = \frac{E}{T} \tag{1}$$

where P is the power [W], E is the energy consumption [J] and T is the time [s].

The proposed system, which utilizes an inverter technology has an alternate production pattern. Three functions are defined to demonstrate the production. The first function is implemented according to Eq. (2) using a square wave step function [13]:

$$y(x) = a_h(-1)^{\left\lfloor \frac{2(x-x_0)}{T} \right\rfloor} =$$

$$a_h sgn[\sin\left(\frac{2\pi(x-x_0)}{T}\right)] =$$

$$a_h \frac{2i}{\pi}[tanh^{-1}\left(e^{-\frac{i\pi(x-x_0)}{T}}\right) - tanh^{-1}\left(e^{\frac{i\pi(x-x_0)}{T}}\right)] \tag{2}$$

where y(x) is the square wave function with the following variables: half-amplitude (a_h), period (T), and offset (x_0).

The second function is based on the Beta distribution function. This function can be defined according to the following formula:

$$\beta(x, y) = \int_0^1 t^{x-1}(1-t)^{y-1}dt \tag{3}$$

where x, and y are two shape parameters for the Beta distribution function [14]. The last distribution function considered in this study is the Normal distribution. The probability density of the Normal distribution is given by the following equation [15]:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{4}$$

where μ is the mean of the distribution, and σ is the standard deviation of the distribution.

3.1.1. Cost analysis

The payback period (PB) is estimated by defining the present value function according to the following equation:

$$PV = -C + \sum_{n=1}^{N} \frac{(C_{dir} - C_{inv})}{(1+i)^n} \tag{5}$$

C is the initial investment cost, the expected cost saving in the energy consumption is represented by $C_{dir} - C_{inv}$. This value is function of the production variables. *N* is the number of years, *i* is the actualization rate of the cash flows and it is assumed to be 20% for the proposed energy system. Then, the payback period can be defined according to Eq. (6):

$$P_b = N: PV = 0 \tag{6}$$

This equation defines the number of years required to get back the initial investment cost.

In the second method of estimating the payback period, which is defined on the basis of a more simplified model of the PB, this parameter can be estimated according to the following equation:

$$P_b^* = \frac{I_c}{A_n} \tag{7}$$

where I_c is the cost of the investment, and A_n is the annual cash flow. Furthermore, the cost of energy for the production system can be calculated according to Eq. (8) [2]:

$$Cost = E_s \times D \times C_{kWh} \tag{8}$$

where E_s is the energy consumption [kWh/day], D is the number of operating days per year, and C_{kWh} is the average cost of energy.

3.2. Modulation process

With the purpose of evaluating the impact of the inverter configurations on the system reliability and its energy saving, the suitability of several inverter configurations, based on criteria of electricity demand, production cycle and the duration of the time, when the machine is turned off (Δt_1) and on (Δt_2), are investigated. To analyze the modulation process for the energy system production rate and to suggest the optimum configuration of the energy system, inverter distribution of power output is denoted as a model, i.e. patterns from 1 to 8 as in Fig. 2. In this figure, the curves show the proposed waveform of the power expected at the inverter output terminals according to instantaneous production patterns of the machine, considering a variable speed drive system.

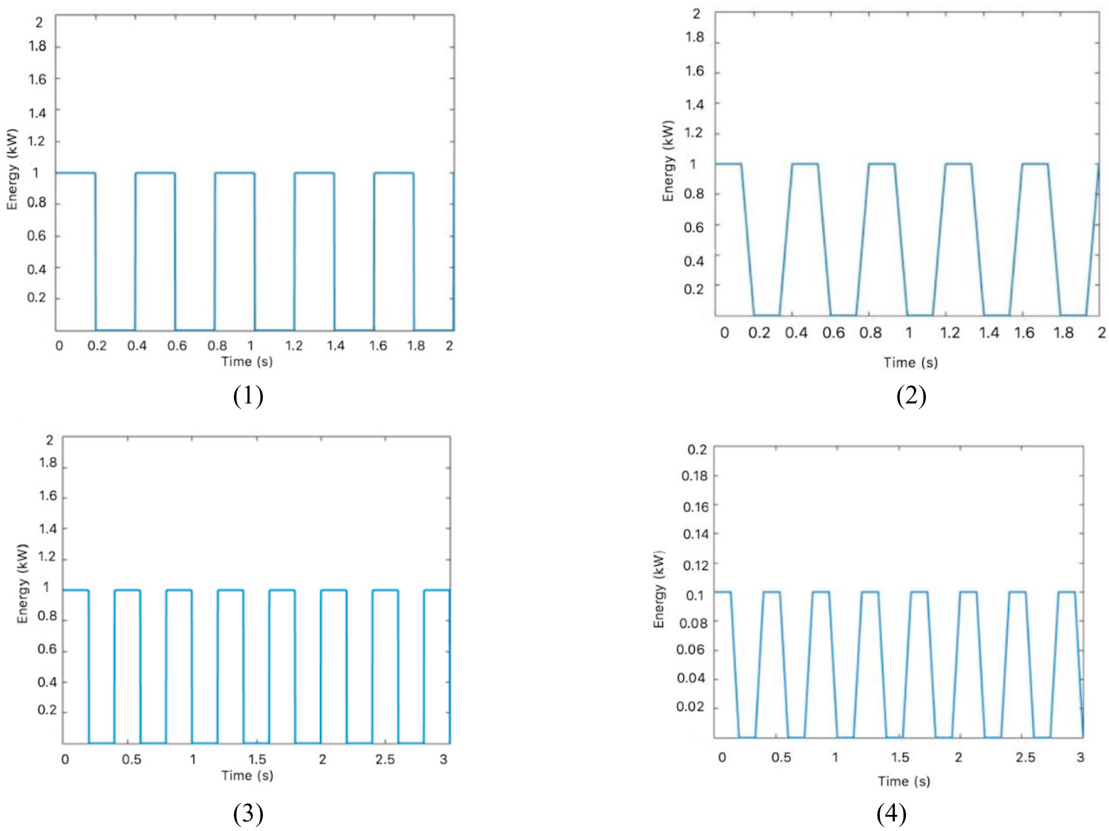
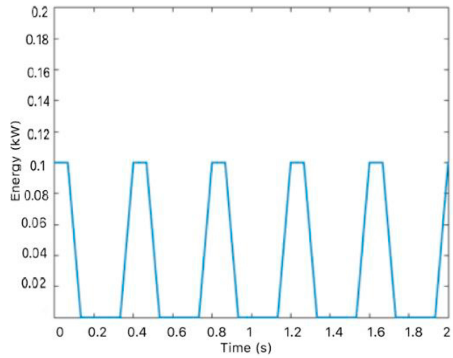


Fig. 2. Production patterns of the system by considering different distribution functions.



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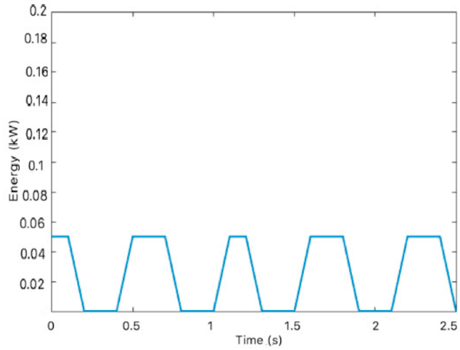

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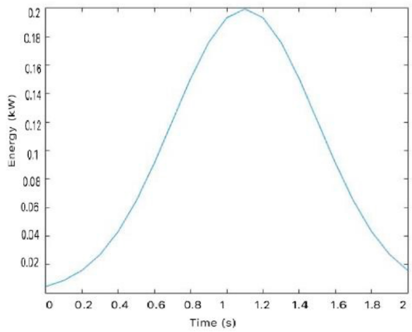

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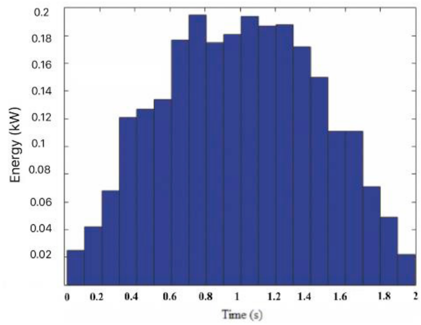

(8)

Fig. 2 (*continue*). Production patterns of the system by considering different distribution functions.

The inverter power output is analyzed using the square wave step function, Beta, and Normal distribution functions. Table 1 shows the working intervals and production cycles.

Table 1. Production cycle and interval characteristics for the studied models.

Model No.	Production cycle	Δt_1 [s]	Δt_2 [s]
1	10	0.200	0.200
2	10	0.150	0.150
3	15	0.200	0.200
4	10	0.100	0.300
5	10	0.085	0.200
6	10	0.100	0.200
7	1	2.000	0.000
8	20	0.100	0.100

4. Results and discussion

This section describes the obtained results including the energy analysis and the economic evaluation of each production type. Table 2 presents the investment cost for different system configurations according to the production type, which are developed based on each model and the system component.

Table 2. Investment costs for different system configurations.

System component / Model No.	C [k€]
Inverter (0.1 kW)	0.01893
Inverter (0.05 kW)	0.01459
Battery (0.1 kW)	0.02115
Energy source and the production machine	0.45985
Models (1-6, 8)	0.50000
Model 7	0.49500

Results show that adjusting the machine production rate according to the demand function plays a key role for its performances and configuration. Table 3 depicts the variations of the energy consumption, energy saving and the economic parameters including the annual net cash flows, the payback period and the cost of energy (COE) for each production type.

Table 3. Investment cost and energy analysis of the system for each proposed model.

Model No.	Energy consumption [kJ]	Energy saving [kJ]	A_n [k€]	P_b [years]	P_b^* [years]	COE [c€/day]
1	0.100	0.100	0.086187	5.88	5.81	30
2	0.080	0.120	0.085961	4.55	5.82	24
3	0.160	0.140	0.086503	7.73	5.78	32
4	0.050	0.150	0.008665	8.61	5.77	10
5	0.071	0.128	0.086403	7.14	5.78	21
6	0.051	0.198	0.086941	10.30	5.75	12
7	0.098	0.101	0.086208	11.00	5.74	29
8	0.250	0.150	0.086725	9.03	5.76	75

The minimum energy consumption is observed in the case of the fourth model of Fig. 2 with the value of 0.05 kJ. Another parameter discussed in Table 3 is the payback period. By considering the interest rate as an economic parameter, the least payback period is observed in the case of the second model of Fig. 2, with 10 production cycle and P_b equal to 4.55 years.

Fig. 3 compares the energy saving and the payback period for each developed model of the energy system. Most of the models have a payback period lower than 10 years with an energy saving varying from a minimum of 0.1 kJ up to 0.198 kJ. If the payback period increases, the energy saving increases too.

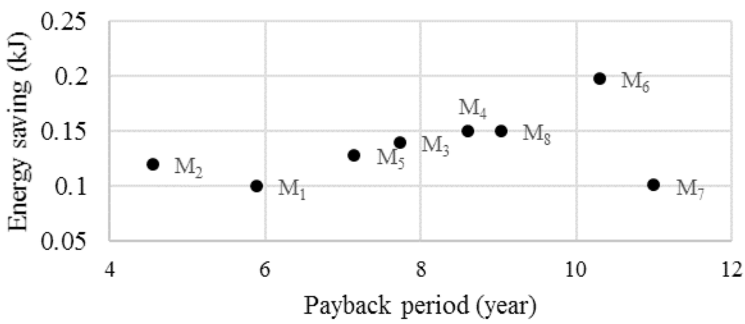

Fig. 3. Trade-off evaluation between the payback period and the energy saving.

Finally, the COE ranges from a minimum of 10 c€/day considering the fourth model up to a maximum of 75 c€/day considering the eighth model. Globally, by taking into consideration both the P_b and the COE, the most efficient production model is determined using the second proposed model with 10 production cycles and Δt_1 and Δt_2 of 0.15 s.

5. Conclusions

In this study, the inverter technology is incorporated within an energy system to assess the energy consumption of production machines. The comparison of the simulation results shows the efficiencies of the system in terms of the energy consumption and cost. Results highlight that the incorporation of the inverter can significantly increase the efficiency of an industrial system by adjusting the distribution of the energy demand. In addition, when the inverter is used, the distribution of the inverter power output based on the energy demand function plays a significant role in lowering the energy consumption and decreasing the cost of the system. The economic evaluation shows that the optimum system having the least payback period is the one which uses a square wave step function on a rectangular basis with 10 production cycles and interval values of 0.15 s. The energy saving and energy consumption using this configuration are estimated to be 0.12 kJ and 0.08 kJ, respectively.

This study has several practical implications. By adopting the optimum decision variables for the inverter modulation and its power output, it is possible to propose the most appropriate model of inverter and its configuration by considering different distribution functions. The analysis of the inverter model of power output is not limited to the distribution functions discussed in the present paper and can take into account a wider range of model structures in next research steps. On the other hand, achieving the optimum configuration of the inverter model can be beneficial for industrial experts to adopt more effective strategies during a decision-making process by designing and establishing environmentally friendly and energy efficient industrial machines.

The application of the current research provides useful and significant insights for the design and operation of hybrid energy systems which utilize the inverter together with another source of energy for meeting electricity demand. It could also be used in probabilistic energy flow simulations and optimization process using different distribution functions and by considering power consumption/production data.

Further research has to investigate more complex structures for the distribution functions by taking into consideration the power consumption and production patterns associated with the energy demand. Additionally, different types of energy systems can be integrated to the inverter to assess and compare their effectiveness in terms of energy saving and cost.

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