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Optimal Design of a Direct-Drive Permanent Magnet Synchronous Generator for Small-Scale Wind Energy Conversion Systems

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This paper presents an optimal design of a direct-drive permanent magnet synchronous generator for a small-scale wind energy conversion system. An analytical model of a small-scale grid-connected wind energy conversion system is presented, and the effects of generator design parameters on the payback period of the system are investigated. An optimization procedure based on genetic algorithm method is then employed to optimize four design parameters of the generator for use in a region with relatively low wind-speed. The aim of optimization is minimizing the payback period of the initial investment on wind energy conversion systems for residential applications. This makes the use of these systems more economical and appealing. Finite element method is employed to evaluate the performance of the optimized generator. The results obtained from finite element analysis are close to those achieved by analytical model.

Keywords : permanent magnet synchronous generator, direct-drive, wind energy conversion system, optimization, genetic algorithm, payback period

1. Introduction

Future energy demands and global warming caused by increasing environmental pollution call for the use of renewable energy resources. Renewable energy resources make up a very small share of the total electrical energy production in Iran [1, 2]. Recently, small-scale wind energy conversion systems (WECSs) increasingly are being used in either on-grid or off-grid applications [3, 4]. Permanent magnet synchronous generators (PMSG) are widely used in small-scale wind power generation because of their high efficiency, high power factor, and enhanced power density [5-7]. They do not need separate excitation and cooling systems and they require less maintenance in comparison with electrically excited synchronous and induction generators [8]. The design optimization of PMSGs for wind power generation has been proposed in several studies so far. Different objectives have been considered for the optimization of PMSGs. Improvement of annual energy output is considered as an objective function in optimal design of a direct-drive PMSG [9, 10]. Loss minimization and efficiency improvement are also of concern to some researchers [11, 12]. In this paper, a design optimization is presented to minimize the cogging torque in a surface-mounted PMSG [13]. A double-layer permanent magnet dual-mechanical port machine is also proposed and optimized for an improved output torque performance [14].

Since the economic aspects of small-scale WECSs is one of the most important issues for customers, this paper proposes the payback period as an objective function in optimization procedure. A region with relatively low wind-speed is selected as a model to incorporate site matching in the design optimization of the generator. Analytical models of the PMSG and the wind turbine are presented. Cost models for different parts of WECS are then suggested and used to calculate the economic aspects of the system (i.e., the present worth and payback period considering interest and energy inflation rates). The genetic algorithm (GA) method is then applied to the model to optimized generator parameters aimed to minimize the payback period of the initial investment. Finite element method (FEM) is finally carried out to validate the performance of the optimal designed PMSG.

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2. Modeling of Wind Energy Conversion System

2.1. Wind turbine model

A three-blade horizontal-axis wind turbine is selected along with a direct-drive system to avoid the cost and maintenance of a gearbox [15]. Therefore, the output of the wind turbine directly transmitted to the generator shaft is given by:

$$P_{shaft} = \frac{1}{2}\rho_{air}\pi R^3 U^2 C_\rho(\lambda)\,\omega_r \tag{1}$$

where ρ_{air}, R, U, C_ρ, λ, and ω_r are density of air, blade radius, wind speed, turbine power coefficient, tip speed ratio, and angular frequency of the shaft, respectively. The tip speed ratio is given by:

$$\lambda = \frac{\omega_r R}{U} \tag{2}$$

Therefore, the shaft torque can be determined as [15]:

$$T_{shaft} = \frac{P_{shaft}}{\omega_r} = \frac{1}{2}\pi R^3 U^2 C_T(\lambda) \tag{3}$$

where $C_T = C_p/\lambda$ is the torque coefficient of the turbine. It is shown that there is an optimal value for tip speed ratio in a wide-speeds range maximizing the torque coefficient [16]. The characteristics of the wind turbine used in our research are listed in Table 1. Recent investigations show that the average wind speeds in most regions of Iran are relatively low [17]. It is also shown that small-scale WECSs are feasible and recommended in places like Shahrbabak in the Kerman province of Iran, for example, where the average wind speed is around 5.3 (m/s) [18]. Therefore, our system is designed for regions with average wind speeds of around 5.5 (m/s).

2.2. Permanent magnet synchronous generator model

A three-phase radial flux configuration is selected for PMSG. The numbers of poles and slots are determined through a design optimization procedure. The rms value of the fundamental component of phase excitation voltage in PMSG is given by [16]:

$$E_f = 4.44\, f N_{ph} k_{w1} \varphi_{PM} \tag{4}$$

where f, N_{ph}, and k_{w1} are the electrical frequency of the generator, the number of winding turns per phase, and the fundamental harmonic winding factor, respectively. Also φ_{PM} stands for the flux per pole due to the magnet first harmonic flux density, which is determined as [16]:

$$\varphi_{PM} = \frac{8}{\pi^2}\tau L B_{mg}\sin\left(\frac{\sigma\pi}{2}\right) \tag{5}$$

where τ, L, B_{mg}, and α are the pole pitch, the stack length, the air-gap magnet flux density, and the pole arc to pole pitch ratio, respectively. The air-gap magnet flux density is obtained using the magnetic equivalent circuit (MEC) of the machine. Therefore, the magnet pole dimensions are determined by (5) and the MEC of the machine. The main dimensions of the generator as a function of output power are given by [16]:

$$D^2 L = \frac{2\varepsilon P_{gen}}{k_{w1} n_s \pi^2 SEM_{pk} SEL_{pk} \cos\phi} \tag{6}$$

where D, ε, n_s, SEM_{pk}, SEL_{pk}, and $\cos\phi$ are the air-gap diameter, the excitation induced voltage to terminal voltage ratio, the synchronous speed, the specific magnetic loading, the specific electric loading, and the estimated power factor of the generator, respectively. We calculate the generator main dimensions by selecting the ratio of air-gap diameter to stack length. The specific magnetic loading is equal to the value of the fundamental component of air-gap magnetic flux density due to permanent magnets, and the specific electric loading is determined as [16]:

$$SEL_{pk} = \sqrt{2} h_s K_{sf} J\left(1 - \frac{w_t}{\tau_s}\right) \tag{7}$$

where, h_s, K_{sf}, J, w_t, and τ_s are the slot height, the slot fill factor, the current density, the tooth width, and the slot pitch, respectively. The stator slots dimensions, finally, are determined by (7). Current density is kept constant at a relatively low value of 4 A/mm^2 to prevent complex cooling system.

Table 1. Turbine characteristics.

Turbine characteristics	Value
Cut-in speed	3.5 m/s
Nominal turbine speed	5-10 m/s
Cut-off speed	20 m/s
Average wind speed	5.5 m/s
$C_{p\text{-}opt}$	0.39
λ_{opt}	6.0

3. Economic Calculations

3.1. Cost model

The payback period of initial investment is selected as the objective function in the optimization problem. Therefore, it is necessary first to determine the initial investment and annual income. The initial investment is the total cost of generator, turbine, control system, power electronics converters, and also tower and installation costs, which is calculated as:

$$C_t = (C_{PM} + C_{lam} + C_{cu})k_m + C_{tur} + C_p + C_i \quad (8)$$

where C_{PM}, C_{lam}, C_{cu}, k_m, C_{tur}, C_p, and C_i are the cost of permanent magnet materials, the cost of laminations, the cost of copper windings, the manufacturing cost coefficient containing the cost of the frame and other parts of the machine, the cost of the turbine, the cost of power electronic convertors and control system, and the cost of installation, respectively.

The cost of the generator depends on the volume of consumed material. The base costs of raw materials used in this paper are listed in Table 2. The cost of the power electronics converter is assumed to be constant because of the constant output power. The turbine cost depends on the blade diameter and is modeled by a cost function as [19]

$$C_{tur}(D) = 0.8C_T(7)\left(0.9\left(\frac{D}{7}\right)^3 + 0.1\right),$$

where $C_T(7)$ is the total cost for a baseline turbine with a 7-meter-blade diameter.

The installation costs and the cost of the control system are also assumed to be constant during the optimization procedure. Costs of different parts of the system are presented in Table 2.

3.2. Payback-period calculation

The annual price of electrical energy produced by WECS is given by:

$$S = AEO*C_E \quad (9)$$

where AEO and C_E are the annual energy output and the cost of energy, respectively. The annual energy output is given by [15]:

$$AEO = \sum_{i=1}^{n} P(U_i)H(U_i) \quad (10)$$

where $P(U_i)$ is the output power of the wind generator at the speed of U_i. Also $H(U_i)$ is the total number of hours per year in which the wind speed is U_i and given by:

$$H(U_i) = 365 \times 24 \times f(U_i)\Delta U \quad (11)$$

where $f(H_i)$ is the probability density function for a wind with a speed of U_i. In this paper, the Rayleigh distribution function has been selected for wind-speed prediction [16].

Assuming n as the effective lifetime for the system, the present worth of energy generation in the total lifetime is given by [20]:

$$PW = C_t\left[\frac{1-(1+j)^n(1+i)^{-n}}{i-j}\right] \quad (12)$$

where i and j are the interest rate and the inflation rate of energy cost, respectively. The payback-period time is equal to the value of n when the present worth is equal to initial investment as [20]:

$$t_p = \frac{\ln\left[1 - \frac{C_t(i-j)}{S}\right]}{\ln\left[\frac{1+j}{1+i}\right]} \quad (13)$$

4. Parameters Study

In this section, the effects of four generator design parameters on the payback period of WECS are investigated. Selected design parameters with their variation boundaries are listed in Table 3. Some of the other generator parameters are kept constant during these analyses, which are presented in Table 4.

Effects of the specific current loading and the number

Table 2. Costs of different parts of system.

Parts and materials	Cost
cooper	10 $/kg
magnet	80 $/kg
lamination	2 $/kg
Turbine with 7-m diameter	2000 $
Control system	800 $
Power electronics convertors	1500 $
Tower and installation	2000 $

Table 3. Design variables and their boundaries.

Design parameters	Boundary	Unit
Nominal turbine speed	5-10	m/s
Number of pole pairs	2-10	–
Specific electrical loading	10-100	kA/m
Stack length to air-gap diameter ratio	0.1-1.5	–

Table 4. Design constants.

Design parameters	Value	Unit
Nominal voltage	250	v
Nominal output power	3500	watt
Number of slots per pole per phase	2	–
Winding current density	4	A/mm^2
Magnet arc angle	150	Electrical degree
Air-gap length	0.5	mm
Slot opening	1	mm

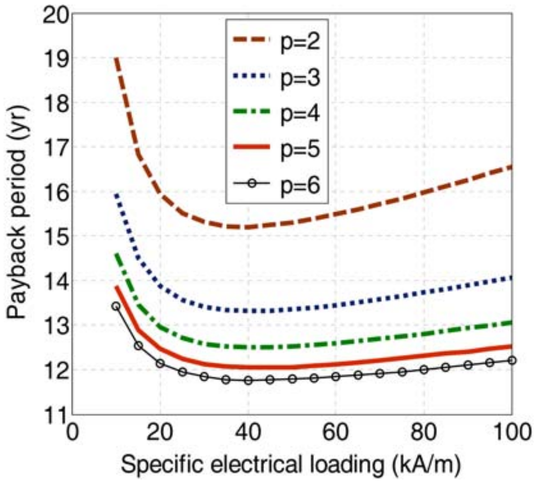

Fig. 1. (Color online) Effects of specific electrical loading and number of pole pairs on payback period.

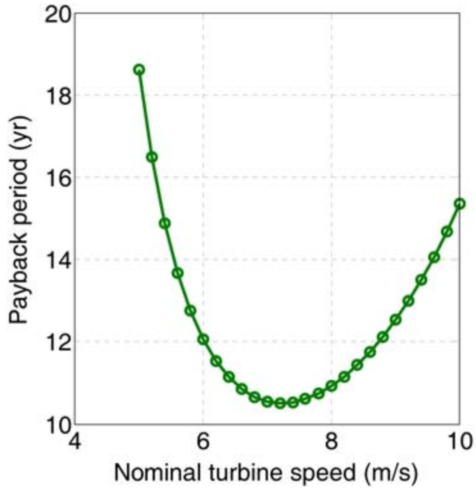

Fig. 3. (Color online) Effect of nominal turbine speed on payback period.

of pole pairs on the payback period of a wind energy conversion system are shown in Fig. 1. It is shown that a higher number of pole pairs significantly reduce the payback period. Therefore, the highest number of pole pairs, which is limited by minimum teeth-width, is selected for the optimal generator. It is also observed that, an increase in specific electrical loading decreases the payback period initially. However, the payback period does not considerably change afterwards, and eventually it undergoes a gradual increase. Therefore, an optimal value for the specific electrical loading exists and should be determined during the optimization procedure.

The effect of length to diameter ratio on the payback period is also shown in Fig. 2. It is shown that there is also an optimal value for this ratio minimizing the payback period. This value is around 0.6, but it varies with a

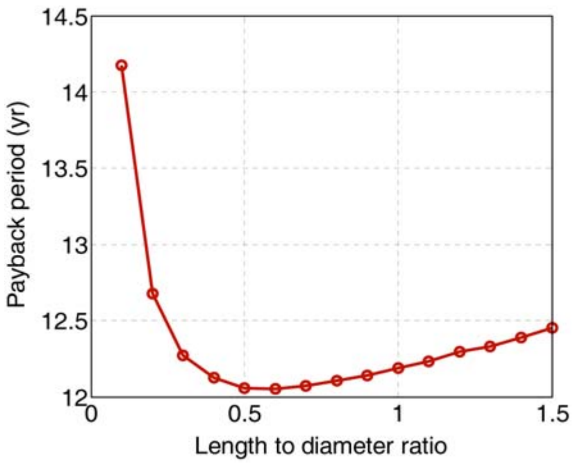

Fig. 2. (Color online) Effect of length to diameter ratio on payback period.

change in other parameters and should be optimized during an optimization program, considering the variation of other design variables. It is observable that the payback period significantly increases for smaller ratio values. However, higher ratio values lead to a gradual increase in the payback period. Finally, the effect of the nominal turbine speed in which the generator produces its nominal output power is investigated in Fig. 3. It is shown that the payback period reaches its minimum value for a specific value of the nominal turbine speed. This optimal value is approximately 7.5 m/s, though it greatly depends on the average wind-speed of a selected site. Therefore a kind of site matching analysis is presented, showing that an optimal design of generator parameters is needed to reach the shortest payback period for the WECS.

5. Optimization Method

GA is a random search technique to find a global optimal solution in a complex multidimensional search space. A real-code GA method is employed to optimize the generator design parameters. Four generator parameters (e.g., the number of pole pairs, the air-gap length to diameter ratio, the nominal turbine speed, and the specific electrical loading) are selected as a design, with boundaries listed in Table 3. Some design constraints presented in Table 5 are also applied to the optimization in order to have a realistic design.

The payback period obtained in the previous section is selected as a fitness function in the GA program. Evolution of fitness function of the best individual obtained by GA is illustrated in Fig. 4. It is observed that, the payback period for optimal design is less than 10 years for the

Table 5. Design constraints.

Parameters	Value	Unit
Tooth width	>5	mm
Permanent magnet height	> 2	mm
Outer stator diameter	< 0.3	m
Number conductor per slots	> 20	–

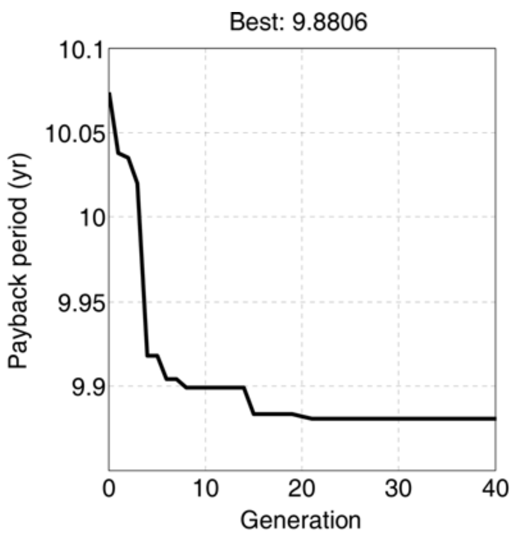

Fig. 4. Fitness function evolution of the best individual during GA generations.

Table 6. Optimal design characteristics.

Parameters	Value	Unit
Nominal turbine speed	7. 522	m/s
Number of pole pairs	10	–
Specific electrical loading	50633	kA/m
Stack length to air-gap diameter ratio	0.766	–
Annual output energy	11.433	MWhr
Total system cost	6852	$
Payback period	9.88	yr
Present worth of system	12119	$
Present worth to initial cost ratio	1.93	–
Leakage inductance	11.5	mH
Magnetizing inductance	62.1	mH
Stator winding resistance	4.7	ohm

Table 7. Optimal generator dimensions.

Parameters	value	Unit
Blade diameter	7.2	m
Air-gap diameter	0.208	m
Axial length	0.162	m
Stator outer diameter	0.298	m
Magnet height	3	mm
Conductors per slot	71	–
Inner rotor diameter	0.185	m
Tooth width	5.5	mm

annual interest rate of 6% and the annual energy inflation rate of 3%. The optimal payback period is smaller than half of the total lifetime of the wind turbine, which is about 20 years. The present worth of WECS is around $12,199, which is more than 1.76 times of the initial cost of the system. It is notable that this system is designed for a region with relatively low wind-speed and with low-cost electrical energy. Therefore, the payback period decreases considerably for regions with the high wind-speed and higher electrical energy costs. Optimal values of design parameters and the performance characteristics of the optimal generator are presented in Table 6. The dimensions of the optimal generator are also presented in Table 7.

6. Finite Element Analysis

In this section, the FEM is employed to evaluate the performance of the optimal PMSG. The local saturation, cross magnetization, and flux leakages, which are neglected in analytical model, are considered in FE analysis. A commercial software FLUX2D is used for FE analysis. Magnetic laminations with the grade of M800 are used in the rotor and the stator. Neodymium iron born material

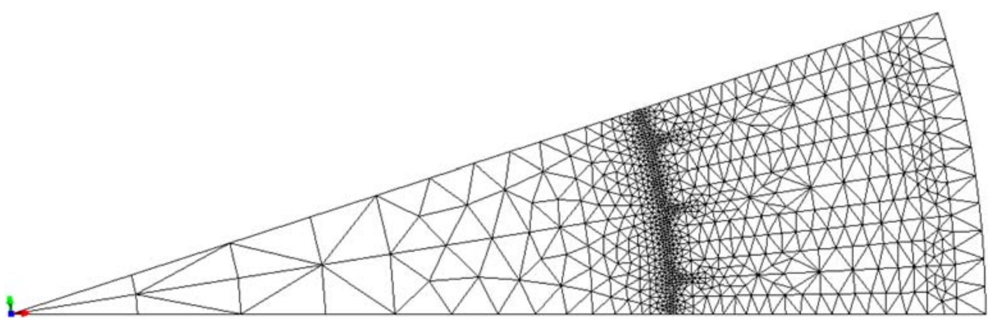

Fig. 5. (Color online) Meshed model of optimal PMSG.

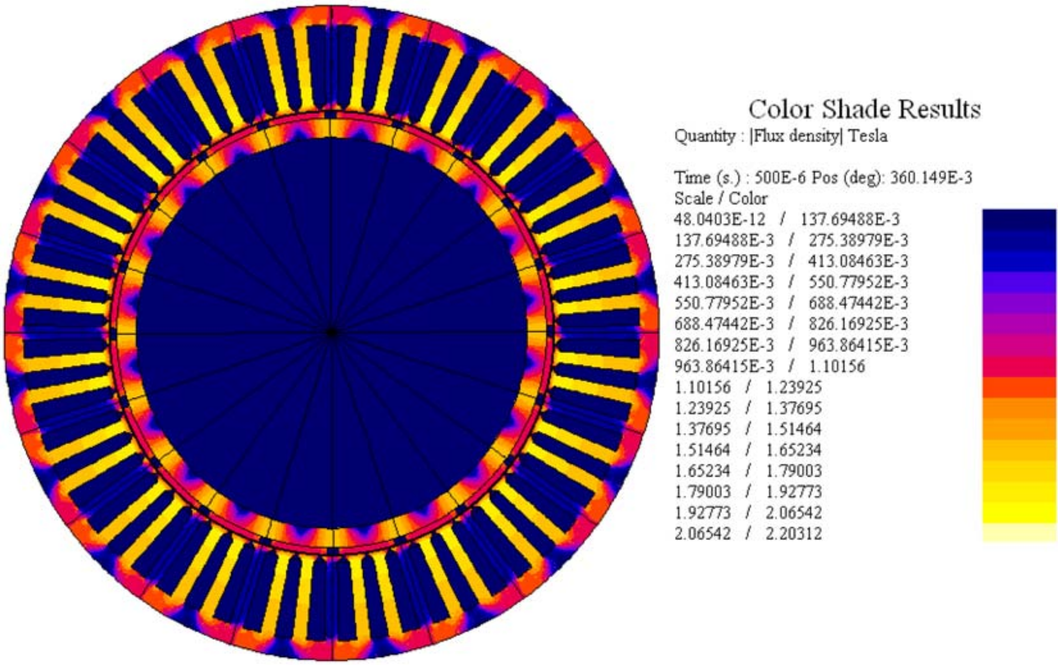

Fig. 6. (Color online) Magnetic flux distribution of the optimal PMSG in no-load condition.

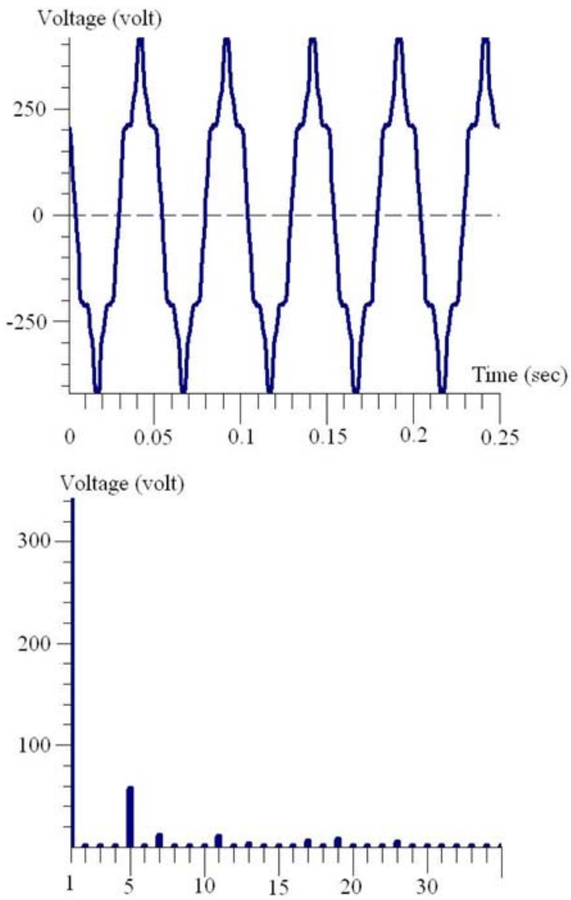

Fig. 7. (Color online) Excitation voltage of the optimal PMSG and its harmonic contents.

with the grade of N45 with 1.3 (T) residual flux density and the maximum working temperature of 150 degrees centigrade is also selected as permanent magnets material. Thanks to the symmetry, only one pole of the machine is analyzed. Therefore, the analysis domain is reduced to 1/10 of the whole model, resulting in a considerable reduction in computation time. The meshed model of one pole piece of the generator containing 1665 rectangular elements is depicted in Fig. 5.

The magnetic flux distribution of the generator due to the permanent magnets is illustrated in Fig. 6. It is shown that the flux densities in different parts of the generator are in a normal range that is close to the values obtained by analytical calculations. The excitation voltage of generator due to the permanent magnets, as well as its harmonic contents, is also depicted in Fig. 7. It is observable that the fundamental component of the voltage is around 245 volts, which is close to its analytical value. Also, the waveform has a 5th harmonic component, approximately 17% of that of the fundamental component. However, the output voltage of the generator is rectified, and therefore it does not have adverse effect on power quality.

Further, this harmonic can be reduced by adjusting the stator slots opening.

7. Conclusion

An optimal design of a permanent magnet synchronous generator for a grid-connected small-scale wind power conversion system is presented. Analytical models of the turbine and the generator, along with a cost model for different parts of the system are derived. Economic aspects of wind energy conversion system WPES, such as present worth and payback period considering interest and inflation rates in the typical lifetime of the system are analyzed, and the effects of four generator design parameters are investigated. An optimization procedure based on GA method is then employed to optimize design parameters, minimizing the payback period for a region with relatively low wind-speed. It is shown that the present worth of optimal WECS with a typical 20-year lifetime is around 1.72 times of the initial investment with 6% of the annual interest rate and 3% of the annual energy inflation rate. Therefore, the payback period is around 9.9 years, which is less than half of the total lifetime. FEM is finally carried out to evaluate the performance of optimal PMSG confirming the validation of the analytical model and design optimization.

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