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Kana Padinharu, D.K., Li, G.-J. orcid.org/0000-0002-5956-4033, Zhu, Z.Q. et al. (3 more authors) (2024) Comparison of direct-drive vernier wind generators for potential use at ≥10MW power level. IET Electric Power Applications, 18 (10). pp. 1279-1292. ISSN 1751-8660

https://doi.org/10.1049/elp2.12477

Received: 18 April 2024 | Revised: 20 June 2024 | Accepted: 1 July 2024

DOI: 10.1049/elp2.12477

IET Electric Power Applications

ORIGINAL RESEARCH

Comparison of direct-drive Vernier wind generators for potential use at ≥10 MW power level

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Funding information

Engineering and Physical Sciences Research Council, Grant/Award Number: EP/R004900/1

Abstract

This paper investigates the benefits and challenges of the multi-MW direct-drive offshore wind Vernier generators. It is worth noting that the comparison of generator topologies presented in ref. [1] was for the same power level and therefore a reduced machine volume for the surface-mounted permanent magnet Vernier (SPM-V) generators. This would mainly impact the capital expenditure (CAPEX) cost between the different investigated machines. Whereas in this paper, the performance is compared for the same machine volume that allows the Vernier generators to produce a much higher energy yield than a conventional SPM generator. As the extra energy yield would be beneficial over the lifetime of the turbine, this will have a bigger impact than the CAPEX cost savings with a reduced machine volume. In addition, a novel Vernier machine with magnets on both the stator and rotor has been proposed to further improve the energy yield. In addition to the basic electromagnetic performance, the levelised cost of energy (LCOE) of the three generator topologies, that is, the conventional SPM, SPM-V and the proposed Vernier machines, has been compared. The direct-drive powertrain systems with SPM-V and the proposed Vernier generators can achieve LCOE of 12.3% and 24% lower than that of the conventional SPM generators, indicating their huge potential as an alternative to reduce the overall cost of energy.

KEYWORDS

electric generators, electric power generation, machine theory, permanent magnet generators, permanent magnet machines, wind power

1 | INTRODUCTION

The offshore wind sector has seen a rapid annual growth by around 24% since 2013. And in 2019, the total contribution from offshore wind towards the global wind market is 10% and this figure is expected to double by 2025 [2]. There is an increasing trend of adopting fewer but larger wind turbines (≥10 MWs) rather than using more but smaller wind turbines to achieve the same power level. This can significantly reduce the tower and foundation as well as installation costs, which help to drive down the levelised cost of energy (LCOE) and make the offshore wind power even more competitive against fossil fuel alternatives. Direct-drive permanent magnet (PM) machines have been widely regarded as one of the most suitable candidates for large offshore wind generators thanks to their high torque and power density and high efficiency [3]. Without gearboxes, both the transmission losses and the failure rates of the drivetrain system can be significantly reduced [4, 5]. In addition, the high power density feature of the PM generator is very desirable for offshore wind applications. This is because, for the same power level, lighter generator helps to reduce the top head mass, resulting in reduced tower and foundation masses and costs. In the past decades, continued efforts have been made to improve the power density of PM machines by developing some unconventional machine topologies such as transverse flux PM machines [6] and partitioned stator PM machines (magnetically geared machines with dual airgaps) [7] etc. These machines, although can achieve significantly improved torque/power density, often have complicated mechanical structures. This increases their manufacturing costs and reduces their reliability and hence impedes their penetration into the offshore wind sector.

The surface-mounted permanent magnet Vernier (SPM-V) machines [see Figure 1b], based on the same principle of magnetically geared machines [8], also have much higher torque/power density than conventional SPM machines [see Figure 1a] but with comparable efficiency [1, 9]. In addition, different from the transverse flux PM machines and partitioned stator PM machines, the SPM-V machines often have a very simple machine structure, just like the SPM machines (but with higher rotor pole numbers). This simple machine structure combined with high power density makes them ideal for offshore wind power applications. However, due to large leakage inductances, the Vernier machines, particularly the high power ones, often have low power factor [10–12]. As a result, from a drivetrain (generator + converter) point of view, their poor power factors significantly increase the power converter ratings and thereby the overall system cost. Moreover, the poor converter efficiency reduces the overall system-level efficiency that can negatively impact the SPM-V machine's overall drivetrain system performance [1, 13]. However, if the extra power output from the Vernier generators is significant enough to offset the power losses in the whole drivetrain system and generate a much higher energy yield, they can still be a promising alternative. It is worth noting that the high power generation in Vernier machines comes as a trade-off with higher machine cost and mass, which will be discussed in detail in this paper.

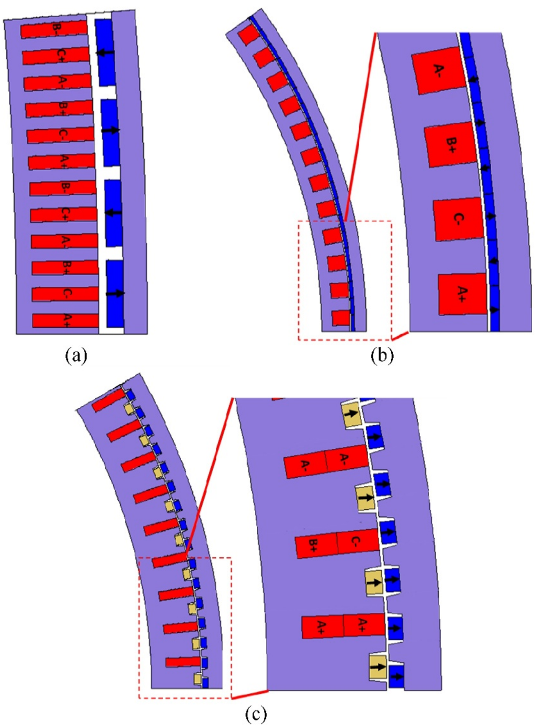

FIGURE 1 Comparison of the 2D models (2 pole pair) of the investigated machines. (a) Conventional SPM machine, (b) SPM-V machine, and (c) proposed Vernier machine.

In previous studies, it is found that the SPM-V machines exhibit better torque performance towards lower slot/pole numbers because of their lower inter-pole PM leakage fluxes. But Vernier machines with lower slot/pole numbers are generally massive and more costly than the conventional SPM machines designed with the same machine volume [14]. This is due to their large winding inductance resulting in a higher armature reaction that saturates the machine. Therefore, larger rotor and stator back irons are required to alleviate the saturation and this increases the mass and cost. Similarly, a high armature reaction could cause PM irreversible demagnetisation [14, 15]. Hence, the Vernier machines may require larger PM thickness and can therefore increase the total PM volume and cost of the generator. In addition, higher generator losses from the same machine volume requires a better cooling system. The above challenges can result in increased capital expenditure (CAPEX) cost for the drivetrain systems. Therefore, it will be interesting to investigate if the higher power generation capability and energy yield of the Vernier generators (with the same machine volume as a conventional SPM machine) can offer any benefits over the lifetime of the offshore wind turbine. In other words, can *the Vernier generators achieve lower LCOE compared to the conventional SPM machines*?

This paper will be dedicated to answer this question. For the comparison in this paper, two Vernier topologies have been chosen, that is, the typical SPM-V [see Figure 1b] and a proposed Vernier machine with magnets on both the stator and the rotor [see Figure 1c]. They are compared based on the LCOE and benchmarked against the conventional SPM generator [see Figure 1a]. LCOE is a measurement widely used to assess and compare different methods of energy production. A 10 MW direct-drive generator presented in ref. [16] has been chosen for this investigation. The step-by-step approach adopted for the comparison in this paper is given below.

- Calculation of annual energy production (AEP) using power curve [16], wind speed distribution (Weibull curve), generator losses (2D finite element analysis—FEA) and converter losses (analytical model).
- Calculation of CAPEX and operation cost by considering the main components such as direct-drive generator, power converters, tower, foundation, turbine blades, nacelle cover, hub etc.
- Calculation of LCOE for the lifetime of the turbine (20 years) and comparing the selected generator topologies.

2 | WIND TURBINE CHARACTERISTICS AND MODELLING

The main characteristics of the 10 MW conventional SPM generator used in this paper are shown in Table 1. These are similar to those presented in ref. [16].

TABLE 1 10 MW Wind turbine characteristics.

Wind turbine characteristics [16]	
Rated power (MW)	10
Rotor diameter (m)	170
Rated wind speed (m/s)	12
Rated rotor speed (rpm)	10
Optimum tip speed ratio - λ	9.5
Maximum aerodynamic rotor efficiency (%)	51.5
Density of air (kg/m^3)	1.225
Mass, cost and loss models for system-level analysis [14, 17]	
Density of steel core (kg/m^3)	7650
Density of magnet, NdFeB (kg/m^3)	7400
Density of copper (kg/m^3)	8940
Cost of steel core (€/kg)	2.5
Cost of magnet, NdFeB (€/kg)	50
Cost of copper (€/kg)	15
Cost of structural steel (€/kg)	2
Cost of generator side converter (€/kVA)	20
Cost of grid side converter (€/kVA)	20
Converter loss at rated power (%)	3

The amount of shaft power (P_{sh}) available using these characteristics can be calculated as follows:

$$P_{sh} = \frac{1}{2}\rho_{air} C_p(\lambda, \theta)\pi r^2 v_w^3 \quad (1a)$$

where ρ_{air} is the density of air, r is the wind turbine rotor radius, v_w is the wind speed and $C_p(\lambda, \theta)$ is the power coefficient or the aerodynamic efficiency. C_p is a function of the tip speed ratio (λ, ratio of the tip speed to wind speed), and a typical variation of C_p with λ is shown in Figure 2 [18]. This variation depends on the shape of the used blades and there is an optimal λ where C_p is maximum. For this study, the maximum value of C_p is 0.515 at an optimal λ value of 9.5 [16] as quoted in Table 1. Below the rated wind speed, λ is maintained constant at this optimal value to obtain the maximum energy yield. This would mean that the rotor speed is proportional to the wind speed. Above the rated wind speed, the rotor speed is kept constant to the rated speed of 10rpm to limit the turbine output power. This is generally done by reducing the C_p using pitch control. The variation of the turbine rotor speed with wind speed is shown in Figure 3. The shaft power from (1a, 1b) needs to be corrected for the specific blade design for the augmented lift due to rotation [16] and the final shaft power curve is shown in Figure 4.

For the calculation of energy yield, a Weibull distribution with an average wind speed of 10 m/s and a shape factor, k = 2.3, is used, as shown in Figure 5. The integration of the area under the Weibull distribution curve will be equal to 1. This frequency distribution curve gives information about how often the wind blows and with what strength.

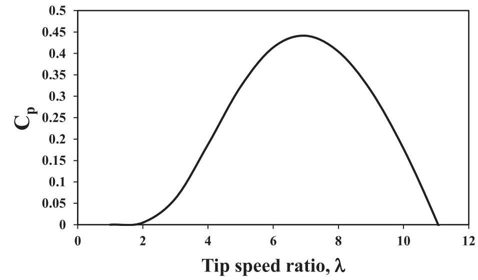

FIGURE 2 Typical variation of power coefficient (C_p) with the tip speed ratio (λ).

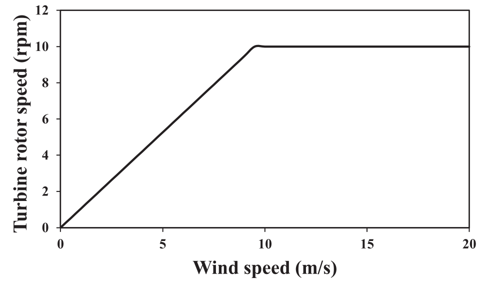

FIGURE 3 Variation of turbine rotor speed with wind speed.

3 | DESIGN OF CONVENTIONAL AND VERNIER MACHINES

3.1 | Features of the investigated generators

The 2D cross-sections of the three machine topologies investigated for this study are shown in Figure 1 and the open-circuit flux line distributions of these machines are shown in Figure 6. The key parameters of the 10 MW conventional SPM machines, that is, the outer diameter, the stack length and the rotor speed, are the same as that presented in ref. [16]. It is worth noting that the investigated designs of both the conventional SPM and the Vernier machines are globally optimised for maximum torque and they all have an outer rotor topology.

For a fair comparison between the machines, the outer rotor diameter and the stack length are maintained the in same way. Moreover, to ensure similar thermal performance between the machines, the copper loss per surface area of the stator slot wall is kept the same. The key parameters of the optimised conventional SPM machine are highlighted in Table 2. Vernier machines can be designed with different gear ratios and slot/pole number combinations. The study performed for the 10 MW SPM-V machine with G_r = 5, discussed in ref. [1], has been used here to select an optimal slot/pole number for the SPM-V machine. The summary of the performance comparison for different slot/pole number combinations is shown in Table 3.

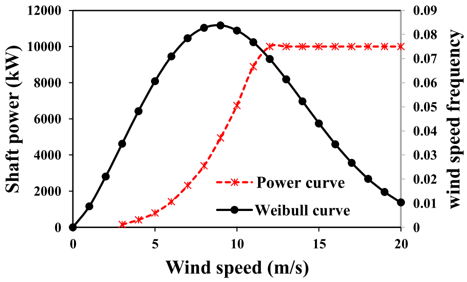

FIGURE 4 Variation of shaft power and wind speed frequency distribution (Weibull curve) with wind speed.

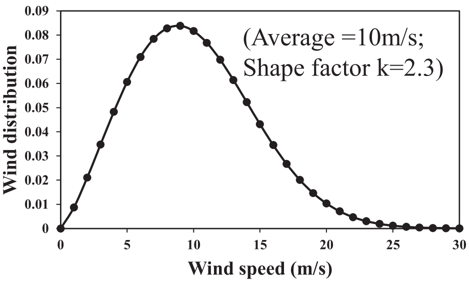

FIGURE 5 Weibull distribution curve with an average wind speed of 10 m/s and a shape factor, k = 2.3.

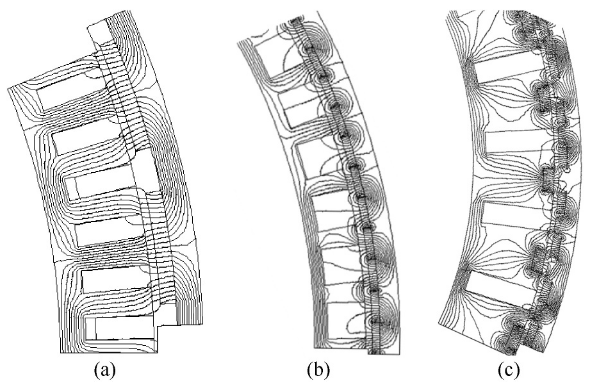

FIGURE 6 Open-circuit flux line distribution of (a) Conventional SPM, (b) SPM-V, and (c) proposed Vernier machines.

TABLE 2 Key parameters of 10 MW conventional SPM and Vernier machines.

	Conventional SPM	SPM-V	Proposed Vernier
Rated speed (rpm)		10	
Outer diameter (m)		10	
Airgap length (mm)		10	
Stack length (m)		1.8	
Gear ratio	1	5	8
Frequency (Hz)	26.66	16.66	32
Magnet volume (m^3)	0.92	1.71 (+86%)	1.84 (+100%)
Phase current (Arms)	8973	21,990	44,278
Electrical loading (AT/mm)	54.8	46.2	44.8
Turns/phase	32	11	6
Copper loss per stator slot wall area (kW/m^2)		0.45	
Copper loss (active length, kW)	137.5	48.5	56
Power output (MW)	10	14.9	20.45
Torque output (MNm)	9.56	14.24	19.55
Power factor	0.95	0.59	0.4
Cogging torque (%)	15	7	0.48
Torque ripple (%)	18	8.2	3.5
Generator efficiency (%)	97.75	98.5	98
Generator active mass (Ton)	63	174	246
Total generator mass (Ton)	309	426.5	492
Power density (MW/Ton)	0.032	0.035	0.042
Specific power (MW/m^3)	0.071	0.105	0.145
Torque density (MNm/Ton)	0.031	0.033	0.040
Specific torque (MNm/m^3)	0.068	0.101	0.138
Generator cost, active material (k€)	539	914.5	1381

The slot/pole number combination $Z = 240$, $P_r = 200$, and $P_r = 40$ is optimal in terms of power factor, efficiency, torque to mass and torque to cost. However, $Z = 120$, $P_r = 100$, and $P_r = 20$ has much higher torque capability with similar torque to the cost ratio as $Z = 240$, $P_r = 200$, and $P_r = 40$. Moreover, the power factor and efficiency are not much compromised. Since the energy yield of the turbine is largely driven by the output power, the SPM-V machine with the slot/pole number $Z = 120$, $P_r = 100$, and $P_r = 20$ is chosen.

Unlike the conventional SPM and the SPM-V machines, the minimum gear ratio possible for the proposed Vernier machine is 11 with single-layer integer slot windings. Such a high gear ratio could mean a very low power factor. The previous studies have shown that the power factor of multi-MW Vernier machines with $G_r = 5$ is very poor (~0.4–0.5). Moreover, the risk of irreversible demagnetisation is also high at this G_r specifically for lower slot/pole number designs. Further, increasing the gear ratio to 11 will only worsen the performance. Hence, a double layer winding configuration is adopted for the proposed Vernier machine [as shown in Figure 1c] which allows for reducing the gear ratio to a lower value of 8. A higher slot/pole number, that is, $Z = 216$, $P_r = 192$, and $P_r = 24$, is chosen for the proposed Vernier machine because of its higher torque capability than the SPM-V machine for the same gear ratio. And a higher slot/pole number also reduces the risk of potential irreversible demagnetisation.

The key parameters of the final optimised designs are compared in Table 2. The series turns/phase of the stator winding for the investigated machines is adjusted to limit the

TABLE 3 Performance comparison of Spm-V machine with different slot/pole number combinations ($G_r = 5$).

Slot/pole number	E_{Ph-PU}	$Torque_{PU}$	Power factor	Torque/mass	Torque/cost	Efficiency
$Z = 72, P_r = 60, P_s = 12$	1.7	1.56	0.33	0.43	0.89	97
$Z = 120, P_r = 100, P_s = 20$	1.6	1.55	0.42	0.72	1.15	97.7
$Z = 240, P_r = 200, P_s = 40$	1.26	1.25	0.47	0.95	1.14	97.9
$Z = 360, P_r = 300, P_s = 60$	0.99	0.98	0.43	0.84	0.93	97.7
$Z = 480, P_r = 400, P_s = 80$	0.78	0.77	0.4	0.66	0.76	97.6
$Z = 960, P_r = 800, P_s = 160$	0.33	0.33	0.14	0.35	0.43	92.8

Note: (1) E_{Ph-PU}—Normalised EMF with conventional SPM machines EMF as the baseline reference; (2) $Torque_{PU}$—Normalised torque with conventional SPM machines torque as the baseline reference.

terminal voltage near to 690V. Since the Vernier machines have relatively higher operating frequency and higher phase winding inductance, their series turns/phase for the same terminal voltage is much lower than the conventional SPM machine. The Vernier topologies are designed with much higher PM volume and reduced electrical loading than the conventional SPM machines to improve their power factor. This also helps to increase the PM thickness and reduce the armature reaction flux which in turn lowers the risk of demagnetisation. For choosing the right PM volume, performances such as torque, power factor and irreversible demagnetisation have been analysed for different PM volumes. The PM volume varies from 100%, that is, 0.92 m^3 used in the existing reference conventional SPM machine, to 200% or 1.84 m^3. For each PM volume, the machines are globally optimised for maximum torque. The variation of the normalised torque with the excess PM volume used is shown in Figure 7a. The torque of the conventional SPM machine with 100% PM volume is the baseline for the evaluation of normalised torque. It can be observed that the Vernier machines can achieve much higher torque than the conventional SPM machine for the same PM volume. The proposed Vernier machine at 100% PM volume can achieve almost 65% and 29% higher torque than the conventional SPM and SPM-V machines, respectively. Moreover, with increasing PM volume, its increase rate of torque is much higher than that of the other two machines.

The variation of power factors with increasing PM volume is shown in Figure 7b. Even with a lower electrical loading compared to the conventional SPM machines, the power factor of the Vernier machines is much lower, which is in the range of 0.3–0.6. However, with increasing PM volume, the Vernier machines exhibit much better power factor improvement capability than the conventional SPM machines. An increase in PM volume by 100% can result in a power factor improvement of 34% and 25% for the proposed Vernier machine and the SPM-V machine, respectively. Whereas this increase is only 2% for the conventional SPM machines.

In most of the analyses discussed in ref. [1], the comparison between the conventional SPM and Vernier machines is performed for the same phase currents and copper loss. However, it is worth noting that the Vernier machines achieve higher torque density at lower slot/pole numbers. For the same copper loss and phase currents, this will result in a much higher

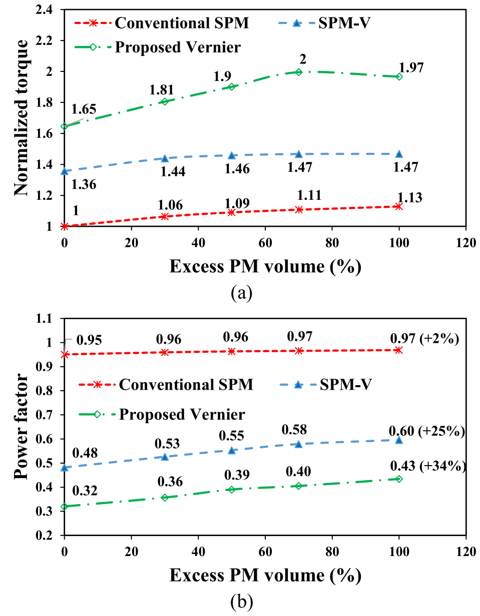

FIGURE 7 Performance comparison with increasing PM volume. Torque of the conventional SPM machine with 0% excess PM volume is the baseline reference for the calculation of normalised torque. (a) Normalised torque, and (b) power factor.

copper loss per stator slot wall area. This in turn indicates that the Vernier machines will be hotter than the conventional SPM machines and therefore needs better cooling strategies. For these reasons, the present investigation is performed for the same copper loss per slot wall area between the machines. The slot wall area includes the three sides of the stator slots that are in contact with the winding insulation through which the heat generated by windings can be dissipated by conduction to the iron core. To achieve the same copper loss/slot wall area as the conventional SPM machines, the Vernier machines are designed with lower electrical loadings and increased stator slot depth. It can be observed from Table 2 that for this operating condition, the copper loss in the Vernier machines is significantly lower than the conventional SPM machines and can increase their efficiency. However, an increased slot depth, a large back iron due to lower slot/pole number and a high PM volume make the Vernier machines bulky, massive and costly. A detailed segregation of mass and cost of each active component of the generator and their performance comparison will be discussed in the next section.

3.2 | Generator electromagnetic performance comparison

The comparison of the torque waveforms and their spectra is shown in Figure 8. It can be observed that the proposed Vernier machine has almost doubled the output torque compared to the conventional SPM machine. Moreover, the torque ripple is also much lower than the conventional SPM and the SPM-V machines. The high torque ripple in these two machines is mainly driven by the cogging torque, which is of sixth harmonic order, as shown in Figure 8b. The comparison of torque ripple and cogging torque is highlighted in Table 2.

For the evaluation of generator efficiency, only the electromagnetic (EM) losses such as the PM eddy current loss, stator and rotor iron core loss and the copper loss have been considered. Although the AC winding losses in Vernier machines are found to be higher, they are assumed to be mitigated using loss reduction techniques as explained in ref. [19]. It is also well established that the Vernier machines often have high PM eddy current loss and hence require PM segmentation. For this study, the rotor PMs of both the SPM-V and the proposed Vernier machines have 4 circumferential segments. In addition, the stator PMs of the proposed Vernier machine have 3 circumferential segments. The number of axial segments for both the stator and rotor PMs is assumed to be 36. Since the conventional SPM machine has low PM eddy current loss, only the axial segmentation (36 axial segments in this paper) of the PMs is considered. The comparison of the EM losses between the conventional SPM and SPM-V machines is shown in Figure 9. It can be observed that the iron core loss in the proposed Vernier machine is much higher than the other two machines resulting in their high total EM losses. But because of their higher torque capability, the efficiency achieved is almost 0.25% better than the conventional SPM machines as shown in Table 2. However, the SPM-V machines could achieve higher efficiency than the proposed Vernier machine by 0.5%. This is mainly due to their significantly lower iron core losses than the proposed Vernier machines. The relatively higher operating frequency (almost double) with similar electrical loading results in a higher iron core loss in the proposed Vernier generator compared to the SPM-V generator.

The comparison of mass and cost of active components of different investigated generators is shown in Figure 10. It can be observed that the higher power generation in the Vernier machines comes with a price such as higher generator mass and cost. The low slot/pole number design for the Vernier machines to achieve higher torque requires larger back irons for the stator and rotor cores. Moreover, to have a similar thermal performance, the stator slot depth and thereby copper volume have to be increased, resulting in an increased mass and cost. Also, a higher PM volume to mitigate the risk of irreversible demagnetisation significantly increases the cost of

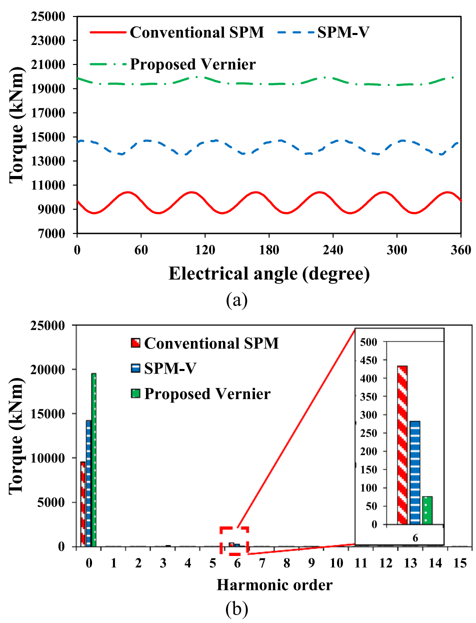

FIGURE 8 Comparison of instantaneous torques between conventional SPM and Vernier machines. (a) Waveforms and (b) spectra.

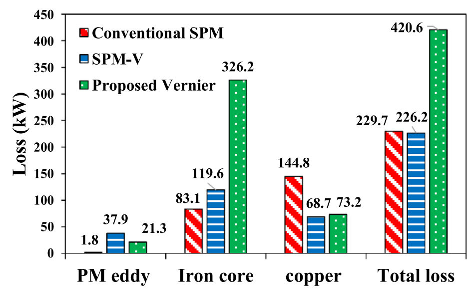

FIGURE 9 EM losses comparison for conventional SPM and Vernier machines.

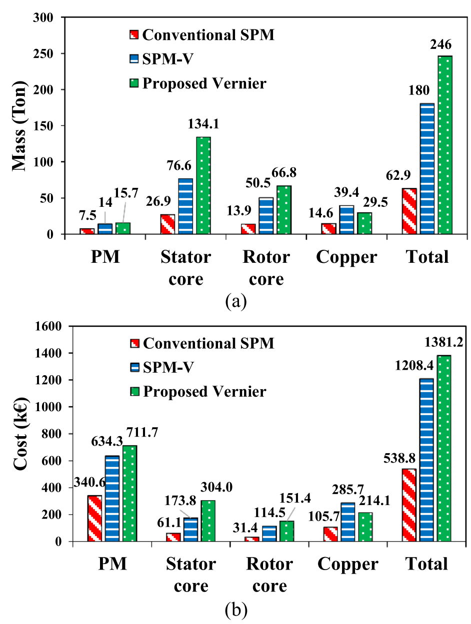

FIGURE 10 Comparison of mass and cost of generator active components between conventional SPM and Vernier machines. (a) Mass (Ton) and (b) cost (k€).

the Vernier machines. The overall masses of the SPM-V and the proposed Vernier machine are almost 3 and 4 times higher than that of the conventional SPM machines, respectively. Whereas the costs of SPM-V and the proposed Vernier machine are 2.25 and 2.5 times higher than that of the conventional SPM machines, respectively.

4 | SYSTEM-LEVEL COMPARISON BASED ON LCOE

Based on the investigations in section III, it is found that purely from the generator CAPEX cost point of view, both the Vernier machines might not be competitive against the conventional SPM machine. However, in order to reveal the full potential of the Vernier machines, it will be interesting to evaluate their benefits in terms of generated revenue over the lifetime of the wind turbine. This is because the Vernier machines, with the same machine volume as the conventional SPM machine, can have significantly higher power generation capability, and hence considerably higher energy yield. If the generated revenue over the lifetime of the wind turbine is much higher than the CAPEX cost involved in building the wind turbine or in other words a lower LCOE, then Vernier machines can still be an attractive alternative.

The formula for LCOE considering both the CAPEX and operation costs is given by [20].

$$\mathrm{LCOE} = \frac{NPV}{NPE} = \sum_{t=1}^{20} \frac{C_t + O_t}{(1+d)^t} \Big/ \sum_{t=1}^{20} \frac{E_t}{(1+d)^t} \tag{1b}$$

where NPV is the net present value which includes the CAPEX cost (C_t) and operation cost (O_t), NPE is the net present energy that is equivalent to the AEP, t is the period ranging from 1 to the lifetime of the turbine, which is assumed to be 20 years in this case. d is the discount rate which is assumed to be 8.9% [20] for this study. The operation cost is assumed to increase at a rate of 2% annually.

The calculation of AEP required for calculating the LCOE is presented in the following section.

4.1 | Annual energy production (AEP) comparison

As the Vernier machines can achieve much higher torque, the rated wind speed can be higher than the conventional SPM machines. The comparison of the shaft power for different wind speeds between the conventional SPM and Vernier generators is shown in Figure 11. It is worth noting that the comparison in this section is under a strong assumption that the generators could extract their corresponding powers without the need to adjust the overall wind turbine structure. However, in practice, to increase the extracted power, the blade size would need to be increased, and hence the blade speed would need to be reduced, so does the generator speed, as will be detailed in section IV.B.

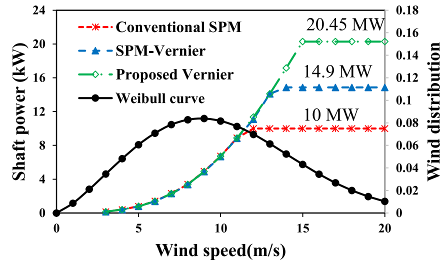

FIGURE 11 Comparison of shaft power between the conventional SPM and Vernier generators for different wind speeds.

The step-by-step approach for calculating the AEP from the power curve is described below.

1) Knowing the power (P) and induced EMF (E_b) at a certain wind speed, the generator phase currents can be calculated assuming a maximum torque per ampere (MTPA) operation with a zero d-axis current as

$$I_{ph} = P/(3E_b) \tag{2}$$

2) Calculate the generator EM losses using 2D FEA for the operating phase current.
3) Calculate the converter losses (p_{Conv}) for the conventional SPM machine using the following analytical model [17].

$$p_{Conv} = \frac{p_{ConvN}}{31}\left(1 + 10\frac{I_s}{I_{sN}} + 5\frac{I_s^2}{I_{sN}^2} + 10\frac{I_g}{I_{gN}} + 5\frac{I_g^2}{I_{gN}^2}\right) \tag{3}$$

where p_{ConvN} is the total converter losses (including the generator and grid side converters) and is assumed to be 3% of the rated generator power as shown in Table 1. I_{sN} and I_{gN} are the rated generator and grid side phase currents, respectively. I_s and I_g are the operating generator and grid side phase currents, respectively.

For the Vernier machines, the generator currents for the same operating power can be much higher than the conventional SPM machines due to their poor power factor. Therefore, the generator side converter losses are scaled accordingly for these higher operating phase currents. Whereas, the grid side converters of the Vernier machines will operate at the same power factor as that of the conventional SPM machines. Hence, the grid side converter losses are assumed to be proportional to the operating power of the generator.

4) Calculate the grid power (P_g) by subtracting the generator and converter losses from the shaft power.
5) Calculate the AEP from the grid power as given below

$$\mathrm{AEP} = \sum_{i=1}^{n} P_{gi} \times f_{wi} \times 8760 \times 10^{-6}\ \mathrm{GWhr} \tag{4}$$

where P_{gi} and f_{wi} are the grid power and the frequency of wind distribution for the wind speed i.

The comparison of the generator phase currents versus wind speed is shown in Figure 12. It can be observed that below the rated wind speed (12 m/s), the generator phase currents are inversely proportional to their power factor. The high generator phase currents will negatively impact the generator side converter in terms of their efficiency and cost. Moreover, several parallel converter modules may be required to carry these high currents.

The comparison of different generator EM losses with wind speed is shown in Figure 13. The PM loss in the proposed Vernier machines is constantly lower than the SPM-V machine for the full range of wind speeds. Although the operating frequency of the proposed Vernier machine is higher, sharing the PMs between the rotor and stator results in a lower PM width that helps reduce the eddy current loss. However, the PM eddy current loss is a smaller proportion of the overall EM losses.

As discussed in the previous section, the stator core loss is the dominant loss component in the proposed Vernier machines, as shown in Figure 13b. It is interesting to note that the stator core loss drops at a faster rate for the Vernier machines compared to the conventional SPM machine. This is because in the Vernier machines with low slot/pole numbers, the stator core loss is dominated by the armature reaction flux which drops with the reduced phase currents. Hence, below the rated wind speed (maximum aerodynamic efficiency region), the stator core loss for the Vernier machines is lower than that of the conventional SPM machines.

Unlike the conventional SPM machines, the fundamental armature MMF and the rotor are rotating asynchronously in the Vernier machines. Hence, they have high rotor core losses compared to the conventional SPM machines, which have almost negligible rotor losses, as shown in Figure 13c. It is worth reiterating here that the Vernier machines are designed with a lower electrical loading and an increased copper volume to have the same copper loss per slot wall area as the conventional SPM machines. Hence, the copper loss in the Vernier machines is much lower, as shown in Figure 13d.

The comparison of the generator total EM losses and efficiency versus wind speed is shown in Figure 14. In the maximum aerodynamic efficiency region, the Vernier machines have lower or similar total EM losses compared to the conventional SPM machines. This has resulted in better or similar efficiency for the Vernier machines in this region. Because of lower stator core losses, the SPM-V machines exhibit better efficiency than the proposed Vernier machine over a wider range of wind speeds.

The comparison of the generator side and grid side converter losses is shown in Figure 15. Because of the poor power factor, the generator side converter losses will be higher for the Vernier machines even in the regime below rated wind speed (12 m/s) with the same output power for the investigated machines. With a relatively lower power factor (0.4) for the proposed Vernier machine, its generator side converter losses are higher than the SPM-V machines. The grid side converter losses follow the output power of the generator and therefore the losses will be the same below the rated wind speed.

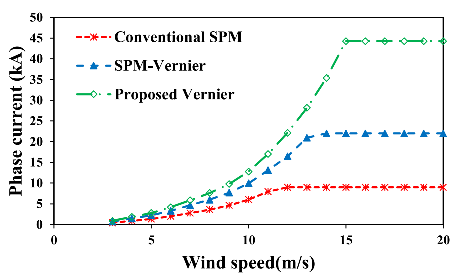

FIGURE 12 Comparison of generator phase currents versus wind speed between the conventional SPM and Vernier generators.

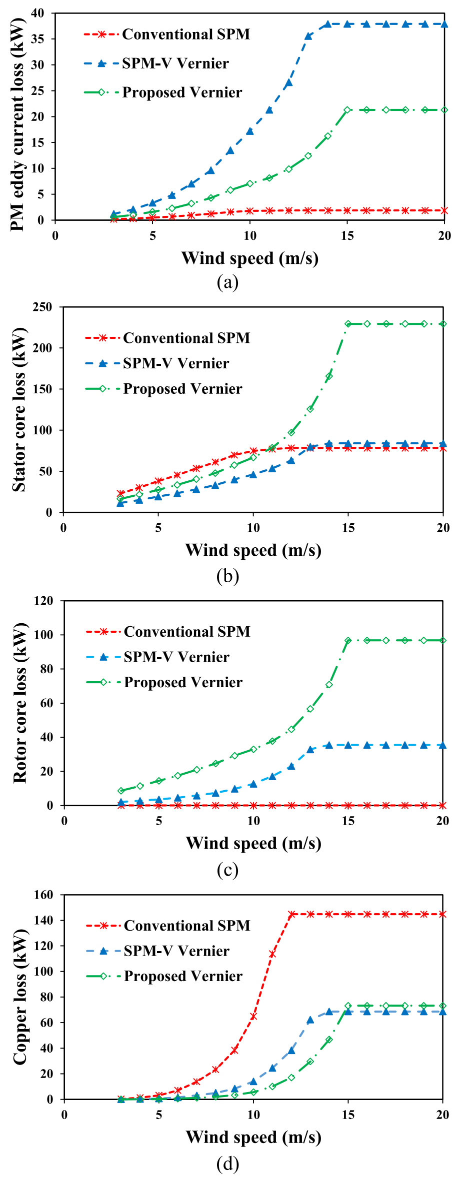

FIGURE 13 Comparison of generator EM losses. (a) PM eddy current loss, (b) stator iron core loss, (c) rotor iron core loss, and (d) copper loss.

The comparison of the overall converter efficiency and the system-level efficiency (including the generator and converter) is shown in Figure 16. The low power factor of the proposed Vernier machine designed with a higher gear ratio of 8 has resulted in higher converter losses and poor efficiency. The high converter losses also have reduced the overall system-level efficiency of the proposed Vernier generator, which is lower than that of the conventional SPM generator. However, with relatively better power factors and lower generator losses, the SPM-V machines have comparable system-level efficiency as the conventional SPM machines below the rated wind speed.

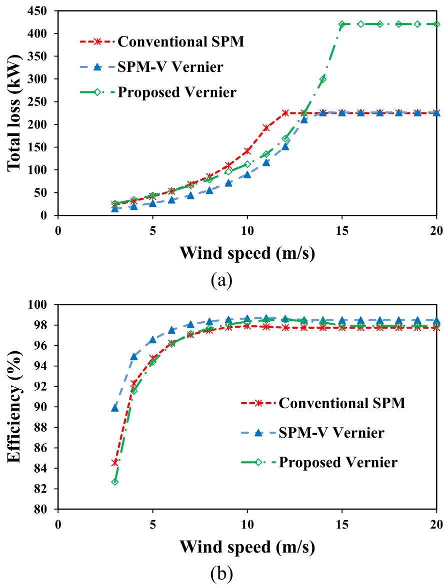

FIGURE 14 Comparison of generator total EM losses and efficiency. (a) Total EM losses and (b) efficiency.

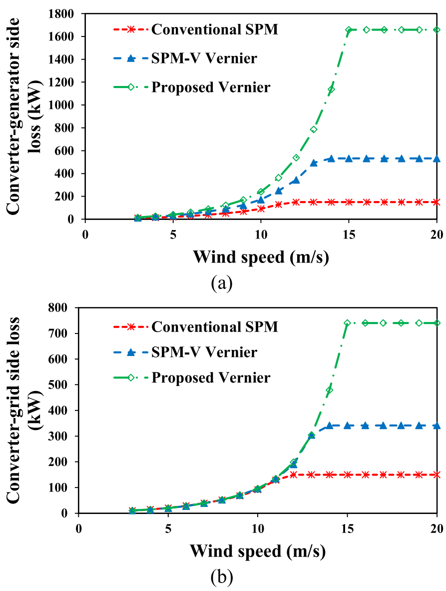

FIGURE 15 Comparison of generator side and grid side converter losses versus wind speed. (a) Generator side converter losses and (b) grid side converter losses.

Although the total losses in the proposed Vernier machine are higher, the maximum grid power achieved is still much higher than that of the conventional SPM and SPM-V machines as shown in Figure 17a.

From the grid power and the wind distribution, the AEP can be calculated for each wind speed and is shown in Figure 17b. The area under the curve represents the total AEP from a particular generator system and this implies that the proposed Vernier machine has the highest AEP. The values of

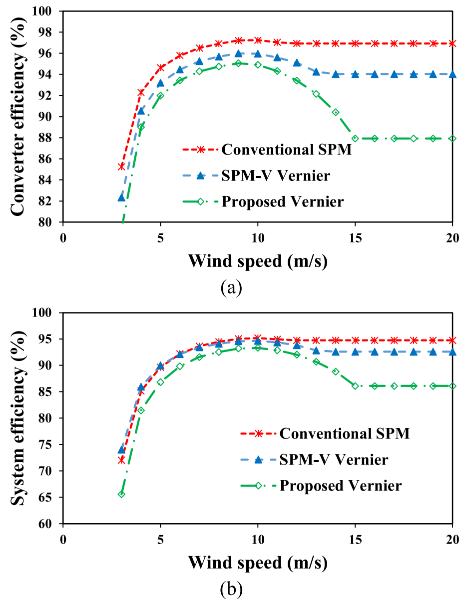

FIGURE 16 Comparison of the overall converter (generator side + grid side converter) and system-level (generator + converter) efficiency with wind speed. (a) Overall converter efficiency and (b) system-level efficiency.

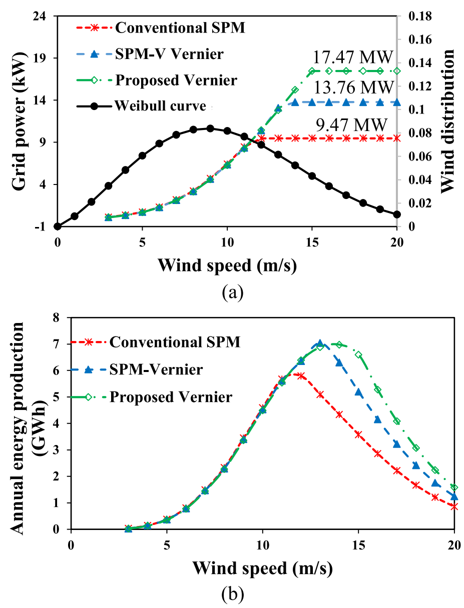

FIGURE 17 Comparison of grid power and annual energy production with wind speed. (a) Grid power and (b) annual energy production.

the total AEP between the three machines are 46.5GWhr for the conventional SPM machine, 56.36GWhr for the SPM-V machine, and 61.53GWhr for the proposed Vernier machine. It is observed that the AEP for the SPM-V and the proposed Vernier machine systems are higher than that of the conventional SPM generator systems by 21.2% and 32.3%, respectively. This excess AEP can result in significant revenue over the lifetime of the turbine. Although the AEP for the Vernier machines is already higher, the currently investigated turbine blade diameter (170 m) designed for the 10-MW power level may not be optimal for the Vernier generator systems with higher power generation capability. From Figure 17a, it is clear that the AEP for the Vernier machines can be improved by aligning the rated wind speed of the Vernier generators towards the average wind speed of 10 m/s. This can be done by choosing a larger blade diameter and thereby increasing the shaft power for lower wind speed. The study of AEP for the three machines with varying turbine blade diameters will be discussed in the next section.

4.2 | AEP for varying turbine blade diameters

The approach adopted for the calculation of AEP for different rotor blade diameters is described below.

1) The optimal tip speed ratio of 9.5 is assumed to be constant for all the investigated rotor blade diameters. Hence, the new generator rotor speed (ω_{new}) for a given wind speed can be calculated by

$$\omega_{new} = \omega_b \times 170/D_{new} \tag{5}$$

where 170 refers to the baseline rotor blade diameter and D_{new} is the new rotor blade diameter, and ω_b is the baseline generator speed using the baseline rotor blade diameter.

2) The new shaft power (P_{sh-new}) for a given wind speed is derived from the baseline shaft power (P_{sh-b}, at 170 m rotor blade diameter) by scaling them in proportion to the turbine blade swept area and is given by

$$P_{sh-new} = P_{sh-b} \times D_{new}^2/170^2 \tag{6}$$

3) Knowing the new generator speed and the shaft power with wind speed, the AEP can be calculated using the steps presented in section III. A.

The comparison of AEP calculated for the different rotor blade diameters is shown in Figure 18. It can be observed that the AEP for the SPM-V and the proposed Vernier generator systems can be considerably increased with larger rotor blade diameters. The optimal blade diameters for the SPM-V and the proposed Vernier generator are around 220 and 230 m, respectively. With the optimal blade diameters, the AEP can be

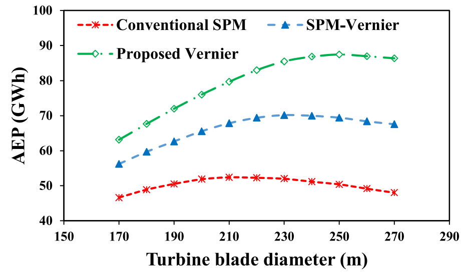

FIGURE 18 Comparison of AEP for different turbine rotor blade diameters between the conventional SPM and Vernier generators.

increased by 34% and 65% for the SPM-V and proposed Vernier machines, respectively.

The calculation of CAPEX and operation cost required for LCOE is described in the next section.

4.3 | CAPEX and operation cost calculation

The analytical model used for the cost calculation of different wind turbine components is described below.

(1) Generator: The total mass (M_{tot}) of the conventional SPM generator including the active and structural materials is given by [21].

$$M_{tot} = 97.7 \times P/\sqrt{N} \tag{7}$$

where P is the rated power and N is the rated speed (rpm).

The generator active material mass can be deduced from the 2D FE modelling using the mass densities given in Table 1. The structural mass can then be calculated by subtracting the active mass from M_{tot}. Having segregated the active and structural masses, their costs can be calculated using the cost model given in Table 1. The structural mass and cost of the Vernier generators are assumed to be the same as the conventional SPM generators as they are designed with the same outer diameter. Whereas the active mass and cost of the Vernier generators can be deduced from 2D FE modelling, similar to the conventional SPM machines.

(2) Converter [17]: Both the generator side and grid side converter costs ($k€$) can be calculated by (kVA rating × 20 €/kW)/1000. The cost models used for other structural components such as tower, hub, blades, nacelle etc., are derived from the scaling model presented by the National Renewable Energy Laboratory (NREL) in ref. [22]. The analytical models for the calculation of mass and cost of each component are given below:

(3) Turbine blades mass and cost presented here are for one blade. The cost includes both material (first term) and labour (second term) cost. The mass can be calculated by Mass (kg) = $0.4948 \times R^{2.53}$, where R is the turbine rotor radius. And the cost can be calculated by Cost (\$) = $[(0.4019 \times R^3 - 21{,}051) + (2.7445 \times R^{2.5025}]/(1 - 0.28)$.

(4) Hub mass can be calculated by Mass (kg) = 0.954 × Mass per blade + 5680.3, and its cost can be calculated by Cost ($) = Hub mass × 4.25.
(5) Nacelle cover mass is Mass (kg) = Cost ($)/10, and its cost is Cost ($) = 11.537 × Rated power + 3849.7.
(6) Tower mass is Mass (kg) = (0.2649 × Swept area × Hub height + 1779) × 0.55, and its cost is Cost ($) = 1.5 × Mass (kg). A correction factor of 0.55 has been used in the tower mass calculation to match the 10 and 15 MW reference designs developed by NREL presented in ref. [23].
(7) Foundation mass is not needed, but its cost is Cost ($) = 303.24 × (Swept area × Hub height)$^{0.4037}$.
(8) Offshore operation and maintenance (O&M) cost can be calculated by O&M Cost ($) = 0.02 × AEP (kWh). It is worth noting that the operation cost for a given turbine rotor diameter is maintained constant for the three generator topologies investigated in this study. Also for the calculation of LCOE for the lifetime of the turbine, this operation cost is assumed to be increased by 2% annually.

Although many other components add to the cost of the wind turbine, for simplicity, only the major cost components have been considered here. The total CAPEX cost for a given turbine rotor diameter is equal to the summation of the cost of all the above-mentioned components. The comparison of the calculated mass and cost of different structural components with the increasing turbine diameter is shown in Figure 19. The mass of the turbine is mainly dominated by the tower, whereas the cost is mainly driven by both the tower and the blades.

The comparison of the mass and cost of the generator and converter for the three different machines are shown in Table 4. As mentioned in section III.B, the higher power generation capability of the Vernier machines comes with a price such as higher overall cost and mass. Having calculated the AEP, CAPEX cost and the operation cost, the LCOE can be calculated using (1a, 1b). The comparison of the LCOE for the three investigated generators with the increasing turbine rotor diameter is shown in Figure 20. It can be observed that the LCOE for the Vernier machines is constantly lower than that of the conventional SPM machine across all the investigated turbine rotor diameters. The LCOE for the SPM-V and the proposed Vernier generators at the optimal turbine rotor diameter are 12.3% and 24% lower than that of the conventional SPM generator, respectively. These low LCOE for the Vernier generator systems indicate that they have huge potential to be an alternative to the existing conventional SPM generators that help reduce the overall cost of energy.

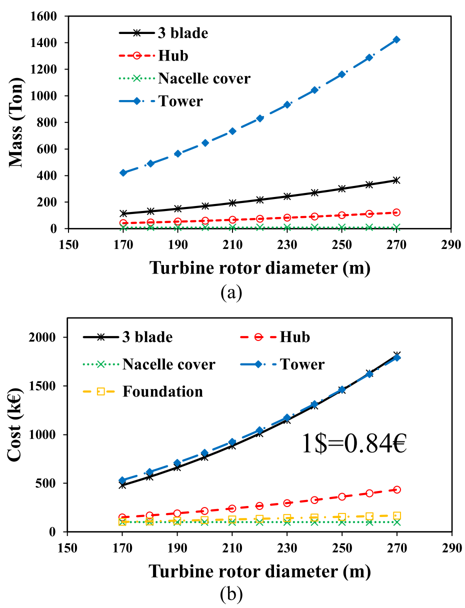

FIGURE 19 Comparison of (a) mass and (b) cost of wind turbine components versus the increasing turbine rotor diameter.

5 | EXPERIMENTAL VALIDATION

To validate the numerical predictions in this paper, a 3-kW small-scale prototype has been built, the specifications of which are listed in Table 5. It has the same machine topology as the proposed 10 MW machine [see Figure 1c]. However, instead of using double-layer windings, it adopts single-layer windings in order to simplify the winding process, as shown in Figure 21. This modification does not alter the electromagnetic performance of the machine, and it might only increase the magnetic saturation under the overload condition.

It is worth mentioning that, owning to the external rotor structure, the prototype has used a single endplate with a single

TABLE 4 Comparison of the cost and mass of the generator and converter.

	Conv. SPM	SPM-V	Proposed Vernier
Generator mass (Ton)			
Active material	63	180.5	246
Structural material	246	246	246
Total	309	426.5 (+38%)	492 (+59%)
Generator cost (k€)			
Active material	539	1208.4	1381
Structural material	492	492	492
Total	1031	1700.4 (+65%)	1873 (+82%)
Converter cost (k€)			
Generator side	210	507	1009
Grid side	210	326	431
Total	420	833 (+98%)	1440 (+243%)
Total system-level cost (generator + converter)	1451	2533.4 (+75%)	3313 (+128%)

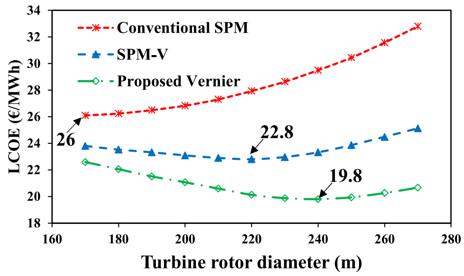

FIGURE 20 Comparison of LCOE between the conventional SPM and Vernier generator systems with the increasing turbine rotor diameter.

TABLE 5 Key parameters of the prototype machine.

N° of rotor pole pairs	66	Stack length (mm)	110
N° of stator slots	36	PM volume (m^3)	4.08×10^{-4}
N° of stator winding pole pairs	6	Rotor PM over total PM volume (%)	55
N° of stator PM pole pairs	36	PM material NdFeB	$Br = 1.3$ T
Rotor outer diameter (mm)	426.4	Phase current (Arms)	2.5
Rated speed (rpm)	170	Efficiency	96.2%
Airgap length (mm)	2	Turns/phase	832

bearing, and both are on the left-hand side of the machine, as shown in Figure 21c. This arrangement inevitably leads to rotor eccentricity. Although the best effort has been made to mitigate this issue, the open-circuit performance such as the measured phase EMF is still slightly lower than the simulated counterpart, as shown in Figure 23a. It is worth noting that the proposed Vernier machine exhibits significantly lower cogging torque (see Figure 22) compared to its rated torque. In addition, the prototype generator is coupled with the drive motor, it becomes nearly impossible to separate the cogging torque from the torque ripple produced by the drive motor. As a result, the measured cogging torque cannot be accurately determined using the existing test rig.

Regarding the onload performance, due to the existing rotor eccentricity issues, the phase current has been limited to a maximum rms value of 1.8 A in order to safeguard the integrity of the test rig. One example of the measured 3-phase currents can be seen in Figure 23b and the corresponding simulated and measured torque waveforms are shown in Figure 23c. Similar to the phase EMF, the average value of the measured torque is also slightly lower than the simulated counterpart. In addition, the measured torque ripple is higher than the simulated one, which is primarily attributed to the rotor eccentricity. The average torques at different phase rms currents have also been measured and compared against the simulated results, and a generally good agreement between them can be observed, as shown in Figure 23d.

To conclude the onload tests, the power factor, an important performance indicator for Vernier machines, has also been measured. However, due to existing eccentricity

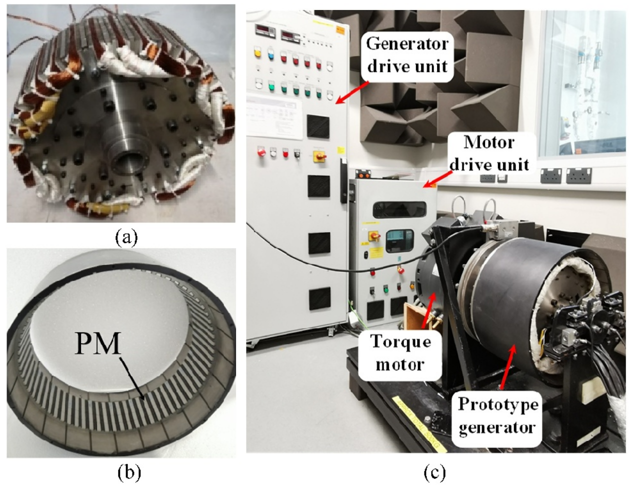

FIGURE 21 Prototypes of the proposed 3kW Vernier generator. (a) stator, (b) rotor, and (c) complete machine on a test rig.

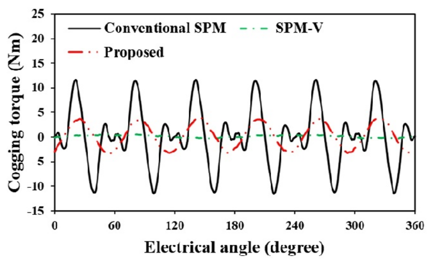

FIGURE 22 Simulated cogging torques of the 3kW conventional SPM and Vernier generators.

issues, the maximum rotor speed was limited to around 40rpm in order to safeguard the integrity of the test equipment. Figure 24 shows the measured power factor against phase rms current at various rotor speeds. As expected, with an increase in phase rms current, the power factor of the proposed Vernier machine drops. However, as the speed rises, the rate of decline in the power factor becomes less pronounced.

6 | CONCLUSION

This paper compares three Multi-MW offshore wind power generators such as the conventional surface-mounted permanent magnet (SPM) machine, the surface-mounted permanent magnet Vernier (SPM-V) machine and a proposed Vernier machine with magnets on both the stator and rotor. The comparison is under the condition that all machines have the same volume that allows Vernier generators to produce a much higher power and thereby energy yield than a conventional SPM generator. It is found that although the Vernier machines have a much lower power factor and slightly lower system efficiency than the conventional SPM machine, they can produce significantly higher power. For example, the conventional SPM-V machine can produce 50% higher power, and it is 100% higher for the proposed Vernier machine. In addition, both the Vernier machines have much lower

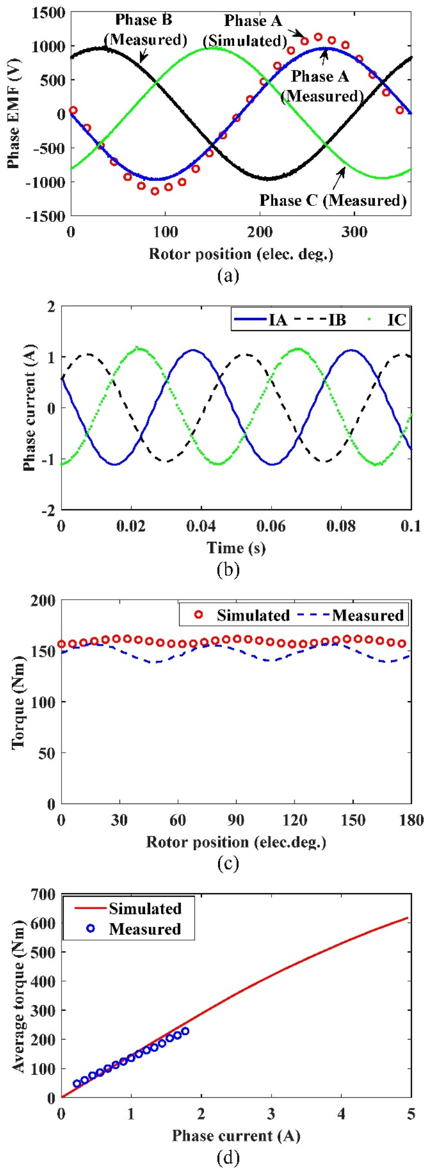

FIGURE 23 Comparison between simulated and measured results. (a) 3-phase EMFs, (b) 3-phase currents, (c) onload torque waveform, and (d) average torque versus phase rms current.

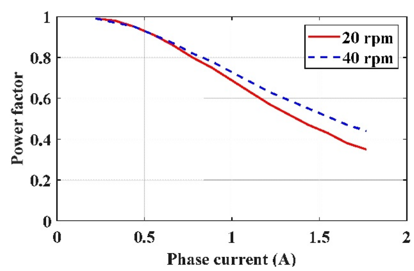

FIGURE 24 Measured power factor versus phase rms current at different rotor speeds.

torque ripple (and cogging torque) but slightly higher efficiency than the conventional SPM machine. However, the lower power factor means that the Vernier machines have larger converter power ratings and hence higher costs. As a result, both Vernier machines have higher capital expenditure (CAPEX) cost.

However, by having much higher power generation capability than the conventional SPM machine, the longer term benefits of Vernier machines in terms of revenue generated for the lifetime of the turbine have also been investigated to fully reveal their potentials in offshore wind application. This is because if the revenue for the lifetime of the wind turbine is much higher than the CAPEX cost involved in building the wind turbine, or in other words a lower levelised cost of energy (LCOE), then the Vernier machines can still be an attractive alternative. The comparison results have shown that the direct-drive powertrain systems with SPM-V and the proposed Vernier generators can achieve a 12.3% and 24% lower LCOE compared with the conventional SPM generators, indicating their significant potential for reducing the overall cost of energy for offshore wind power.

AUTHOR CONTRIBUTIONS

Dileep Kumar Kana Padinharu: Conceptualisation; Formal analysis; Investigation; Validation; Visualisation; Writing original draft. **Guang-Jin Li**: Conceptualisation; Funding acquisition; Investigation; Methodology; Supervision; Validation; Writing original draft; Writing review & editing. **Zi-Qiang Zhu**: Funding acquisition; Resources; Writing review & editing. **Peng Wang**: Validation. **Richard Clark**: Funding acquisition; Resources. **Ziad Azar**: Funding acquisition; Resources.

ACKNOWLEDGEMENTS

This work is supported by the UK EPSRC Prosperity Partnership "A New Partnership in Offshore Wind" under grant no. EP/R004900/1.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data subject to third party restrictions.

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How to cite this article: Kana Padinharu, D.K., et al.: Comparison of direct-drive Vernier wind generators for potential use at ≥10 MW power level. IET Electr. Power Appl. 1–14 (2024). https://doi.org/10.1049/elp2.12477