Abstract—Micro-turbine based high speed gensets exhibit several interesting features such as compactness and light weight, low maintenance, fuel flexibility, relatively low emissions, durability, high reliability etc. They represent an interesting solution in the distributed generation perspective, especially when employed as mid-low power co-generation units possibly exploiting byproducts of farming activities. This paper presents the preliminary design and FEM/circuital analysis of a high-speed permanent magnets synchronous brushless machine useable as generator in such units. Results concerning different operative conditions and current waveforms are reported and commented, considering the opportunity to employ a controlled AC/DC converter in spite of the usual diodes rectifier bridge.

I. INTRODUCTION

The global power demand is constantly rising both in metropolitan areas, where the grid development is often strictly limited by lack of space, high costs and bad acceptance from inhabitants, and in rural areas, where the grid is usually either limited to unreliable low-power feeders or is absent at all. Contemporaneously, the use of renewable or less polluting energy sources that are inherently spread over the territory, such as wind, sun, biomass etc., is rapidly increasing mainly for environmental reasons. Consequently, nowadays the classic concentrated-generation scenario of power systems, based on a limited number of generation plants equipped with large synchronous generators directly connected to the grid, is evolving towards the distributed-generation model, including a large number of various types of small generation units located in close proximity of the loads and featuring a static converter as controllable mains interface.

In this context, gensets based on high-speed micro-turbines represent an interesting solution when some source of hot pressurized gas may be conveniently arranged. In fact, micro-turbines feature a relatively simple and robust structure ensuring high reliability, low maintenance requirements and long durability especially in comparison with internal combustion engines (e.g. [1]). Moreover, as the source of hot pressurized gas may be fully separated from the turbine, a much higher flexibility in the selection of the primary energy source and of the process converting it into thermal power is available with respect to internal combustion engines, yet without the complications of the intermediate water-vapor circuit of large turbine plants. In fact, conventional fuels may be used to be burnt into a combustion chamber usually located in close proximity of the turbine and supplied with pressurized air provided by a dedicated compressor, thus leading to a powerful hot flow of exhaust gases which is directly conveyed to the turbine. Alternatively, the compressed air flow may be conveyed into a heat exchanger heated by any power source, such as biomass combustion, before being injected in the turbine. In co-generation units, before being dispersed in the atmosphere via a noise-absorbing funnel the decompressed gas flow, which is only partly cooled, may be conveyed into a heat exchanger to obtain hot water for service or building heating or even for cooling by means of external chiller machines. In most of commercial solutions, the compressor is directly driven by the turbine itself, which provides then the required mechanical power; alternatively, it may be driven by a dedicated electric motor, thus permitting to optimize the overall system efficiency by suitably adjusting in independent way the shaft speed of compressor and turbine, according to the electric and thermal load conditions.

Micro-turbines are mainly identified by their relatively small power, about in the range 30-300 kW: in fact, in such range rather high design speeds, usually in the order of several tens of [krpm], are adopted for convenience. This inherently leads to very compact and lightweight structures (e.g. [2, 3]), albeit high-accuracy machining is required to keep pace with the exacerbated mechanical problems concerning suspension, balancing etc. Moreover, unless cumbersome, expensive and inefficient gearboxes are used, the electric generator has to be coupled directly to the turbine. This means that the generator must also be designed to be able to face speeds much higher than usual, thus requiring a specific attention to aspects such as iron losses and skin effect that are strongly augmented at high frequency. Moreover, a suitable static conversion system must be interposed between generator and power terminals, since usually a standard frequency output is required.

II. SYSTEM ARCHITECTURE

The most popular architecture adopted for micro-turbine based gensets, depicted in fig. 1, consists in a generator directly driven by the turbine and supplying in turn a dual
stage static conversion systems acting as power conditioning interface (e.g. [4]). In such solution, 2 converters operating as AC/DC and DC/AC are connected via a capacitors-supported DC bus, which effectively decouples their instantaneous operation thus simplifying the system control, even permitting that one of them is fully uncontrolled type. A suited filter is also usually interposed between the DC/AC converter and the mains, to achieve an adequate power quality level.

In particular, usually the DC/AC converter consists in a VSI inverter, while the filter includes L series and C parallel elements in a low-pass arrangement as seen from converter side. In fact, when properly designed such configuration permits to finely adjust either the currents injected in the mains, in case of parallel-grid operation, or the output voltages directly provided to the loads, in case of islanded operation without any connection to the grid.

On the other hand, a simple, reliable and inexpensive diodes rectifier is often preferred as AC/DC converter, since during normal operation the power flow direction is fixed. Obviously, in such case the generator typology must be wisely selected to permit supplying a simple diodes bridge. In most cases a drum-type radial-flux permanent magnets synchronous brushless machine (PMSM) is chosen (e.g. [5, 6]), since the inherent self-excitation permits such machine to operate without specific requirements about the load. In particular, usually a DC-brushless machine structure is selected, since it ideally generates a flat top phase voltage spanning over 1/3 of the period per each sign thus permitting to ideally provide a constant DC output voltage by means of a diodes rectifier. Moreover, this topology usually features a simple 1 slot per pole per phase winding scheme with surface mounted magnets (SM-PMSM), thus achieving the simplicity and low cost design goals better than more sophisticated sinusoidal AC brushless machines e.g. using internal magnets arrangements.

Nevertheless, in practice the presence of several non-ideal aspects, such as slots openings, iron saturation, simultaneous conduction during phase commutation etc. affect the operating conditions of the generator. Hereafter such differences are investigated, also aiming to estimate the possible benefits deriving from the use of a VSI inverter as a controllable AC/DC converter permitting to shape the waveforms of the currents drawn from the generator. The analysis is carried out referring to a potentially realistic case study, presenting first a preliminary design.

A. Application Scenario

The considered case study refers to the following data: SM-PMSM DC-brushless type generator featuring rated power \( P_N = 90 \text{ kW} \) at rated speed \( \Omega_S = 50 \text{ krpm} \), with 3-phase system output featuring line-to-line voltage \( V_{\text{vol}} = 400 \text{ V}_{\text{r.m.s.}} \).

Hypothesizing that a common 3-phase VSI inverter is used as DC/AC converter, it may be then assumed that the rated no-load voltage of the DC bus may be about \( V_{\text{DC}} = 760 \text{ V} \) to ensure a 200 V margin above the theoretical peak line-to-line output voltage, amounting to about 560 V, to pace with voltage drops on output inductors while still retaining an adequate dynamic capability for the regulation of currents. Assuming first that the AC/DC converter is constituted by a simple diodes rectifier bridge, the above voltage margin is further justified from the generator voltage drop due to load currents. Accordingly, the reference value for flat-top phase voltage of the generator, referred to the ideal operation involving only 2 active phases at any time instant, equals to \( V_{p/k} = 380 \text{ V} \).

Keeping into account the unavoidable flow of heat from turbine to generator via conduction along the shaft, the rotor temperature is expected to be rather high: the material of permanent magnets has then to be wisely chosen, in order to ensure that it operates below its maximum temperature and within the linear part of the demagnetization curve.

Usually, the rotor magnetic yoke and the shaft are obtained by machining a unique bulk piece of ferromagnetic steel and the magnets are locked onto it by means of an external enclosure. In fact, using a simple gluing, as usual in small machines operating at low speed, would be unfeasible or unsafe at the assumed rated speed, due to the much larger centrifugal forces. The magnets enclosure may be either partial, e.g. a series of metallic rings, or total, typically consisting either in a thin non-magnetic metallic sleeve or in a carbon/glass fiber bandage [7,8]. Despite metallic sleeves feature easy manufacturing and a good mechanical strength, their high electric conductivity is actually a drawback. In fact, despite at steady state the rotor field map should be ideally invariant, several perturbations actually arise due to stator slotting, current harmonics etc. which may induce significant eddy currents in the sleeve, affecting the generator efficiency and distorting the field map itself. Therefore, in the considered design a non-conducting rotor bandage was assumed.

B. Analytical Modeling and Preliminary Design

A preliminary design was obtained using a simplified analytical model taking into account the main electromagnetic and thermal phenomena under suitable simplifying hypotheses, such as radial shape of main field lines and negligible effects of magnetic saturation and slot openings. Basing on such model, a spreadsheet was get ready permitting to compare several preliminary design variants, taking into account all of the more relevant aspects such as flux density, current density, temperature etc. The most promising variant, below described, was finally selected.

The machine features a 4-poles arrangement with axial length of active parts \( l = 200 \text{ mm} \).

The rated electric frequency of the machine is then \( f_r = 1667 \text{ Hz} \). Due to such relatively high value, which makes potentially serious the matter of iron losses especially due to eddy currents, the stator core is composed of thin (\( \delta = 0.1 \text{ mm} \)) non-oriented silicon-iron laminations featuring the B-H curve reported in Fig. 2. The stator features a macroscopically isotropic core with external diameter \( D_r = 134.6 \text{ mm} \); radial yoke thickness \( h_y = 10.2 \text{ mm} \); slots depth (dents height) \( h_s = 13 \text{ mm} \). The 1 slot per pole per phase layout typical of DC-brushless machines is selected, adopting a 3-phase Y connected balanced winding thus leading to a 12 semi-open slots layout. The stator winding, deployed in 2 layers, is then composed of 4 series-connected coils per phase featuring 2
equivalent turns per coil; each turn is composed indeed of 60 enameled wires (diameter $d_w = 0.05 \text{ mm}$) connected in parallel in a Litz-wire-like fashion, aiming to reduce the skin effect and related stray losses due to operation at rather high frequency.

The magnetic field inside rotor should be ideally time invariant at steady state, meaning that no eddy currents should be induced even when bulk conductive parts are present. Anyway, flux pulsations actually take place due to stator slotting, current harmonics etc.: aiming to ensure a good efficiency, the rotor yoke is composed of the same thin silicon iron laminations used for the stator, which are shaped as a simple cylindrical sleeve since an isotropic brushless machine is designed. The yoke external diameter is $Dr = 75 \text{ mm}$ whereas its thickness $h_r = 9 \text{ mm}$ is lower than in stator yoke just because the much lower entity expected for flux density variations permits to approach more closely the saturation condition without worrying about excessive iron losses.

The rotor is equipped with 4 cylindrical-shaped permanent magnets composed of high quality NdFeB material, whose linear behavior in the second quadrant even at a rather high temperature ($200^\circ$C) is highlighted by the $B(J)-H$ curves reported in fig. 3. The possible segmentation of each magnet along either the axial or the tangential direction was considered to reduce the entity of eddy currents due to flux pulsations; anyway, considering the small size of the machine a bulk structure was finally adopted aiming to manufacturing simplicity. The magnets feature a uniform radial magnetization with a constant thickness $\varepsilon_M = 4.5 \text{ mm}$ and a reduced angular width $\alpha_M = 64.8^\circ$, which was adopted as a wise compromise permitting the flat-top part of e.m.f. waveform to span for about $1/3$ of electric period while minimizing the total flux per pole and thus the yoke thickness.

The thickness of the bandage keeping magnets in place, determined by mechanical stress considerations, is $h_b = 1.1 \text{ mm}$, whereas the air-gap thickness is $\varepsilon_A = 1 \text{ mm}$.

### III. FEM Electromagnetic Model

A detailed electromagnetic analysis of the designed machine was performed by means of a purposely developed FEM dynamic model, aiming to validate the preliminary design and to investigate the impact of secondary effects previously neglected. A 2D approach was adopted since the machine features a radial-flux structure with fairly low diameter/length aspect ratio; the model was developed using a commercial simulation software (MagNet\textsuperscript{8}).

Aiming to reduce the computational burden of simulations, the size of the region actually modeled was minimized by exploiting the cyclic symmetry inherently exhibited by the problem: the model was then limited to 1 pole sector, as shown in fig. 4. Obviously, it was kept in mind that the voltage, torque and power values provided by such model are reduced proportionally. To properly account for the exploited symmetry, suitable periodic boundary conditions were then applied at the cut lines delimiting the modeled sector along the tangential direction. Tangential flux boundary conditions were instead imposed on the circle arcs delimiting the model along the radial direction and bounding the air shells surrounding the machine, aiming to approximate the vanishing field condition. The complexity of the model was further reduced by neglecting both the external case and the shaft, as they play a secondary role in the electromagnetic phenomena. Finally, the effects related to motion were accounted for by setting the rotor speed equal to its rated value.

The mesh was generated by the mesher included in the simulation package employing triangular elements, as shown in fig. 5.a. Wise max element size constraints were imposed for the different objects, as a compromise between accuracy and computational effort. As shown in fig. 5.b, to improve the overall accuracy the most critical part of the model, i.e. the main air-gap, was divided into 6 evenly spaced nested layers featuring high order elements.

Using the embedded tools based on Maxwell stress tensor method, the electromagnetic torque was calculated twice separately referring to stator and rotor parts, by means of...
different boundary surfaces purposely located in the airgap. This permitted also a rapid check of the accuracy of simulation results: in fact, since the two values should result opposite due to the action-reaction principle, any large discrepancy highlights the necessity to further tighten the mesh constraints and the convergence criteria.

By means of the auxiliary circuital parts embedded in the FEM model, the 3 phases of the machine were connected to 4 different types of load. At first, current generators were used to impose 2 of the 3 phase currents, as shown in fig. 6. Such generators feature suitable waveforms, respectively pulsed and sinusoidal in different tests, aiming to investigate the machine behavior under the ideal load conditions typical of DC-brushless and AC-brushless operation. Such conditions might be eventually approximated in practice by using a controlled inverter as active AC/DC converter. At last, as shown in fig. 7 a more realistic 3-phase diodes bridge rectifier AC/DC converter was considered, yet assuming almost ideal characteristics for the diodes in order to highlight the machine behavior. A suitable resistor was used as equivalent load, separately investigating also the effects due to the possible presence of an adequately large capacitors bank (1000 µF) supporting the DC bus. The auxiliary switch and voltage generator that may be noticed in fig. 7 were used to reduce the duration of simulations by forcing a suitable non-zero initial condition in the capacitor, thus shortening the settling time of the startup transient.

The results obtained for the different load scenarios above listed assuming that the output power equals its rated power are reported and commented hereafter.

IV. RESULTS OF FEM ANALYSIS

A. Rectangular Current Load Condition

In this case, the machine behavior was analyzed assuming a symmetrical set of phase currents featuring the rectangular pulsed waveforms typical of ideal DC-brushless like operation, i.e. constant for 2/3 of each half-period and null otherwise, with null phase shift with respect to the relevant no-load voltages. The current peak value was properly adjusted to achieve the rated output power level: a first estimation was obtained using the average value of the no-current voltage over the central 1/3 of the canonical half-period, whereas the final value $i_{pk} = 111$ A was then obtained by trial process.

As example, the steady-state waveforms of current and of no-load and actual voltages (1/4 of the total, according to the reduced model) are reported in fig. 8, while in fig. 9 a field map shows the flux density in the machine at one of the rotor positions where the axes of magnet and teeth are aligned.

B. Sinusoidal Current Load Condition

In this case, the machine behavior was analyzed assuming a symmetrical set of sinusoidal phase currents with null phase shift with respect to the fundamental component of the relevant no-load voltages, as typical of the ideal AC-brushless like operation. Again, the current peak value $i_{pk} = 120$ A was adjusted to achieve output power equal to the rated value, using for a first estimation the amplitude of the fundamental component of the no-load voltage.

As example, the steady-state waveforms of current, no-load voltage and actual voltage are reported in fig. 10, whereas the flux density map at steady state is shown in fig. 11 again for the same particular rotor position that fig. 9 refers to.
C. Diodes Rectifier Bridge Load Condition

Finally, the current waveforms were inherently obtained from the steady-state operation of the system assuming the circuit connection sketched in fig. 7, considering both disconnected and connected capacitor conditions. In the first hypothesis, the waveforms of the 3 phase voltages and of the DC bus voltage at null currents are reported in fig. 12. The relevant voltage and current waveforms for a phase across the instant when the capacitor is connected to the DC bus, corresponding to 90° rotor position, are reported in fig. 13 for rated power load conditions: the variations in the trends of the current and actual voltage may be noticed. In fig. 14 the trends of the output voltages for the 2 situations are compared, highlighting the strong ripple reduction ensured by the capacitor. Finally, in fig. 15 a flux density map is reported for the same case, referring to the same rotor position as fig. 9, 11.

D. Considerations

The steady-state waveforms of the phase voltages at null currents, shown in fig. 12, exhibit a quasi-ideal shape affected by a small dip in each active part, due to stator denting, and by a rounded corner between flat portions and transition ramps. The spectrum calculated for such waveform is reported in fig. 16, highlighting the presence of low order harmonics.

As expected, the actual voltage waveform under pulsed rectangular current, shown in fig. 8, exhibits evident spikes due to the ideally instantaneous current steps, besides a steep variation near the center of each half-period due to the corresponding current steps in the other phases. Obviously, in practice such spikes would equal the DC bus voltage, thus determining the real limited \( \frac{dI}{dt} \) slope of the current profile. On the other hand, in the actual voltage waveform obtained under sinusoidal currents (fig. 10) no spike or steep variation is present; anyway, a somewhat larger deviation from no-load voltage, due to armature reaction, may be noticed.

Accordingly, the DC bus voltage obtained by means of the diodes rectifier bridge under no load when the capacitor is disconnected, shown in fig. 12, exhibits a small periodical ripple having 6 times the base frequency, due to the deviations from the ideal trapezoidal trend of the phase voltages both in the flat parts and at the transition corners. Such ripple appreciably increases when rated load is applied, amounting to about 20%. Anyway, the ripple in the rectified voltage is drastically reduced when the capacitor is connected to the DC bus, as clearly noticeable in fig. 14.

In Tab. 1 are finally reported several results obtained at steady state from the FEM simulations carried out. It may be noticed that the average electric power output is about the same, according to the comparison criterion adopted.

It may be noticed that a not negligible amount of Joule losses arises inside the magnets due to eddy currents. In sinusoidal mode such losses assume the lowest value, whereas the highest values are obtained in rectangular mode.
Actually, as the electric conductivity of magnets is not null some amount of losses is unavoidable in any machine even at steady-state due to flux pulsations induced by stator slotting; anyway, when current waveforms differ from a balanced sinusoidal set are used, the phenomenon is enhanced by the presence of counter-rotating fields due to current harmonics.

A reduced entity of rotor losses may turn into a lower temperature of the magnets, aiding to preserve them from demagnetization and increasing machine performances, even possibly permitting to slightly reduce their thickness thus saving on manufacturing costs. Resistive losses inside windings result also lower in sinusoidal mode than in the other modes, since the related current rms value is a bit lower. Accordingly, the highest efficiency values are obtained by the sinusoidal case and by the rectifier load with d.c. capacitor. Anyway, it is worth noting that the calculations concerning the rectangular waveform case, apparently providing a significantly lower efficiency, are affected by the critical behavior at each transition. Moreover, the values reported in Tab. 1 do not account neither for mechanical losses nor for additional and copper losses inside frontal connections, which were not modeled.

The considered operative modes also determine rather different ripple values in the electric power delivered to the load via the AC/DC converter. Assuming that no energy storage is present in the converter except for the capacitor in the second rectifier bridge variant, the smallest ripple is again achieved by the sinusoidal condition, whereas the first rectifier variant exhibits the worst performances.

Finally, comparing the ripple in the electromagnetic torque determined at steady state by the different current waveforms is also significant. In fact, although actual speed oscillations should be very limited due to the low-pass filtering effect of inertia at the very high speed considered, ripple may produce vibrations, acoustical noise and mechanical stress in the shaft, which might reduce its life due to fatigue. Therefore, even under this point of view the sinusoidal condition results the less critical one, while the two variants employing a diodes rectifier load exhibit much higher torque pulsation levels.

Therefore, in overall terms the above results suggest that the balanced sinusoidal currents condition should provide the most interesting mix of performances, despite the DC-brushless structure of the machine. Nevertheless, achieving an almost sinusoidal waveform of the currents flowing in the generator would require a remarkably more complex and expensive AC/DC converter than a simple diodes rectifier. In fact, using the structure schematized in fig. 1 a VSI inverter should be used, whose switching frequency should also result much higher than the rated frequency of the generator to achieve a low current distortion. Nevertheless, considering also the voltage and current ratings required, only modern fast and expensive IGBTs might result adequate. Alternatively, more common and affordable slower components might be used at a lower switching frequency, provided that a suited passive filter was interposed between converter and generator, yet involving further costs. Nevertheless, using an inverter-based AC/DC converter might permit to achieve a greater flexibility and a better control of the operation of the genset, making easier to track the overall maximum efficiency point. Such solution might also permit to startup the turbine by operating the generator as crank motor, when required.

V. CONCLUSION

Permanent magnets synchronous machines are often used as generators directly driven by high speed micro-turbines, representing an interesting solution in the perspective of distributed generation and co-generation. This paper presented the preliminary design and the 2D electromagnetic dynamic FEM modeling of such a machine, referring to a DC-brushless structure mainly intended to be connected to a capacitors-supported DC bus by means of a diodes rectifier bridge as usual. Simulation results were reported and commented referring to 4 current waveforms scenarios: ideal rectangular, ideal sinusoidal and realistic derived by actual connection to a rectifier bridge with and without a DC capacitors bank. The obtained results show that the sinusoidal balanced currents provide the best performances. Although some inaccuracies are present in the calculations, this suggests considering the employ of a controlled inverter as AC/DC converter to permit approaching such operating conditions while also achieving a greater employ flexibility, yet with higher complexity and cost.

REFERENCES