

VARIABLE FLUX MEMORY MOTORS TO OPTIMIZE WIND POWER ENERGY PRODUCTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This Application claims priority, pursuant to 35 U.S.C. § 119(e), to U.S. Provisional Application No. 63/069,399 entitled, "VARIABLE FLUX MEMORY MOTORS TO OPTIMIZE WIND POWER ENERGY PRODUCTION," filed on August 24, 2020. The content of which is hereby incorporated by reference in its entirety.

BACKGROUND

[0002] Synchronous electric motors with permanent magnets such as variable-flux memory motors have a wide range of applications in industrial, commercial, and residential, applications, such as fans, pumps, compressors, elevators, and refrigerators, industrial machinery, and electric motor vehicles because of their high efficiencies. Also, because of using permanent magnets instead of windings in the rotors of the synchronous electric motors, there is no need for a rotor cooling. These advantages along with others (*e.g.*, being brushless) make the synchronous electric motors popular where high torque, high efficiency, or low maintenance for electric motors is needed.

SUMMARY

[0003] According to one or more embodiments, a turbine comprises: a variable flux memory motor (VFMM) generator that converts an input kinetic energy of the turbine to electrical power; and a controller. The controller: monitors a power load on the VFMM generator or the input kinetic energy of the turbine; receives a signal indicating a change in the power load or input kinetic energy of the turbine; and changes a magnetization state of the VFMM generator to set operation of the VFMM generator.

[0004] According to one or more embodiments, a method to control efficiency of a turbine comprising a VFMM generator comprises: monitoring a power load on the

VFMM generator or an input kinetic energy of the turbine; receiving a signal indicating a change in the power load or input kinetic energy of the turbine; and changing a magnetization state of the VFMM generator to set operation of the VFMM generator.

[0005] Other aspects of the invention will be apparent from the following description and the appended claims.

BRIEF DESCRIPTION OF EXHIBITS

[0006] Exhibit A shows and describes systems, methods, and examples in accordance with one or more embodiments of the invention. Exhibit A is hereby incorporated by reference in its entirety. Details in Exhibit A are provided for purposes of illustration and are not intended to limit the scope of the invention to the particular details disclosed therein.

BRIEF DESCRIPTION OF DRAWINGS

[0007] FIG. 1 shows a synchronous electric motor.

[0008] FIG. 2 shows a cross-sectional view of a variable-flux memory motor (VFMM) in accordance with one or more embodiments.

[0009] FIG. 3 shows a wind turbine.

[0010] FIG. 4 shows an efficiency map of a conventional generator.

[0011] FIG. 5 shows an efficiency map of a VFMM generator according to one or more embodiments.

[0012] FIG. 6 shows a diagram in accordance with one or more embodiments.

[0013] FIG. 7A shows a diagram in accordance with one or more embodiments.

[0014] FIG. 7B shows a diagram in accordance with one or more embodiments.

[0015] FIG. 8 shows a diagram in accordance with one or more embodiments.

[0016] FIGS. 9A-9E show diagrams in accordance with one or more embodiments.

[0017] FIG. 10 shows a diagram in accordance with one or more embodiments.

[0018] FIG. 11 shows a flow chart in accordance with one or more embodiments.

[0019] FIG. 12 shows a flow chart in accordance with one or more embodiments.

DETAILED DESCRIPTION

[0020] Specific embodiments of the invention will now be described in detail with reference to the accompanying figures. Like elements in the various figures are denoted by like reference numerals for consistency.

[0021] In the following detailed description of embodiments of the invention, numerous specific details are set forth in order to provide a more thorough understanding of the invention. However, it would have been apparent to one of ordinary skill in the art that the invention may be practiced without these specific details. In other instances, well-known features have not been described in detail to avoid unnecessarily complicating the description.

[0022] FIG. 1 shows an exploded view of a conventional synchronous electric motor (100) (hereinafter, will be referred to as “synchronous motor”) including a rotor (101), a stator (102), and stator windings (103) arranged around a rotor hub (104). The synchronous motor may also include a terminal box for connecting input power, a cooling fan, a rotor position sensor, temperature sensors, liquid cooling housings, etc. The rotor (101) includes multiple poles, each including permanent magnets (105) (PM).

[0023] The synchronous motor (100) may operate via a multi-phase AC input such that the phases of the AC input may have a delay of “360 degrees divided by the number of phases” from each other. For example, the synchronous motor (100) may operate via a three-phase AC input, in which each phase is delayed from the other two phases by 120 degrees. To create the three-phase AC input, a power converter may convert DC power fed to the power converter from a high voltage DC source (e.g., a battery). By applying the three-phase AC input to the synchronous motor, the stator windings create a three-phase magnetic field that interacts with the magnetic fields of the PMs (105) and cause the rotor (101) to rotate with a fixed number of revolutions per minute (RPM) speed in a steady-state (hereinafter, will be referred to as “RPM”). The RPM of the synchronous motor is fixed to limiting factors such as number of poles,

available voltage, and flux linkage (λ_m), which is provided and is fixed by the PMs. Synchronous motors have a wide range of applications in industrial, commercial, and residential, applications, such as fans, pumps, compressors, elevators, and refrigerators, industrial machinery, and electric vehicles.

[0024] In one or more embodiments, because the λ_m provided by the PMs is fixed, the synchronous motors with PMs have a narrow constant power speed range (CPSR), which is the speed range at which the drive of the motor can maintain a constant power with limited values of input voltage and current of the motor. Thus, increasing the CPSR of the synchronous motors without using advanced control techniques such as implementing flux-weakening control methods is difficult. Because of the narrow range of CPSR for the synchronous motors, using a transmission system may be required to change a CPSR of a system driven by the synchronous motor. Even using such advanced methods extend the CPSR of the synchronous motors to 2 to 3. On the other hand, the CPSR of the VFMM according to one or more embodiments may achieve 4 to 6.

[0025] In general, embodiments of this disclosure relate to designs of VFMMs, rotors for VFMMs, and methods for magnetizing VFMMs. A VFMM is a type of synchronous motor in which magnetization of rotor magnets of the VFMM can be adjusted (*i.e.*, changed) during an operation of the VFMM. The adjustment of the magnetization of the rotor magnets (hereinafter, will be referred to as “VFMM magnetization” for simplicity) changes relationship of the back electromotive force (back EMF) to RPM of the VFMM. According to one or more embodiments, to facilitate the change in the VFMM magnetization, the rotor magnets are made of a soft-ferromagnetic material such as aluminum nickel cobalt (AlNiCo) or some types of ceramics. Hereinafter, the rotor magnets made of a soft-ferromagnetic material will be referred to as “soft magnets.” The soft magnets are Low Coercive Force Magnets (LCF). According to one or more embodiments, the soft magnets may be AlNiCo with grades 1-9 or magnets comprised of AlNiCo, cast, ceramics, some grades of samarium cobalt, or sintered construction of these materials. It is apparent that one of ordinary skill in the art could use specific amounts of these materials to achieve a desired function of the VFMM.

[0026] The VFMM in accordance with one or more embodiments is a better substitute to a synchronous motor because a maximum achievable RPM with a limited bus voltage of the VFMM may be more efficiently attained through changing the VFMM magnetization. In other words, the CPSR of the VFMM could have a wider range compared to the CPSR of the synchronous motor. Thus, there is no need to couple the transmission system to the VFMM.

[0027] According to one or more embodiments, the soft magnets can be quickly and efficiently magnetized and demagnetized while the soft magnets are assembled inside the motor. Accordingly, using the VFMM potentially reduces manufacturing costs of electric motor-equipped systems due to being magnetized or demagnetized during assembly.

[0028] Soft-ferromagnetic materials have high permeability (same as hard-ferromagnetic materials such as alloys of iron and nickel) but low coercivity (unlike hard-ferromagnetic materials). Because of the low coercivity of soft-ferromagnetic materials, changing the magnetization of soft-ferromagnetic materials requires relatively smaller magnetic field compared to hard-ferromagnetic materials.

[0029] In one or more embodiments, only soft magnets may be used as the magnets of the rotor of the VFMM and there may be no hard magnets (i.e., magnets made of hard-ferromagnetic materials) mounted on the rotor. Alternatively, in one or more embodiments, both of the soft magnets and hard magnets may be used as the magnets of the rotor of the VFMM. Embodiments of this disclosure may have advantages over synchronous motors, which use only hard magnets, because hard magnets are made of rare-earth materials and are significantly more expensive than soft magnets (e.g., AlNiCo). Thus, partially or entirely using soft magnets instead of hard magnets in the VFMM significantly reduces manufacturing costs of the VFMM compared to traditional synchronous motors.

[0030] Additionally, another advantage of using the soft magnets is that control and change of the overall magnetization of the overall magnets of the VFMM can be done in a wide range. According to one or more embodiments, the overall magnetization of the soft magnets can be changed to any value from 0% magnetization (i.e., the soft magnets are completely demagnetized) to 100% magnetization (i.e., the soft magnets

are magnetized to their maximum capacity). This change in magnetization may occur in a short time (*e.g.*, about 1 millisecond).

[0031] In contrast, hard magnets do not tend to change their magnetization easily. Accordingly, changing the magnetization of hard magnets requires significantly more power than the operating power of a VFMM or other types of synchronous motors. For example, changing magnetization of hard magnets, such as some grades of neodymium iron boron (NdFeB) and samarium cobalt (SmCo) may require a power more than 10 folds higher than a power required for changing magnetization of the soft magnets.

[0032] According to one or more embodiments, a current (hereinafter, will be referred to as the “glitch current”) may be generated due to an unwanted glitch in the VFMM or a controller that controls the VFMM. If a current that is higher than operational current of the stator windings passes the stator windings, this current may temporarily change the magnetization of the soft magnets to an unwanted value. However, it will be easy to revive the magnetization of the soft magnets by another current that is bearable by the stator windings. No matter how high the glitch current be, the magnetization of the soft magnets can be revived via a relatively smaller current than the glitch current because soft magnets can easily accept a different magnetization (compared to hard magnets that require a high current to change magnetization).

[0033] On the other hand, if a synchronous motor that has soft magnets (such as a VFMM) includes hard magnets and the glitch current changes the magnetization of the hard magnets, reviving the magnetization of the hard magnets via a current in the stator windings will be difficult. Such a current capable of reviving the hard magnets may be too high to bear for the stator windings or other parts of the synchronous motor. For example, such a high current may burn the stator windings or may dislocate various components of the synchronous motor such as the rotor and the windings. To revive the hard magnets, the synchronous motor must be opened and the hard magnets must be separated from the synchronous motor to be placed under a high magnetic field. However, as explained above, reviving the soft magnets does not require disassembling the VFMM.

[0034] In one or more embodiments, a certain number or amount of hard magnets may be used to create a magnetization baseline for the VFMM. Because the magnetization of the hard magnets is reluctant to change, the magnetization of the hard magnets will be the magnetization baseline, and the magnetization of the soft magnets will change the overall magnetization from the magnetization baseline (to higher or lower magnetization from the baseline, depending on the torque and RPM of the VFMM).

[0035] FIG. 2 shows a cross-sectional view of the VFMM (200) in accordance with one or more embodiments. The VFMM (200) of FIG. 2 includes a stator (201) that holds the stator windings in slots between adjacent stator teeth (202), and a rotor (203). The rotor (203) includes the soft magnets (204) and ferrous wedges (205) that are mounted on a rotor core (206). The rotor (203) is mounted on a shaft (208). The rotor (203) includes a sleeve (207) that keeps the soft magnets (204) and ferrous wedges (205) together. The sleeve (207) may be 0.5 to 3 millimeter (mm) thick in the radial direction. The thickness is determined by the centrifugal force exerted by the soft magnets (204) and the ferrous wedges (205). Alternatively, in one or more embodiments, the sleeve (207) may adhere to any one of the soft magnets (204), the ferrous wedges (205), and/or the rotor core (206).

[0036] In these embodiments, the sleeve (207) may be from a non-binding material, which does not adhere to the soft magnets (204), the ferrous wedges (205), and/or the rotor core (206). The non-binding sleeve (207) may be from carbon fiber HEX TOW IM10 or a Kevlar tow (i.e., Kevlar twine). Alternatively, the sleeve (207) may be a part of the rotor assembly.

[0037] The d-axis (direct axis) and q-axis (quadrature axis) for the VFMM (200) are shown in FIG. 2. D-axis is the axis that involves minimum reluctance of the rotor (203) to be magnetized while in q-axis the reluctance of the rotor (203) is at its maximum. For example, the d-axis in FIG. 2 is between the adjacent ferrous wedges (205), and the q-axis is away from the d-axis by 90 degrees phase shift. For example, q-axis in FIG. 2 is in the middle of adjacent soft magnets (204) of each pole.

[0038] According to one or more embodiment, examples of the VFMM may be the VFMMs disclosed in: U.S. Patent Application No. 16/383,274 entitled "A VARIABLE-FLUX MEMORY MOTOR AND METHODS OF CONTROLLING A

VARIABLE-FLUX MOTOR” and filed on April 12, 2019; and International Patent Application No. PCT/US2020/057140 entitled “METHODS OF MAGNETIZING AND CONTROLLING A VARIABLE-FLUX MEMORY MOTOR” and filed on October 23, 2020. These references are incorporated herein in their entireties.

[0039] According to one or more embodiments, a VFMM may be used to generate electrical power in a turbine, for example a wind turbine. Hereinafter, the VFMM that is used to generate electrical power is referred to as “VFMM generator.” VFMM generators may have advantages that excel them over conventional generators used in turbines.

[0040] FIG. 3 shows a schematic of a routine wind turbine (300). Turbine blades (310), which rotate via wind’s kinetic energy, rotate a generator (320) that produces electrical power. Because wind’s kinetic energy may fluctuate substantially, a controller (330) measures a real-time wind’s kinetic energy via an anemometer (340), and may instruct various parts of the wind turbine (300) to modify their functions to generate a stable electrical power. For example, the controller (330) may instruct a yaw motor (380) to control the orientation of the whole generator nacelle. In another example, the controller (330) may instruct a blade pitch motor to adjust a blade pitch (350) of the blades (310) in accordance with the real-time wind’s kinetic energy. The blade pitch (350) correlates to an angle of the blades (310) with respect to a rotational axis of the blades (310) (*i.e.*, an axis around which the blades (310) rotate). For example, the rotational axis of the blades (310) is along the low-speed shaft (360). Hereinafter, the wind’s kinetic energy may also be referred to as wind speed, wind direction, wind intensity, or wind power.

[0041] Further, although power generation by a wind turbine is explained in FIG. 3, other types of turbines may function with similar configurations or methods. For example, wave power generators or dam power generators may be configured similar to the wind turbine. For example, an input kinetic energy (*e.g.*, wave kinetic energy or water flow kinetic energy) is transferred to a generator to rotate the rotor of the generator and generate electricity. A controller may measure a real-time input kinetic energy and adjust an amount of the transferring energy to the generator. For example, a controller may dynamically measure the wave kinetic energy or water flow kinetic

energy, and use a mechanism such as a gearbox to increase or decrease the amount of the transferring energy to the generator.

[0042] However, conventional generators used for such turbines may not be sufficiently efficient. FIG. 4 shows an efficiency map of a typical modern electric motor that may be used as a generator. As shown in FIG. 4, efficiencies of 90% and higher are localized to a small region of the operating range of the generator.

[0043] According to one or more embodiments, VFMM generators, however, may enable a broader high-efficiency operating range. For example, FIG. 5 shows an efficiency map of a VFMM generator.

[0044] Because of the vast high-efficiency operating range in the efficiency map of the VFMM generator, more efficient power generation may be obtained while having more flexibility in adjusting operating conditions of the VFMM generator (*e.g.*, generator speed or torque). Accordingly, this could minimize excessive power drain and associated energy consumption. Further, because the vast high-efficiency operating range may increase flexibility in adjusting the operating conditions of the VFMM generator, operating conditions of the VFMM generator may be adjusted faster in response to changes in the input kinetic energy of the turbine (*e.g.*, wind power). Also, electric power generation may be more uniform during the changes in the input kinetic energy of the turbine. Moreover, when multiple VFMM generators are used in a power generation plant (*e.g.*, a wind farm where each wind turbine includes a VFMM generator), the vast high-efficiency operating ranges in the power efficiency maps of the VFMM generators may result into faster and more flexible optimization of the output electrical power by adjusting the operating conditions of the VFMM generators more flexible and faster.

[0045] Typical synchronous generators use either field coils or hard permanent magnets to generate a magnetic field. These structures may have drawbacks. For example, field coils introduce power loss through copper wires and brushes used to conduct current needed to generate magnetic fields. Permanent Magnet Synchronous Generators PMSG (which use hard permanent magnets) may avoid the mentioned drawback of field coils at the expense of using rare-earth magnets. However, because

VFMM generators may use soft magnets instead of field coils or hard permanent magnets, VFMM generators may not have these drawbacks.

[0046] The above-mentioned drawbacks of typical synchronous generators and advantages of VFMM generators can be better understood with reference to FIG. 6, which shows how a rectified voltage of a generator increases linearly with generator speed (in revolution per minute (RPM)). For generators with field coils the slope of the line shown in FIG. 6 can change by changing the current in the field coils. For generators with hard permanent magnets, the slope of the line can be changed by a mechanism known as field weakening, which is a process where fields of the hard permanent magnets are suppressed by a component of a magnetic field generated by a stator. Changing the slope of the line in FIG. 6 by these methods may have issues, which may be overcome by using a VFMM generator, as explained below.

[0047] Creating field in the field coils or creating a suppression field for field weakening may require a high current, which causes power loss in coils that generate the fields. Besides, if a control system that controls the generator fails, the generators do not have an automatic feedback mechanism to lower power generation and avoid an undesirable situation such as fire. In fact, in the absence of a proper suppression field for field weakening, a full rotor field dominates and may generate voltages higher than what the control system can handle.

[0048] However, according to one or more embodiments, the magnetization of soft magnets in the VFMM generator can be changed with a single or sequence of current pulses. This significantly reduces power consumption in compare to using field coils or hard magnets along with the field weakening mechanism. For example, the maximum magnetization state that is indicated by "1" (that is circled) and the minimum magnetization state indicated by "2" (that is circled) in the VFMM generator's operating range shown in FIG. 5 may correlate with slopes "1" and "2" shown in FIG. 6, respectively. As shown in FIG. 5, the maximum magnetization state 1 corresponds to a high torque and a low speed (rotational velocity) of the VFMM. On the other hand, the minimum magnetization state 2 corresponds to a low torque and a high speed of the VFMM. Because the power efficiency in the efficiency map of FIG. 5 does not differ much between magnetization states 1 and 2, there may be less power loss in compare to the typical generator.

[0049] Additionally, with the VFMM generator being more efficient over a wider operating range, an optimal power generation of the VFMM generator may be obtained at all times. This may be done for a single VFMM generator and for a networked of VFMM generators across a power plant such as a wind farm.

[0050] For the typical modern electric motor discussed above with reference to FIG. 4, the efficiency of the typical modern electric motor significantly varies across the efficiency map shown in FIG. 4. For example, the efficiency of the typical modern electric motor varies significantly between the higher torque region and the higher speed region. Even in each of the regions, the power efficiency is not stable (*i.e.*, uniform). Further, the efficiency of the typical modern electric motor in the higher torque and higher speed regions is much lesser than the efficiency in the center of the efficiency map. Thus, even small fluctuations in wind power/speed/direction can cause significant efficiency loss.

[0051] As explained above with reference to FIG. 3, the blade pitch motor may move the blades of the wind turbine to adjust the blade pitch based on instruction received from the controller. The blade pitch may be determined and adjusted based on generator speed and input torque for a real-time wind power. For, example, as more electric load is applied on the generator, the blade pitch may be modified to maintain the generator's speed. According to one or more embodiments, a control system may adjust/change the VFMM generator's magnetization state to have the best efficiency, and to change the blade pitch to a suitable position to coordinate the transferring power from the wind to the VFMM generator. Accordingly, the torque associated with the blade pitch/angle can be determined based on the wind power and electric load. According to one or more embodiments, the blade's top speed can be kept within an optimal range by adjusting the blade pitch. Then, the VFMM generator's magnetization state can be adjusted to maximize the VFMM generator's efficiency at a preferred torque and speed.

[0052] According to one or more embodiments, a network of turbines (*e.g.*, a wind farm) may include multiple VFMM generators. The VFMM generators may be connected in the network to receive signals from a central control unit or from each other. The connection may be via Wi-Fi or other communication system. Because

the response of the VFMM generators can be optimized much faster compared to conventional generators, power across the entire farm may be optimized faster. Accordingly, a control system or an operator may be able to instruct all of the VFMM generators across the farm to operate in a way to generate a desired power, for example a consistent power. For example, in the wind farm, there may be horizontal or vertical differences in wind shear profile, which may affect operations of the VFMM generators and/or cause fluctuations in the generated power. As explained below with reference to FIGS. 7A and 7B, the VFMM generators can be coordinated by adjusting their magnetization states such that the combination of the VFMM generators generates a desired power.

[0053] FIG. 7A illustrates a wind farm with rows A-H of wind turbines (circles) by way of example. In FIG. 7A, wind speed and direction (wind profile) across the wind farm are uniform, as shown by similar arrows. The uniformity in the wind profile may lead to a uniform alignment of the wind turbines and to similar power generation profiles for each of the wind turbines. Although the wind profile is uniform in this example, the power generation in the wind farm may not be optimized and may require adjusting operating conditions of the VFMM generators. According to one or more embodiments, operating conditions of the VFMM generators based on their efficiency maps can be performed faster than for a network of conventional generators.

[0054] FIG. 7B shows another example of a wind farm where wind profile may change across the wind farm. For example, in FIG. 7B, a speed of wind profile 2 is higher than a speed of wind profile 1, and a speed of wind profile 3 is higher than the speed of wind profile 2. The change in the wind profile can occur due to a number of factors such as natural inhomogeneities in the terrain of the farm (*e.g.*, different elevations for the wind turbines, vertical wind profile over boundary layers, or different heat and moisture fluxes). In this example, each of the VFMM generators may be quickly and dynamically optimized to respond to a different wind profile. For example, according to one or more embodiments, a control system can respond immediately to the changes in the wind profiles, and move operation conditions of each of the VFMM generators to an appropriate operating condition in the efficiency map. However, for conventional generators, the different wind profiles could result to the generators no

longer operating efficiently in their corresponding power efficiency maps, and that it would be difficult to adjust their operating conditions because of the small high-efficiency region in their efficiency maps (as shown in FIG. 4).

[0055] In one or more embodiments, the blade pitch motor that controls the blade pitch or the yaw motor that controls the orientation of the generator nacelle may be a VFMM. With this, optimizing the blade pitch to have an optimum power generation may be performed faster. This is because the VFMM can provide more torque when needed than a conventional motor of a comparable efficiency by shifting into a low speed-high torque mode or various other combinations of speed and torque (which are inversely related) across the uniform power efficiency map of the VFMM. The VFMM yaw motor or VFMM blade pitch motor may have a similar power efficiency map as shown in FIG. 5.

[0056] In some circumstances, for example when the wind speed is higher than normal, the power generation by the VFMM generator may be more than the amount a power grid needs at that time. According to one or more embodiments, the excess generated power may be stored in an energy storage system, such as a bank of Li-ion batteries, for short to long term energy storage.

[0057] According to one or more embodiments, a VFMM generator in a turbine may be safer than a conventional generator in case of a fault such as a short circuit in a power converter fed by the generator. For example, if the generator is a hard permanent magnet motor (*i.e.*, a generator that uses hard permanent magnets to generate power), during a converter fault, the generator's electromagnetic field continues to feed the fault. This may result in high torque pulsations and high converter currents, which may cause significant electrical damages or even fire in the converter or the entire turbine. However, for VFMM generators, a short circuit (*e.g.*, a fault in a DC bus) would induce a fault current that would demagnetize the VFMM generator. The demagnetization of the VFMM generator would reduce or stop the generated current by the VFMM generator. This limits or stops the fault current. This situation is further explained with reference to FIG. 8.

[0058] FIG. 8 shows an example of a converter fed by a VFMM generator. In a normal operating condition, the wind turbine rotates the VFMM generator. The VFMM

generator generates electrical power and feeds the electrical power to the converter, which may generate a DC power. Upon occurring a short circuit in a DC bus, the voltages on the VFMM generator's three-phase outputs (a, b, and c) are lowered. The lowered voltages demagnetize soft magnets in the VFMM generator and lowers or stops the power generation by the VFMM generator. A transient behavior of the demagnetization of the VFMM generator is explained below with reference to FIGS. 9A-9E and 10.

[0059] FIGS. 9A-9E show an operation of a VFMM generator from time zero to about time 0.06 seconds (sec), wherein a fault occurs at 0.045 sec. First, a normal operation of the VFMM generator between time zero and time 0.045 sec (before occurrence of the fault) is discussed. As shown in FIG. 9A, at time 0.01 sec, by applying a roughly constant torque on the VFMM generator and a roughly constant magnetization state for the VFMM generator's soft magnets, the VFMM generator's RPM starts to linearly ramp up. The VFMM generator's torque and magnetization state (MS) are shown in FIGS. 9B and 9C, respectively. At time 0.04 sec the VFMM generator reaches its operating RPM and continues working at the operating RPM. As shown in FIG. 9D, between times 0.01 sec and 0.04 sec, the currents of the VFMM generator's windings ("motor current") oscillate to reach roughly stable oscillations at 0.04 sec and continue the stable oscillation. As shown in FIG. 9E, similar to the motor current, the voltages of the VFMM generator's windings ("line voltage") oscillate to reach roughly stable oscillations at 0.04 sec and continue the oscillation.

[0060] Now, operation of the VFMM generator after occurrence of the fault at time 0.045 sec is discussed. At time 0.045 sec, a fault such as the short circuit shown in FIG. 8 occurs, and alters the operation of the VFMM generator on and after time 0.045 sec. As shown in FIGS. 9B and 9C, shortly after occurrence of the fault, the torque and magnetization state of the VFMM generator become very low or zero due to a negative direct current (i_d) in the VFMM generator. As a result, the motor current and the line voltage becomes low or zero as well, as shown in FIGS. 9D and 9E. Thus, when the fault occurs, unlike the conventional generators, the VFMM generator's power output may become low or zero, and less or no power would feed to the converter. This feedback mechanism prevents aggravating the fault.

[0061] FIG. 10 shows a relationship between the i_d and magnetic flux density (B) in the VFMM generator. As explained above, upon occurrence of the fault, the negative i_d generates a negative B, which lowers the magnetization state (demagnetizing the soft magnets) of the VFMM generator.

[0062] Consistent with the above-explained embodiments, one or more embodiments are directed to methods that may increase efficiency of turbines and are explained below with reference to FIGS. 11 and 12.

[0063] As shown in FIG. 11, in Step 110, a sensor or a plurality of sensors may monitor power load of a VFMM generator or the input kinetic energy of the turbine. For example, for reporting the input kinetic energy of a wind turbine, the anemometer may detect wind profile and report such information to a controller. As another example, a processing unit that receives values of torque or generator speed (RPM) from the VFMM generator may measure power load and send it to the controller. Each of the controller and the processing unit may include a processor such as a CPU and/or a memory such as RAM to store processing data that is needed for processing. The controller and processing unit may be the same or different components.

[0064] In Step 120, the controller may receive a signal indicating a change in the power load or input kinetic energy of the turbine. In the examples explained with reference to Step 110, the controller may receive the signal from the anemometer or a processing unit reporting the change in the power load or input kinetic energy of the turbine.

[0065] In Step 130, the controller may find a suitable torque or generator speed at which an efficiency of the VFMM generator under the changed power load or input kinetic energy of the turbine is above a predetermined threshold. For example, the controller may use predefined data such as a look up table to find the suitable torque or generator speed based on the changed/new power load or input kinetic energy (*e.g.*, real-time values) of the turbine. The predefined data may be based on a power efficiency map of the VFMM generator. An example of the power efficiency map of the VFMM generator is shown in FIG. 5.

[0066] In Step 140, the controller may change a magnetization state of the VFMM generator to set operation of the VFMM generator under the changed power load or

input kinetic energy of the turbine to the suitable torque or generator speed. For example, after finding the suitable torque or generator speed described in Step 130, the controller sends a current pulse or a series of current pulses to windings of the VFMM generator to magnetize or demagnetize soft magnets of the VFMM generator such that the VFMM generator would operate at the suitable torque or generator speed.

[0067] Further, as shown in FIG. 12, in Step 210, the controller may control a blade pitch of a plurality of blades of a wind turbine. This may give more flexibility to the controller to set the efficiency of the VFMM generator at higher values. For example, the controller may control the blade pitch of the turbine according to the changed power load or input kinetic energy of the turbine.

[0068] In Step 220, the controller may control the magnetization state of VFMM generator according to the blade pitch to control the efficiency of the VFMM generator.

[0069] In one or more embodiments, the described steps may be performed in a different order than what is described above, unless it is stated otherwise. Further, the steps may be omitted or may be performed multiple times to achieve a desired magnetization state of the VFMM generator.

[0070] While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.

CLAIMS

What is claimed is:

1. A turbine comprising:
 - a variable flux memory motor (VFMM) generator that converts an input kinetic energy of the turbine to electrical power; and
 - a controller that:
 - monitors a power load on the VFMM generator or the input kinetic energy of the turbine;
 - receives a signal indicating a change in the power load or input kinetic energy of the turbine; and
 - changes a magnetization state of the VFMM generator to set operation of the VFMM generator.
2. The turbine according to claim 1, wherein
 - the controller finds a suitable torque or generator speed at which an efficiency of the VFMM generator under the changed power load or input kinetic energy of the turbine is above a predetermined threshold, and
 - the controller changes the magnetization state of the VFMM generator to set the operation of the VFMM generator under the changed power load or input kinetic energy of the turbine to the suitable torque or generator speed.
3. The turbine according to claim 1, wherein the controller finds the suitable torque or generator speed based on predetermined data that correlates torques and generator speeds of the VFMM generator to efficiencies of the VFMM generator.
4. A network of turbines comprising a plurality of turbines according to claim 1, wherein
 - the plurality of turbines in the network are connected to a control system, and
 - the control system controls each of the turbines to maintain an efficiency of the each turbine or an efficiency of the network of turbines above a predetermined level.
5. The turbine according to claim 1, wherein the controller further controls:

a blade pitch of the turbine according to the power load or the input kinetic energy of the turbine; and
the magnetization state of VFMM generator according to the blade pitch to control efficiency of the VFMM generator.

6. A wind turbine comprising a plurality of blades adapted to turn in wind, and the turbine according to claim 1 coupled to the plurality of blades such that the VFMM generator converts the input kinetic energy of the turning of the plurality of blades in the wind to electrical power.

7. The wind turbine according to claim 6, further comprising a VFMM that moves the plurality of blades to adjust a blade pitch of the plurality of blades based on an instruction received from the controller,
wherein the controller sends the instruction based on a sensing of a profile of the wind.

8. A method to control efficiency of a turbine comprising a variable flux memory motor (VFMM) generator, the method comprising:
monitoring a power load on the VFMM generator or an input kinetic energy of the turbine;
receiving a signal indicating a change in the power load or input kinetic energy of the turbine; and
changing a magnetization state of the VFMM generator to set operation of the VFMM generator.

9. The method according to claim 8, further comprising:
finding a suitable torque or generator speed at which an efficiency of the VFMM generator under the changed power load or input kinetic energy of the turbine is above a predetermined threshold; and
changing the magnetization state of the VFMM generator to set the operation of the VFMM generator under the changed power load or input kinetic energy of the turbine to the suitable torque or generator speed.

10. The method according to claim 8, further comprising:

controlling a blade pitch of a plurality of blades of the turbine according to the changed power load or input kinetic energy of the turbine; and
controlling the magnetization state of VFMM generator according to the blade pitch to control efficiency of the VFMM generator.

11. The turbine according to claim 1, wherein the VFMM generator comprises one or more soft magnets.
12. The turbine according to claim 11, wherein the one or more soft magnets comprise aluminum, nickel, and cobalt.
13. The turbine according to claim 12, wherein the one or more soft magnets are AlNiCo with a grade of 1-9.
14. The method of claim 8, wherein the VFMM generator comprises one or more soft magnets.
15. The method of claim 14, wherein the one or more soft magnets comprise aluminum, nickel, and cobalt.
16. The method of claim 14, wherein the VFMM generator further comprises one or more hard magnets, and wherein a magnetization state of the hard magnets establishes a magnetization baseline.
17. The method of claim 14, wherein the changing the magnetization state of the VFMM generator comprises changing a magnetization state of the one or more soft magnets.
18. The method of claim 16, wherein the changing the magnetization state of the VFMM generator comprises changing a magnetization state of the one or more soft magnets to a magnetization greater than the magnetization baseline.
19. The method of claim 17, wherein the magnetization state of the one or more soft magnets is changed by applying one or more current pulses.

20. The method of claim 15, wherein the one or more soft magnets are AlNiCo with a grade of 1-9.