Using the M2LC in a Wind Turbine Application

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Revision -

Introduction

In the first installment of the *M2LC Blog* I present one of many possible applications for the use of an M2LC (Modular Multilevel Converter). But first, let me provide a somewhat condensed history of the creation and use of this converter.

The M2LC is a type of AC to DC cell based converter for high voltage/high power applications that does not require the use of a transformer for sustaining each cell voltage.

At present, the bulk of research presented for the M2LC is due to Rainer Marquardt, Professor at the University of Bunderwehr, Munich Germany. An example of a working converter can be found at Benshaw M2LC (M2L-3000 Series Medium Voltage Variable Frequency Drive , Regal-Benshaw). A block diagram of one phase of this converter is shown in Figure 1.

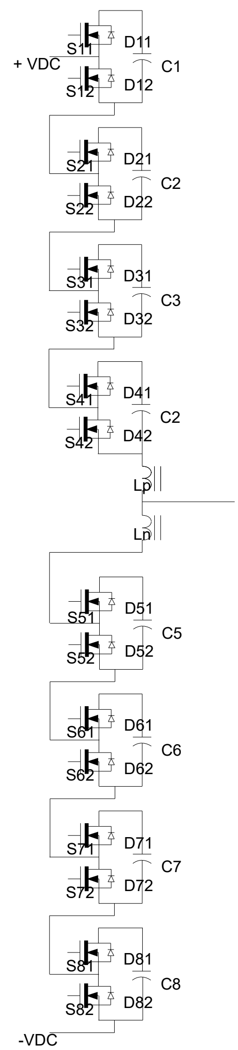

FIGURE 1 Block diagram of one phase of a 5 level M2LC. The transformer and rectifier that generates +/-Vdc is not shown.

The M2L-3000 uses start-of-the-art fiber optics connections between a central controller and series of high voltage switching cell. These isolated connections are *smart* in the sense that they provide not only on/off control to each cell but also isolated current and voltage feedback as well as a gateway for general commands/status. This is done using an embedded 100 Base-FX (POF) interface between each cell and the controller.

Unlike a *neutral point clamp* converter (see Figure 2), energy is stored in capacitors contained in each of the series of *cells* that make up a given phase of the M2LC. Where as in a neutral point clamp, energy is stored in the series of capacitors that define the DC bus. Thus, the DC bus voltage of the M2LC is defined as the sum of all cells whose voltage *contributes* to the series connection between the plus and minus rail at any given instant in time.

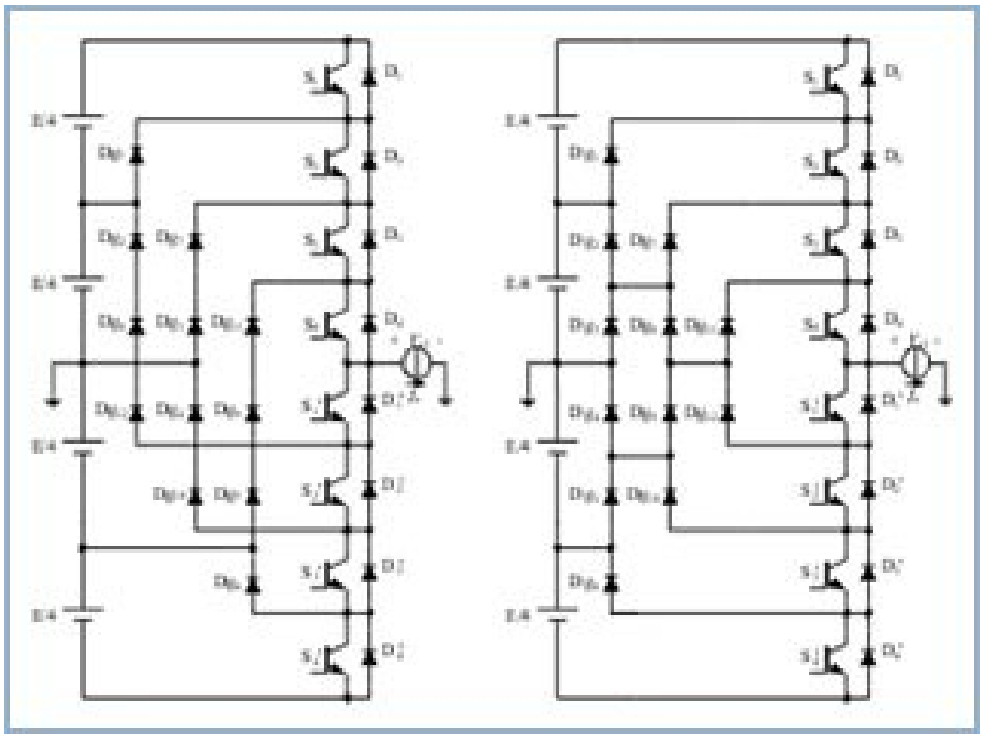

FIGURE 2 Block diagram of two variants of a one phase, 5 level neutral point clamp converter. The transformer secondary and rectifier that generates voltage for each of the capacitors is not shown. (Image courtesy of Ivo Barbi , www.ivobarbi.com)

Also, there is no interdependence between the cells of the M2LC (other than the communications interface) allowing cell stacks to achieve a very high DC voltage[1]. In comparison, the neutral point clamp converter requires secondary voltage blocking components (usually diodes) connected to the capacitor stack making up the DC bus.

Another example of a multi-level converter is the *cascaded H bridge* (see Figure 3). This type of converter requires each cell to be connected to the rectified secondary of a transformer. In this arrangement the cells themselves provide the power in that there is no centralized DC bus.

1 DC voltage on the order of a million volts is possible.

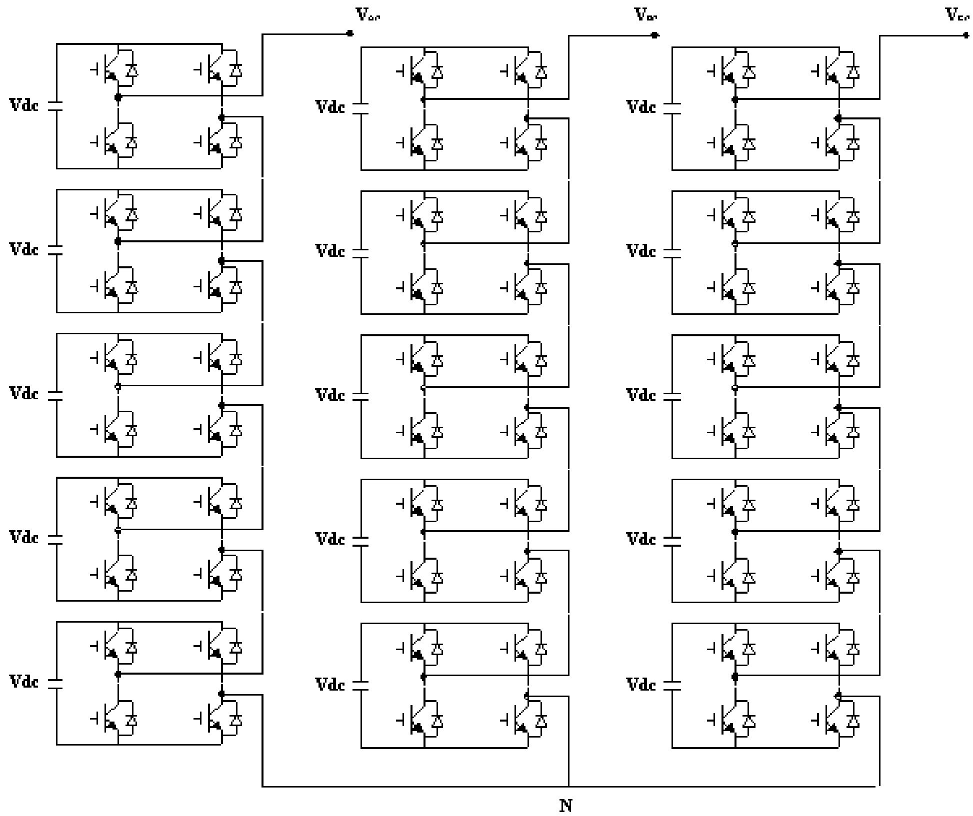

FIGURE 3 Block diagram of a 3 phase,11 level cascaded H bridge converter. The transformer secondaries and rectifier that generates each of the Vdc buses is not shown. (Image courtesy of http://ljs.academicdirect.org/A06/42_58_files/image004.gif)

The M2LC has the advantage of requiring only one rectified source (that providing the +/- Vdc bus, see Figure 1). However, the M2LC (and for that matter the neutral point clamp) suffers one deficiency. Each require roughly twice as many cells to generate the same voltage level count as compared to the cascaded H bridge. The M2LC and neutral point clamp also exhibit problems when when applied to application requiring DC or low frequency AC power control due the fact that the capacitor voltages tend to quickly become imbalanced.

In may be said as far as IGBT count and the complexity of control required to drive each of the IGBT's, the neutral point clamp requires the least amount of resources with the M2LC requiring the most.

I have produced two papers that outline the design of a state-of-the-art M2LC system. One of which is

HighPerformanceM2LCSystem-Rev_A

that presents information on a proposed hardware implementation for this converter that includes details on the advantages of using high speed glass optical fiber as the means of communications between a central controller and each cell of the converter.

Also presented is a paper that describes the use of a special *resonance mode* of operation involving the cell capacitors and the inter-phase inductors that allows the converter to operate as a DC to DC converter making it applicable for applications involving motor speed/positioning control. This paper is found here.

HighPerformanceM2LCResonanceMode-Rev_C

It should be noted that as far as the application that is to be described, the use of this special resonance mode is not necessary[2]. This being the case, the interested reader need only refer to the section titled **Normal Mode** in the link above for a general idea on how the M2LC operates in the classical sense.

Application

With the short background just presented as to some of the various configurations available for high voltage AC to DC power conversion, I will present one application for the M2LC that makes it an ideal candidate for use in wind power conversion and storage.

The current technology used in wind turbine power system design presents a constraint on the range in which mechanical energy is transformed into electrical energy. Large gear boxes are used to transform the rotational frequency of the blades into a generator (usually a field controlled synchronous motors) so as to allow direct connection to the AC grid.

The gear box is quite massive and resides in the wind turbine nacelle (the compartment atop the mask that holds the blades). Like any mechanical device, this type of system is prone to wear and ultimately, failure if not maintained on a regular bases.

An AC-to-AC power converter (connected to the AC grid through a transformer) is used to control the current in the armature of the generator (the field) so as to provide a means to force power flow from the stator of the generator to the AC grid based on the current wind conditions. Since this electrical control mechanism is armature based (motor shaft), *slip-rings* are required to make the electrical connections between the armature and the converter. This provides an additional source of unreliability to the system.

The large gear box also limits the range of wind energy recovery contributing to a high *cost of operation* which compels most energy utilities to limit wind turbine use only to localities that can guarantee a sustained high velocity wind source.

Some of the limiting constraints described above are now being addressed with new designs such as the Siemens SWT-2.3.113 Direct Drive Wind Turbines (see Direct Drive Wind Turbine)

This design replaces the gear-box and field controlled synchronous motor with a direct connected permanent magnet generator[3]. Like traditional wind turbine designs, the control of blade pitch is retained.

This turbine is specificity designed for low to moderate wind conditions. It is my opinion that this design criteria will become the most important in years to come as wind turbines begin to be applied more in zones rated at 4 to 5 meters/sec (in other words, the northeast and southeast corridor, see Wind Map).

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2 Except maybe to start the rotation of the turbine on power up.
3 A bearing system is required to attach the blades to the generator.

Another issue being addresses is the problem of dealing with conditions when wind energy is in excess of the ability to transfer it back into the grid. Here, there is a need for an intermediate energy storage system that must also justify onto itself, a favorable *cost of operation.*

Such a system now exists and is believed by most to be the choice for bulk energy storage. This system is call a *Vanadium Redox Flow Battery* (see Lithium or Vanadium).

An interested reader, may also want to review Vanadium Redox Flow Batteries published by the *Electrical Power Research Institute* (EPRI). Here, the technology is described in detail.

Wikipdia article Vanadium Redox Sites provides a current list of installations using this technology for wind and solar energy storage.

The size of some of the typical installations listed in this document (between .5 and 5 MW) and the size of the Siemens SWT-2.3.113 turbine described above (2.5 MW) suggests that the technology may be best suited for a system to store excess wind energy when one storage battery system is paired with one wind turbine. This is the basis for the sub-system described next.

Figure 5 depicts a wind energy generating/storage system based on the M2LC and a Vanadium Redox Flow battery sub-system. This installation uses three AC/DC converters consisting of two bus connected M2L converters (M2LC_1 and M2LC_2) and one 3-phase 2 Quadrant[4] DC/AC converter (2QC) connected to the battery. A more detailed diagram of the 2QC is shown in Figure 4 below.

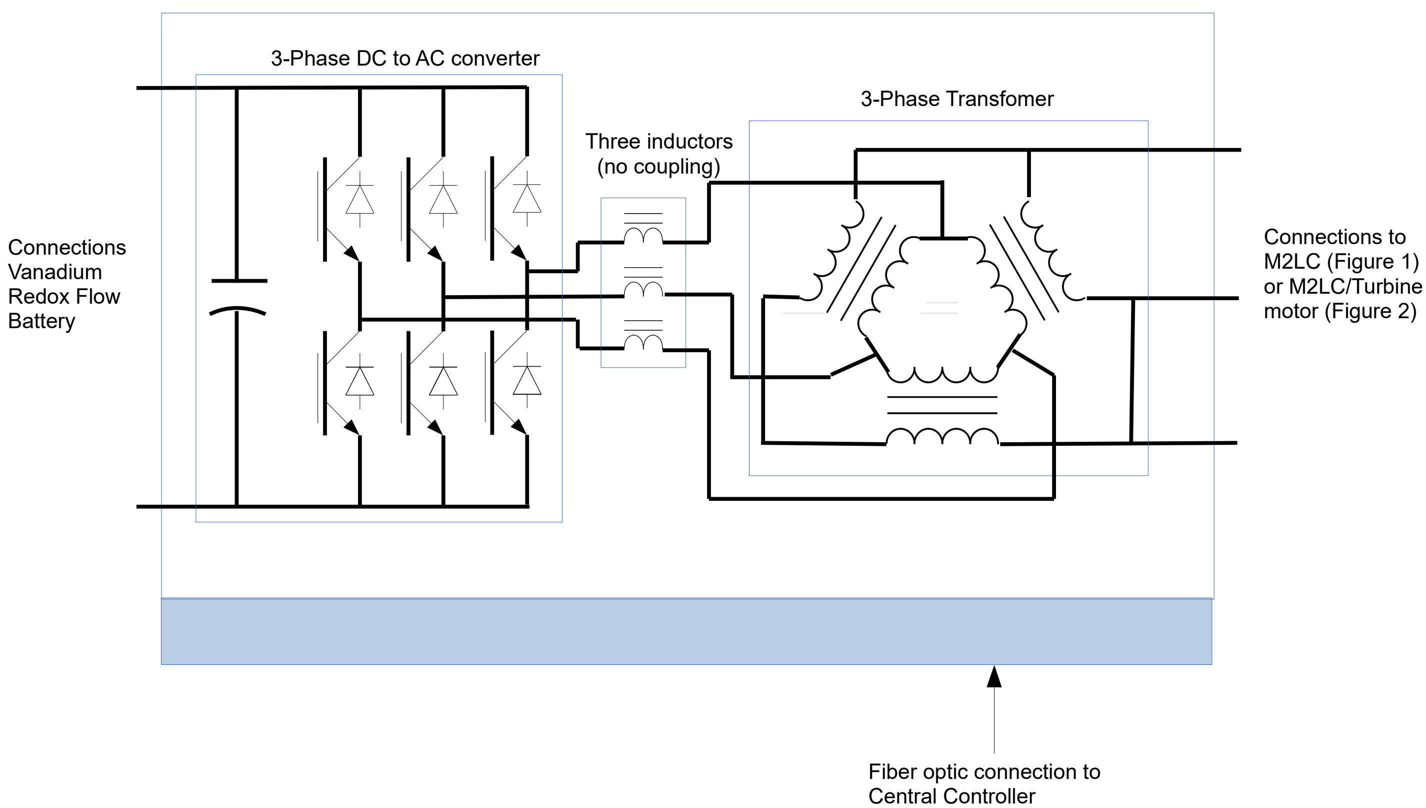

FIGURE 4 Detailed diagram of 4-Quadrant DC-AC converter (4QC) and transformer depicted in Figure 5 below.

4 Two quadrant in the sense of a D/Q transformation allowing bi-directional current in to a DC (single polarity) bus voltage.

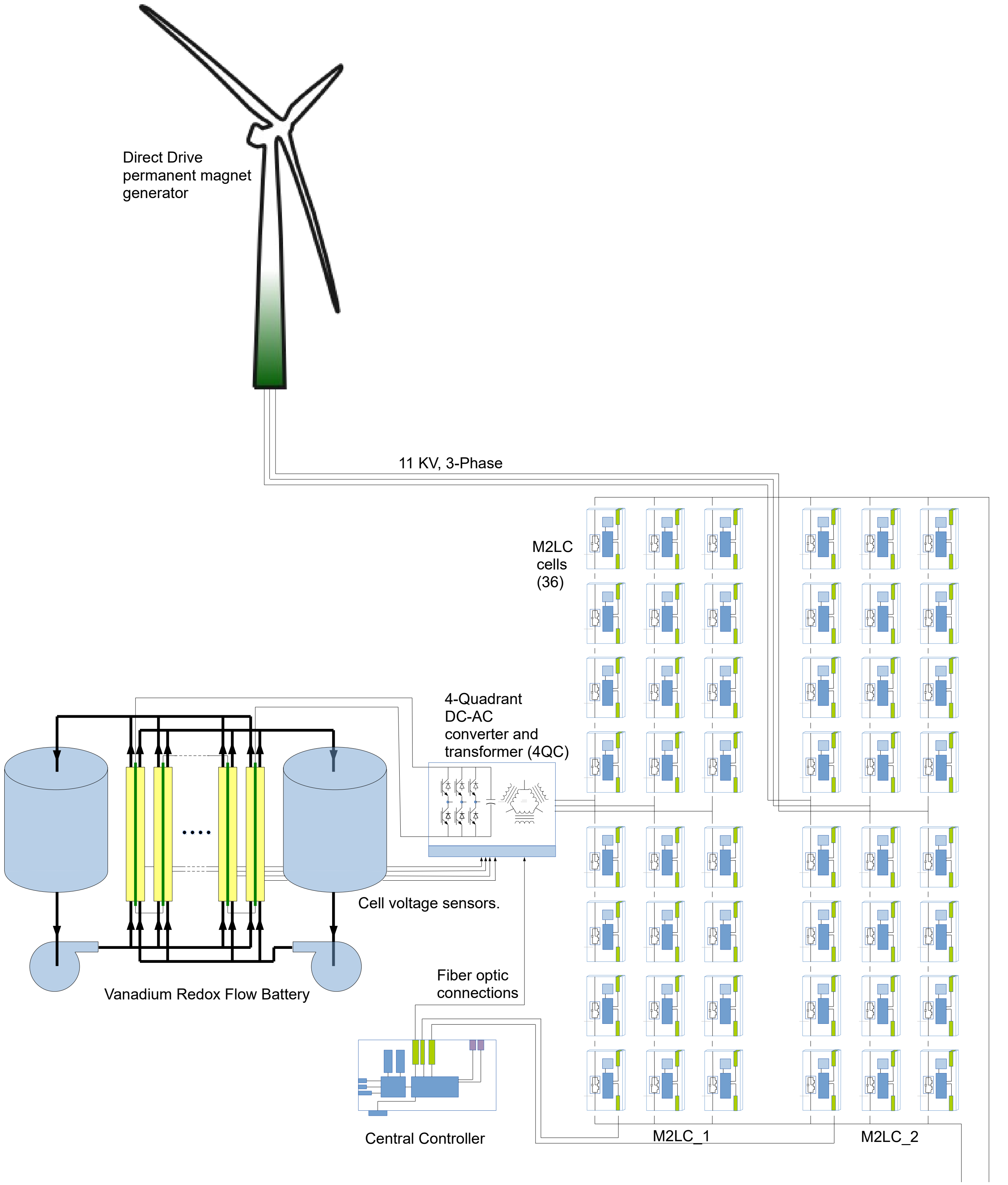

FIGURE 5 Generating and storage substation with no restrictions on the range of turbine voltage generation and battery voltage variation.

Connected between the 2QC and M2LC_1 is a three phase transformer and 3 inductors. A transformer is required because the battery stack cannot operate more than a couple of hundred volts due to the flow of the shared vanadium from the balk storage containers to each of the battery cells. In this example the DC bus of the M2LC's is typically at 13 KV DC.

It would be suggested that this transformer be optimized for 400 Hz operation. That way, its construction would be *iron* based reducing size and cost.

The control of of all three converters would be from a Central Controller (Reference Figure 3 page 5 of HighPerformanceM2LCSystem-Rev_A). This controller would also be responsible for monitoring the cell voltages of the battery in order to control both the 2QC and the M2LC_1 that are connected by the transformer.

The idea here is that the M2LC_1 would operate such that for a given bus voltage (DC grid), an AC voltage of a specified amplitude would be impressed on the transformer secondary connected to this converter. The fundamental frequency of this converter would also be set to maintain a constant volts/Hz relationship. The 2QC would operate at the same selected frequency. M2LC_1 would control it's AC voltage in such a way as to insure that the 2QC can operate in 2 quadrants at all times.

With the three inductors (reference Figure 4), the three phase bridge of the 2QC operates in transconductance mode. Thus the three inductors and transformer look very much like an AC synchronous machine that can *motor* (transfer power from the battery to the DC bus of M2LC_1), or *re-gen* (transfer power from the DC bus of M2LC_1 to the battery) in one direction.

M2LC_2 (reference Figure 5) would be responsible for transferring power from the wind turbine to the DC grid. M2LC_1 and M2LC_2 working together would be responsible for transferring power between their common DC bus and the DC grid (see Figure 6).

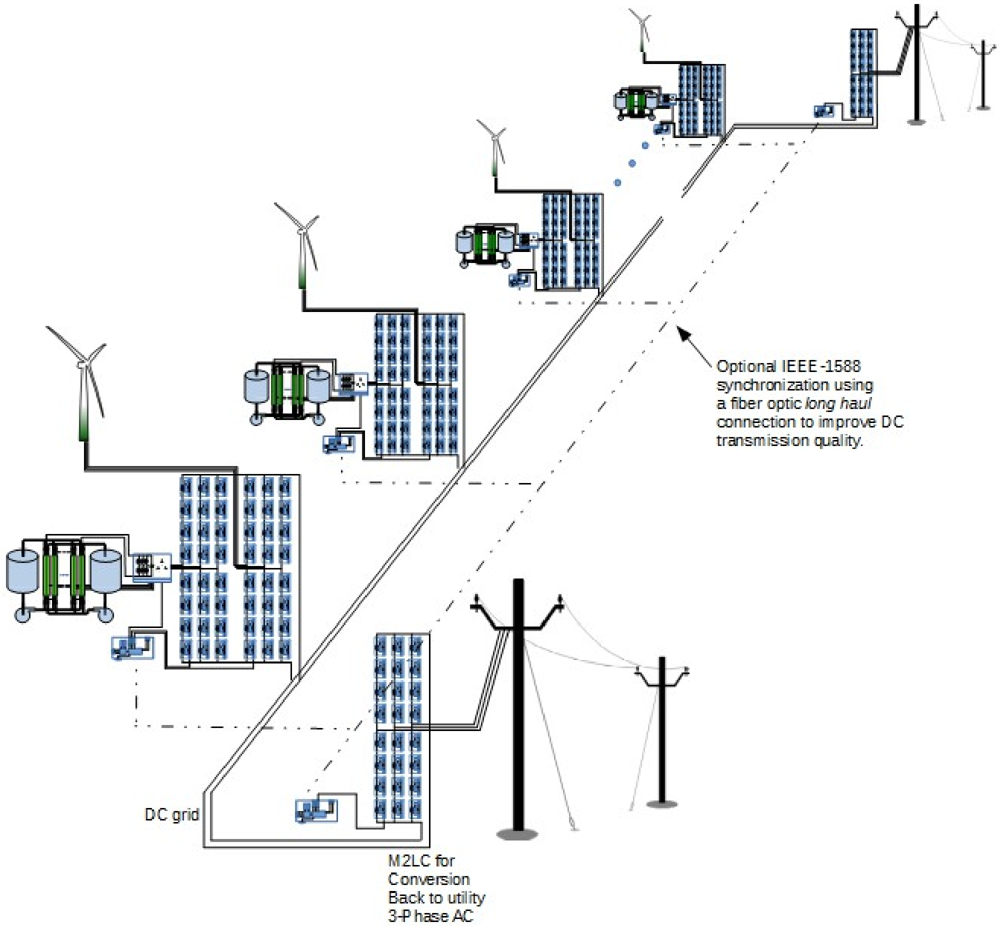

FIGURE 6 Optimized generating and storage substation with restrictions on the range of turbine voltage generation and battery voltage storage.

Because there is a separate M2LC (M2LC_2) connected to the turbine, power can be drawn from wide range of wind speeds. Also with three converters, power can be drawn from the wind and can be transferred to the DC grid and/or to the battery. Or, power can simply be transferred from the battery to the DC grid during times of low wind velocity. This can all be done concurrently.

One important characteristic of this design is *sub-system sharing.* Referring to Figure 6, the DC grid interconnects all sub-systems in the *farm.* This design allows say the turbine of sub-system “x” to transfer power to the battery of sub-system “y” if the battery of sub-system “x” can except no more charge.

At some point, the DC grid must be transformed back to the *legacy* AC utility power grid. This is depicted in Figure 6 by two additional M2L DC/AC converters connected on opposite ends of the DC grid.

Obviously, there is no limit to the number of these DC/AC connection points on the DC grid or there proximity to each other. Also it should be clear from the description of the power generation, storage and distribution of this proposed system that a *one-to-one* pairing of a turbine and battery is not necessary. Alternative arrangements can be realized such as a battery sub-system spaced between groups of turbines. In this arrangement an single M2LC would be associated with each turbine. The battery sub-system would contain a 2QC , transformer/inductors and single M2LC.

In addition, being that power transfer between the DC grid and AC utility lines is done using the a seperate M2LC, DC to AC power transfer can be bi-directional. Upon the detection of excessive high voltage on the AC lines due to external sources (other wind farms), the M2LC can transfer power on to the DC grid and in turn to the battery storage of one or more the sub-systems connected to local the DC grid.

The M2LC cannot be considered a true voltage source converter due to the nature in which voltage on each of the capacitors are switched in and out of the circuit. During the transitions of switching states voltage spikes are present on the +/- VDC bus (see Figure 1). This can cause undesirable transient conditions on the DC grid. One solution to this would be to interconnect the *central control* (Figure 5) of each sub-system with a *long haul* fiber optic connection and use a synchronization protocol such as IEEE-1588 (see PTP) to synchronize the switching algorithms of all M2LC's. This is illustrated in Figure 6.

Finally, the proposed system just presented requires two M2LC's (M2LC_1 and M2LC_2 in Figure 5) in order to get get enough degrees of freedom to handle all operating conditions stated above in a concurrent mannor.

To reduce complexity a sub system shown in Figure 7 can be adopted using only one M2LC. However here the concurrency of all conditions of power flow control are lost. In addition, the range of turbine generating capability relative to the efficient control of battery charging is lost. In other words to draw power form the turbine under all wind conditions, the voltage on the secondary of transformer may become suboptimal in the sense that the range in which *transconductance* control can be maintained on the 2QC is diminished.

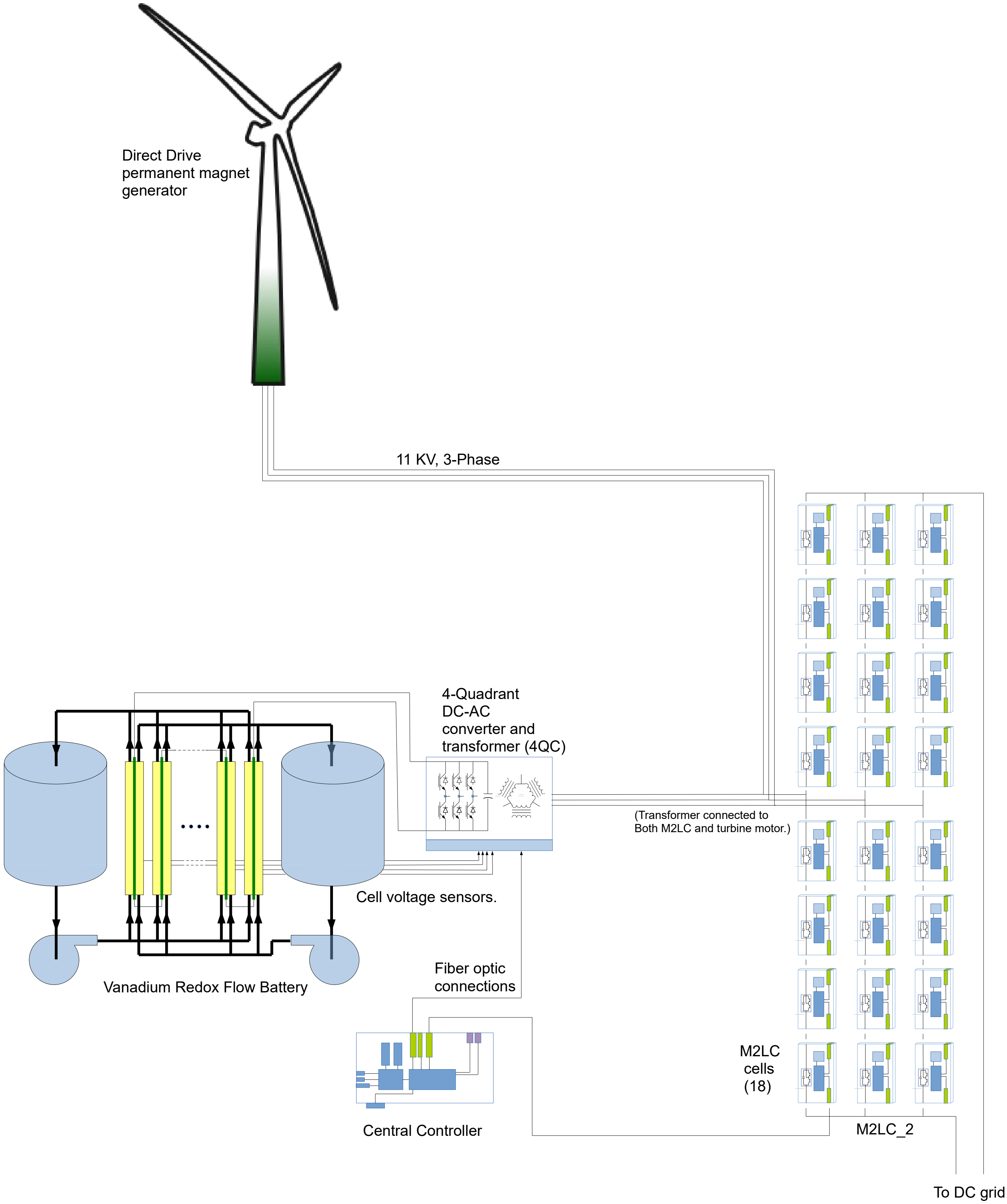

FIGURE 7 Optimized generating and storage substation with restrictions on the range of turbine voltage generation and battery voltage storage.

Summary

A proposal for a state-of-the-art wind turbine generating and battery storage system has just been proposed. This design puts emphasis on energy generating and storage efficiency while maintaining a high degree of operational reliability.

This system promotes the idea of a power grid operating in DC, as proposed by the power engineering design community at large, implemented in a *localized* area with the ability to connect to an existing AC grid.

Also, overall performance can be enhanced do to the ability to transfer and store excess energy from off-site installations such as legacy wind turbines that connect directly to the AC grid.