Analysis of Modulation techniques for Matrix Converters Applied to PMSG Based Wind Energy Conversion Systems

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Abstract: This paper presents a review of the recent advances in matrix converter topologies used with the permanent magnet synchronous generator (PMSG) in wind power generation systems. Two-stage matrix converters known as sparse matrix converters are compared to the conventional matrix converter in terms of implementation complexity, cost, power rating and voltage ratio. Control strategies are combinations of two elementary blocs: the MPPT algorithms and the regulation approach. MPPT algorithms are crucial for the improvement of wind harvest and regulation approaches are generally based on adaptive, non-linear or linear automatic methods that are responsible for current control or field oriented control or reactive power control. On the other hand, several applied to the matrix converter-PMSG scheme are briefly presented.

IndexTerms—PMSG-based wind conversion system, matrix converter, sparse matrix converter, modulation techniques, control strategies

I. INTRODUCTION

Nowadays, wind energy is considered as one of the most promising solutions for electric power generation since it is a clean and available form of energy. In fact, its emission-free and accessible nature made it a perfect solution to overcome the environmental threats and to satisfy the increasing demand on electrical energy [1]. Early wind power systems were based on fixed-speed squirrel-cage induction generators connected directly to the grid. Recently, variable-speed wind conversion systems were developed and mainly consist of a generator-converter combination managed by a corresponding control system. Many combinations and control strategies are proposed in the scientific literature for wind harvest increase, cost optimization and reliability improvement [2-4].

The permanent magnet synchronous generator (PMSG) is gaining interest from the manufacturers and is not only applied in small-scale wind turbines but also in large MW applications [5-6]. This type of generators has many advantages over asynchronous generators and electrical excited synchronous generators used so far in wind power applications [7]. In fact, it has a high power to weight ratio and high efficiency thanks to the absence of exciter power and the elimination of field loss. In addition, the multi-pole PMSG can be either installed directly with no gearbox or associated to a single-stage gearbox, this results in a decrease of maintenance costs and a decrease of noise level.

Power electronic converters are crucial elements for the variable speed wind conversion system since they connect the wind generator to the grid. Their main responsibility is to adapt the generator to the grid requirements regarding frequency, voltage, harmonics, active and reactive power. Different converter topologies were studied during the last decades [2-3]. The PMSG terminals are generally connected to a diode bridge rectifier to reduce the converter cost and a voltage source inverter is installed on the grid-side. A simple dc-link or an intermediate dc/dc buck-boost or boost converter separates the rectifier and the inverter to increase the system reliability [8]. Other back-to-back converter topologies are also associated to the PMSG [9]. In fact, multilevel schemes based on H-bridge or neutral-point clamped topologies are widely used in high scale applications [2]. The matrix converter is a direct ac/ac conversion system that does not need any storage capacitor in the dc stage. This converter is relatively compact and guaranties a unity power factor operation for any load [10-12]. Its high reliability and efficiency attract the attention of researchers lately in applications like PMSG-based offshore wind farms [13].

In this paper, a comparative discussion of matrix converter-based wind generation systems already simulated in literature is proposed. The study is limited on the use of PMSG type of machine. The comparison will be carried out in terms of power range, reliability and efficiency.

This paper will be divided as follows: the possible matrix converter topologies connected to the permanent magnet generator in wind power generation are presented in section I. Modulation techniques and MPPT-based control strategies applied to this particular combination matrix-PMSG are briefly reviewed in section II and III.

Finally MPPT-based control strategies applied to this particular combination matrix-PMSG wind generation application in literature so far are listed in section IV.

II. MATRIX CONVERTERS FOR PMSG-BASED WIND SYSTEMS

The power electronic converter used with a PMSG- based variable-speed wind turbine is a full-scale ac-ac converter that decouples the generator from the grid as shown in Fig. 1 [2]. Different matrix topologies were studied for this particular application so far. The conventional matrix converter [10] that employs nine bidirectional switches is the inspiring configuration of the matrix converter family. Novel variations known as indirect and sparse matrix converters were developed to reduce the number of power transistors and increase the converter efficiency [11-12]. Lately researchers are focusing on new matrix-based modular structures (including three-phase to single phase matrix converters), for high power wind applications like the reduced matrix converter proposed in [13] for offshore wind parks application and the high power matrix converter studied in [14].

A. Conventional three-phase to three-phase Matrix Converter

The topology of the conventional matrix converter is given in Fig. 2 [10]. The elimination of the dc-link capacitor for energy storage improves the reliability of the ac-ac converter and reduces its size; two advantages highly sought in wind generation applications. In addition, this converter provides sinusoidal input current and output voltage, unity power factor and bidirectional power flow. The simulation and experimental results in [15] Confirm that the conventional matrix converter can be applied for the PMSG-based wind generation system. In [16], this converter is used in a dc series wind park topology as a power supply unit interfacing the generator; in fact, its current source side is used to Control the generator while the voltage source side acts as a power supply for the medium-high frequency transformer. Many MPPT-based control strategies for the conventional matrix converter used with the PMSG in wind generation have been studied in the literature and will be presented in section III.

B. Sparse Matrix Converter

Sparse matrix converters are two-stage versions of the conventional matrix converter with reduced number of power transistors and also no passive component [11]. Three configurations of sparse matrix converters are presented in Fig. 3: the sparse matrix converter [17], the very sparse matrix converter [18] and the ultra-sparse matrix converter [19]. All these topologies not only benefit from the advantages of the conventional matrix converter but also have their proper advantages. In fact, the reduction of the number of semiconductors components as shown in Table I, decreases the size, the cost and the complexity of the control of these converters. In addition, the rectifier stage can be commutated at zero current providing increased efficiency by reducing switching losses.

The very sparse matrix converter associated to a PMSG is implemented in a 2.5 MW wind conversion system as described in [20] and is also used with a small scale gearless wind turbine with no transformer as presented in [21]. The super sparse matrix converter was proposed and simulated in [22] for a 4.7 KW wind turbine. In [23], the ultra-sparse matrix converter is associated to a quasi Z-source network connected between the three-switch input rectifier and the output six-switch inverter stage in order to increase the voltage gain limited to 0.866 so far in all matrix converter topologies.

C. Three-phase to one-phase matrix converter

The three-phase to one-phase matrix converter has six bidirectional switches resulting in a more compact design and a simpler modulation technique. While this converter is applied in direct-drive residential wind turbines as presented in [24], researchers are using its topology for higher power wind applications.

In fact, the reduced matrix converter proposed in [13] has a topology inspired by the single-phase matrix converter but with a different operation concept; the active power is constant and the single-phase variables are square wave and not sinusoidal. The reduced matrix converter is applied in offshore wind farms based on HVDC transmission through under water cables to reduce cable losses. The scheme is based on three stages: 3AC-AC inspired matrix converter, a single phase high-frequency transformer and a full-bridge diode rectifier. In [25], the reduced matrix converter is found to be more efficient and has a high power density when compared to 3AC-AC back-to-back converter.

On the other hand, another high power application of the three-phase to one-phase matrix converter is proposed in [26] where it is considered as a single unit in the multi-modular matrix converter. This topology is simulated and experimentally adapted to a 1.5 MW wind generation system in [14].

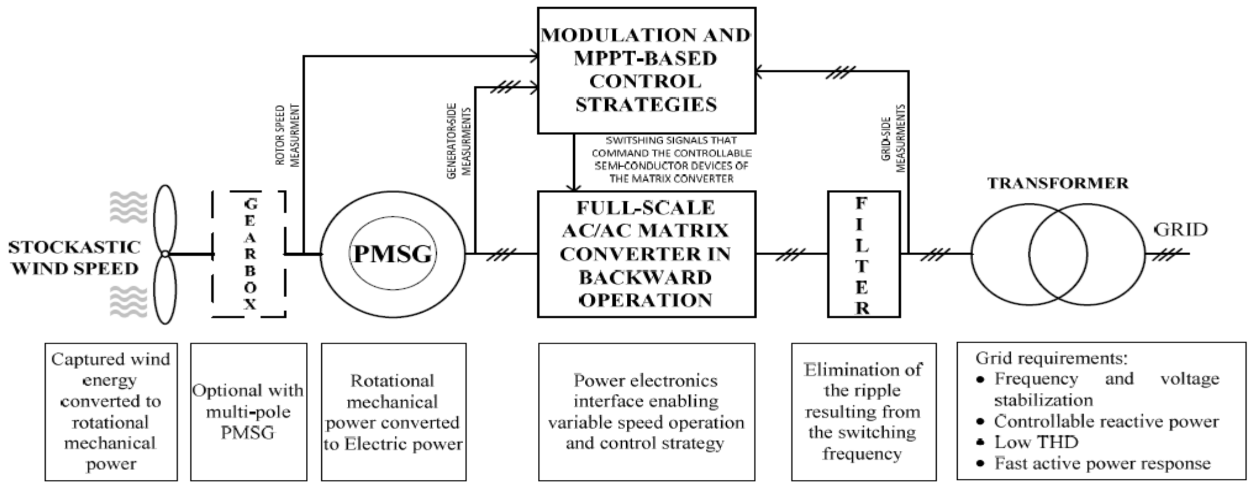

Fig. 1. Basic concept of the wind generation system based on the PMSG and matrix converter combination.

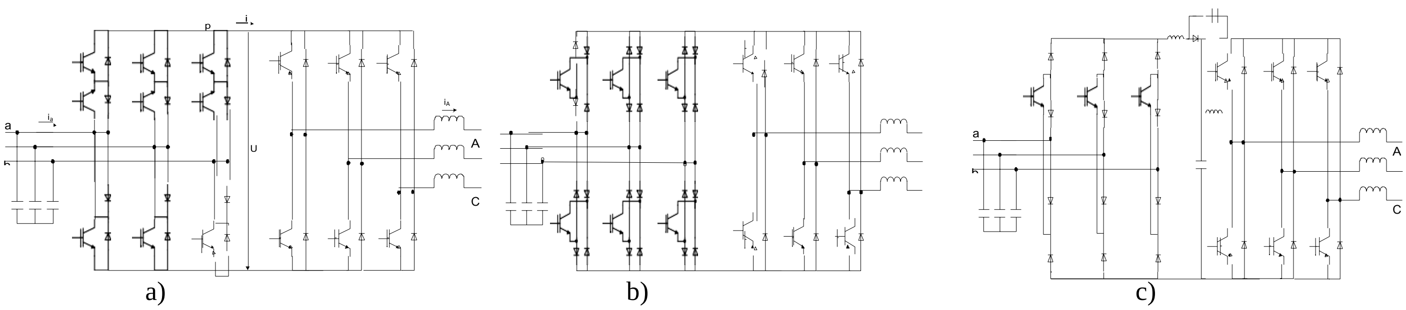

Fig. 2. Two-stage matrix converter topologies with fictitious DC-link:

(a) Sparse Matrix Converter, (b) Very Sparse Matrix Converter, (c) Quasi Z-source Ultra-Sparse Converter.

III. MODULATION TECHNIQUES APPLIED TO MATRIX CONVERTERS

For a proper feedback control design and stability analysis, a mathematical model of the converter is required. Such model could be employed as well for performance evaluation and simulation purposes. Averaged models of the conventional matrix converter in the stationary and the synchronously rotating reference frames are proposed in [32-33]. In [34], the authors present a new simulation technique called switching state matrix averaging that speeds up the simulation of matrix converter platform feeding a PMSG wind turbine.

For the conventional matrix converter, the input current vector $I_{S,abc}$ is constructed from the output current vector $I_{L,ÆBC}$ and the output voltage vector $V_{L,ÆBC}$ is constructed from the input voltage vector $V_{S,abc}$ as (1) shows. The modulation technique consists of determining the switching functions S_{ij} of each controllable semi-conductor device used in the topology of the matrix converter. There are 27 possible switching configurations for the three- phase matrix converter [15].

$$\begin{bmatrix} I_{Sa} \\ I_{Sb} \\ I_{Sc} \end{bmatrix} = S^T \begin{bmatrix} I_{LA} \\ I_{LB} \\ I_{LC} \end{bmatrix} \; and \; \begin{bmatrix} V_{LA} \\ V_{LB} \\ V_{LC} \end{bmatrix} = S \begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix}$$

where:

$$S = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix} \begin{cases} s_{ij} \in [0,1] \\ s_{i1} + s_{i2} + s_{i3} = 1 \\ i,j = 1,2,3 \end{cases} \qquad (1)$$

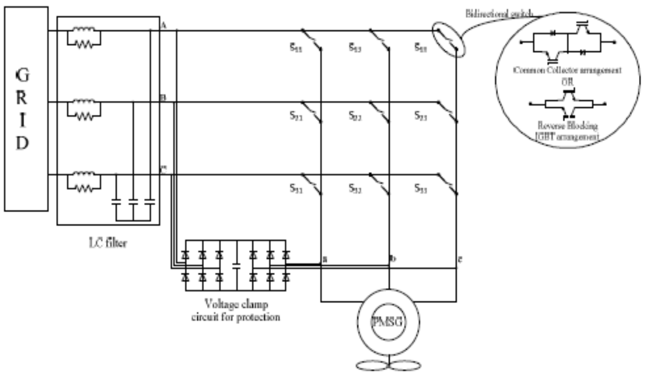

Fig. 3. The conventional matrix converter topology PMSG wind turbine.

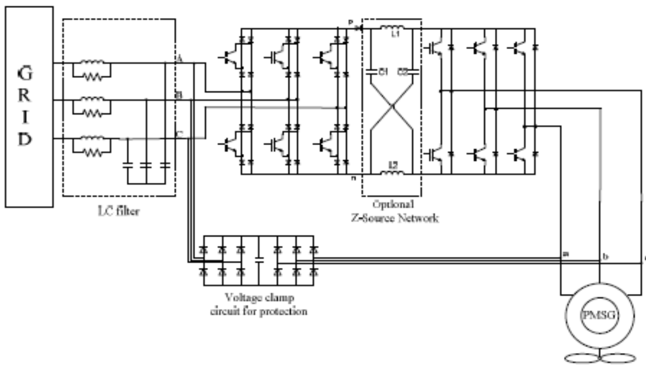

Fig. 4. The Very Sparse matrix converter topology connected to connected to a to a PMSG Wind turbine.

First modulation methods applied to matrix converters were the scalar modulations proposed by Venturini and Roy and are rarely used in wind applications. The Pulse-Width-Modulation (PWM) techniques are the most popular in PMSG-based wind systems and they are divided to two categories: the carrier-based modulation [18-21] and the space vector modulation [16-17]. Both techniques can be applied to conventional matrix converters and sparse matrix converters. In the carrier-based modulation method, the switching functions are selected by using a logical table as a function of the input voltages and the desired levels on the output side. The space vector modulation is based on the instantaneous space-vector representation of input and output voltages and currents and is more used than the carrier-based modulation methods in PMSG-based wind application. Predictive control techniques simultaneously ensure the modulation of the matrix converter and the control of the system variables according to its application. At each sampling time, all 27 switching states are used to calculate the predicted values of the variables to be controlled and then to calculate a “cost function” defined by conditions that the converter must fulfill to operate properly. The switching state that produces optimal value of the function is selected for the next modulation period. According to [15], the space vector modulation being the most complex method in the comparative study, the predictive control seems to be the most promising solution due to its simplicity and flexibility to include additional aspects in the control.

IV. MPPT-BASED CONTROL FOR WIND TURBINE- PMSG-MATRIX SYSTEMS

The overall strategy of a Matrix-PMSG wind power system is given in Fig. 5. In order to capture the maximum power, the generator speed and consequently the generator torque must be controlled. Since the torque is function of the q current component, generally, a field oriented control (FOC) approach is applied for the PMSG by imposing a zero direct axis current. As a result, generator losses are reduced and high torque production is assured.

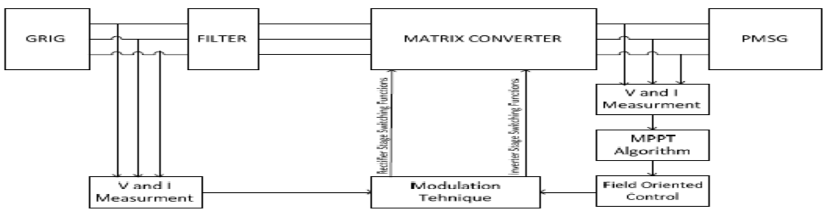

Fig. 5. Basic control concept of the wind generation system based on the PMSG and matrix converter combination.

Unlike back-to-back converters, the matrix converter in wind conversion systems controls the generator and grid- side variables simultaneously. Several control strategies are proposed in literature and aim to improve the system stability and power quality. Maximum power point tracking algorithms are implemented in the control strategy to increase wind harvest based on the nonlinear power- speed characteristics of the turbine. In fact, these algorithms detect the point where the turbine power is maximal according to the available wind velocity and adapt its shaft speed consequently [37].

Control strategies applied to the matrix-PMSG wind system studied and simulated in literature so far are presented in Table 1. An adaptive nonlinear approach called integrator back-stepping associated to a maximum power point tracking algorithm for a PMSG-matrix turbine is simulated in [23]. Results confirm the robustness of this method against system parameter uncertainties. On the other hand, simple PI controllers are used in [22,29] to control the rotor speed, stator current and the filter capacitor voltage while an optimal PID control is introduced in [24] to achieve a better dynamic response. In this strategy, a hill-climb and bisection sensor-less maximum power point tracking algorithm is associated to a particle swarm optimization algorithm and a robust PID controller taking into consideration both output saturation and parameter uncertainty.

TABLE I. CONTROL SCHEMES FOR DIFFERENT MATRIX CONVERTERS APPLIED TO PMSG-BASED WIND GENERATION SYSTEMS

		Simulated Control Schemes for PMSG-Matrix Wind Turbine			Power Rating	Voltage Gain and Particular Limitations
		Modulation Technique	Control Strategy	MPPT Algorithm		
Conventional Matrix Converter	[23]	Space vector modulation	Integrator nonlinear backstepping approach	Search algorithm and adaptive backstepping controller	Simulation 1KW	0.866
	[25]	Singular value decomposition modulation	Simple adaptive controller: reactive power control	not specified	50 KVA	
	[22] [34]	Space vector modulation	PI control	Tip speed ratio (optimal TSR)	7.5 KW	
Indirect Matrix Converter	[24]	Space vector modulation in rectifier and inverter	Optimal PID control based on particle swarn optimization algorithm	Hybrid searching method	Residential wind turbines	0.866
Very Sparse Matrix Converter	[29]	Space vector modulation	Field oriented control	Motoring-generating controller	5.7 KW	0.866
	[28]	Space vector modulation	Soft-switching histeresis current control and field oriented control	Tip speed ratio (optimal TSR)	2.5 MW	
Ultra Sparse Matrix Converter with Z-Source Network	[31]	Space vector rectification and space vector inversion	not specified	not specified	Residential wind turbines	Voltage gain > 1 and Input current displacement range of π/6

A new control structure is proposed and verified in [25] based on singular value decomposition modulation simulated with a simple adaptive controller on a gearless multi-pole PMSG. This study uses the free capacity of the generator reactive power to increase the maximum achievable grid-side reactive power at any wind speed and power level. Other control methods like soft-switching hysteresis current control [28] are studied and tested for the PMSG-matrix wind turbine. Potential intelligent control methods [38] like the fuzzy proportional-integral observer [39-40] and the neural network compensator [41-42] can also be implemented in this particular application [43].

The control of the generator-side converter and the control of the grid-side converter can be designed as a low-voltage ride-through (LVRT) solution for the wind conversion system. In fact, the DC link voltage can be reduced by de- loading the fully rated matrix converter for fault ride through. This can be done by reducing the generator torque via generator side converter control or by blocking the output powers via the grid-side converter control [44].

V. CONCLUSION

Recently matrix converters and PMSG have received considerable attention in wind generation application. The PMSG is increasingly used in medium and large wind applications thanks to the advances in material technologies yielding higher power level converters, new PMSG compact topologies and more complex control strategies. In fact, new semi-conductor components capable of operating at higher frequencies and higher voltage levels are employed in the full-scale power converters and new fast and compact processors are implementing advanced control strategies. This review focuses on the different matrix converter topologies applied so far to PMSG-based wind systems. Besides their numerous advantages promoting their application in wind systems, matrix converters have three major constraints that researchers are striving to overcome: the limitation of the voltage gain, the complexity of their control and their considerable number of power electronic devices. Results of the above-mentioned studies are very promising. In fact, most of the constraints are mastered through new topologies, new modulation and control strategies and new optimizing algorithm making the matrix converter more efficient and more reliable when compared to the back-to-back converter.

Matrix converters combined to z-source network topology solve the problem of voltage gain limitation. In literature, only the ultra-sparse matrix converter which has limitations regarding the power flow direction and the input current displacement range of π/6, was simulated in a PMSG-based wind generation system, and it would be interesting to associate other matrix converter topologies as the very sparse matrix converter to the z-source network to benefit from the advantages of all the subsystems in higher power grid-connected applications.

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