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Lu, Liang; Cutululis, Nicolaos Antonio

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Virtual synchronous machine control for wind turbines: a review

L Lu* and N A Cutululis

Department of Wind Energy, Technical University of Denmark, Frederiksbergvej 399, 4000 Roskilde, Denmark

*E-mail: lilu@dtu.dk

Abstract. Virtual synchronous machine (VSM) control has been put up and developing for the past ten years, but not much work has been done specially focusing on its application on wind turbines (WTs). This paper gives a thorough review of the work that has been done until now about application of VSM control on WTs. Aspects on control schemes, energy storage (ES), frequency and voltage control capabilities, different grid conditions etc. are summarized separately. Further research work in this field is emphasized.

Acronym

| AC | Alternating Current | PWM | Pulse Width Modulation |
| AGC | Automatic Generation Control | Q-V | reactive power – Voltage |
| AVR | Automatic Voltage Regulator | RoCoF | Rate of Change of Frequency |
| CHP | Combined Heat and Power | ROGI | Reduced-Order Generalized Integrator |
| DC | Direct Current | RTDS | Real Time Digital Simulator |
| ES | Energy Storage | SCR | Short Circuit Ratio |
| EV | Electric Vehicle | SG | Synchronous Generator |
| FRT | Fault Ride-Through | SoC | State of Charge |
| GSC | Grid Side Converter | SSC | Storage Side Converter |
| HVDC | High Voltage Direct Current | STATCOM | STATic synchronous COMpensator |
| LVRT | Low-Voltage Ride-Through | SYNC | SYNchronized Control |
| MPPT | Maximum Power Point Tracking | UFLS | Under Frequency Load Shedding |
| MSC | Machine Side Converter | VC | Vector Control |
| PCC | Point of Common Coupling | VI | Virtual Inertia |
| P-f | active Power – Frequency | VISMA | Virtual Synchronous MAchine |
| PFC | Primary Frequency Control | VSC | Voltage Source Converter |
| PI | Proportion Integration | VSM | Virtual Synchronous Machine |
| PLL | Phase Lock Loop | VSYNC | Virtual SYNchronous Control |
| PMSG | Permanent Magnetic Synchronous Generator | VSynC | Virtual SYNchronous Control |
| PSS | Power System Stabilizer | WPP | Wind Power Plant |
| PV | PhotoVoltaic | WT | Wind Turbine |
1. Introduction
With more and more renewable power like solar power and wind power being integrated to the traditional power system, the total inertia of the power system is getting lower and lower. With a smaller inertia, the frequency of the power system may have bigger deviations when there are sudden big changes of generation or load, causing a sudden big active power imbalance (frequency event). In order to maintain the original frequency stability, the idea came to mind is to make grid-integrated converters and their energy sources perform with similar characteristics or functions, like inertial response and primary frequency control (PFC), as synchronous generators (SGs). This is how virtual synchronous machine (VSM) concept was developed [1].

VSM is a control scheme applied to a converter to emulate the behaviour of a SG by using models of a SG within the control scheme. It was firstly put up for distributed generation units, like photovoltaic (PV) arrays and combined heat and power (CHP) in microgrids, and subsequently discussed for other applications like VSC-HVDC, STATCOM, electric vehicles (EVs) and variable speed WTs.

There have been some review papers on VSM control. In 2013, different control schemes of VSM at that stage and its application in microgrids were reviewed in [2], but one important scheme, synchronverter, was missed. Different VSM control schemes were reviewed and categorized in [3] based on the nature of the output reference from SG model: current reference, voltage reference and power reference. Namely, the VSM-controlled converter works as a current source or voltage source. Besides, it gives a classification of different VSM control methods by the level of detail of SG model they are based on. In 2016, three main functions of VSM control were reviewed in [4]: oscillation damping, frequency control and voltage control, without going into details of different control schemes. Different kinds of control schemes in terms of the level of detail of SG models and advanced functions like low-voltage ride-through (LVRT) aimed for PV arrays were reviewed in [5]. In 2017, VSM control schemes were classified in [6], depending on whether their SG models are high-order or low-order, whether they are current sources or voltage sources, and whether there is a need for PLL and ES, without focusing on the type of technology they are applied to. Application of VSM control on PV arrays, WTs, power electronics transformers and flexible AC & DC transmission systems were reviewed in [7]. However, the part related to WTs is rather short, and mainly presents virtual inertia and damping control, not VSM control. In 2018, a simple review about VSM control in microgrids was presented in [8]. To sum up, there is no work presenting a complete and thorough review on the specific application of VSM control on WTs yet. Therefore, a literature review is of great value to summarize what has been done, and more importantly, to identify the further research questions that need to be specially addressed on this topic. This paper gives a relatively comprehensive and detailed review on this topic. This is the main contribution of this paper.

The rest of paper is organized as follows. Section 2 gives a brief introduction of three different initial VSM control schemes as a background and basis. Section 3 summarizes the application of VSM control on WTs in different aspects. Section 4 puts forward some further research needs on this topic, before concluding in Section 5.

2. VSM control
This section lists three different control schemes proposed at the early stage of VSM concept. They provide main foundations for subsequent developments in this field.

2.1. VISMA
The concept of VSM control was firstly introduced by Dirk Turschner, Ralf Hesse and Hans-Peter Beck of Clausthal University of Technology in Germany in 2007 [1,9–11]. They named their scheme as VISMA (VIrtual Synchronous MAchine). A detailed description of the general idea of VISMA to emulate SG’s static and dynamic properties by implementing SG’s model in the control scheme of an inverter is given in [1]. The model emulates a salient SG, which includes all the resistances and reactances of stator windings, field winding and damper winding. A further detailed mathematical expression of the SG model in d-q frame is given in [12]. To avoid unsteady states under asymmetric
load conditions caused by the standard transformation, a more robust three-phase model was applied to investigate the dynamic processes [13].

Based on the simplified three-phase SG model, the control diagram was developed as shown in Figure 1 [14]. In this scheme, three-phase grid voltages at point of common coupling (PCC) are measured to calculate current references based on the SG model. The current references will be compared with the measured currents by the hysteresis controller, which generates switch signals for the converter. In this case, the converter works as a current source, which is not as favorable as a voltage source in weak or islanded grids. Besides, the hysteresis controller in this scheme works at a fixed tolerance band, which makes the switching frequency of the converter not constant but varying within a range. Hence, there are many harmonics in output currents. To improve this problem, a revision of the VISMA control scheme was proposed as shown in Figure 2 [15]. In the updated scheme, the inputs were changed to grid currents measured at PCC and the outputs become reference voltages to the PWM controller. That is why it was named current-to-voltage control. In this case, the VISMA behaves as a voltage source and the outputs have almost no harmonics because of the constant switching frequency of the PWM controller and a proper filter. Furthermore, considering the widely applied PWM-controlled converters in current market, the current-to-voltage control tends to be more easily utilized.

2.2. VSYNC

Almost at the same time of initial publication of VISMA, another claimed VSM control was developed in the three-year VSYNC (Virtual SYNchronous Control) project, started at the end of 2007 under the 6th EU-Research Framework program [16,17,26,18–25]. The basic idea of the control scheme is to modify the active power reference $P_{VSM}$ for the energy storage (ES) by combining two parts. One is proportional to the rate of change of frequency ($RoCoF$) $\frac{df}{dt}$, derived from the rotor motion equation of a SG, to stand for the virtual inertia. The other is proportional to the frequency deviation $\Delta f$, which is the same as active power-frequency ($P$-$f$) droop control. It can be expressed as:

$$ P_{VSM} = K_\omega \Delta \omega + K_i \frac{d\omega}{dt} \quad (1) $$

It should be noted that in this paper we would not discuss this kind of control scheme in the range of VSM control. The reasons are as follows. The virtual inertia part of the active power reference, although related to the swing equation of a SG model, is only approximate to one part of the equation. For the VSM control, we think that at least a full description of the swing equation should be expressed in the control scheme, while variations of control schemes may differ in the electrical equations of a SG model. The converter control in this VSYNC scheme is still traditional vector control (VC), different from the majority of control schemes based on a SG model, which calculate the internal potential and power angle for the PWM controller. Besides, the implementation of virtual inertia requires the presence of an
external voltage with a physical inertia and is not suitable for islanded operation, in contrast with a SG or a VSM implementation [3]. Furthermore, the concepts of virtual inertia and droop control have been developed in separate contexts and there has been a lot of work on those topics. Therefore, the VSM control concept in this paper only focuses on the control schemes that are based on, and derived from a relatively complete SG model, not including work on virtual inertia or $P$-$f$ droop control. It is still worth mentioning that much work in this VSYNC project can be referred, like ES selection and sizing [19,22], real-time simulation with hardware in loop [25,26], field tests [20,21], measurement and remote monitoring [23,24].

2.3. Synchronverter
In 2009, another type of VSM control, named synchronverter, was developed by Qing-Chang Zhong and George Weiss [27–30]. It is based on a fifth-order round rotor SG model without rotor damper windings. This model includes two parts: second-order swing equations for rotor mechanical movement, and third-order electrical equations for stator voltages and back electromotive force in the field winding. After combining with the reactive power-voltage ($Q$-$V$) droop control, the control scheme for regulation of active and reactive power is shown in Figure 3 below.

Several improvements have been since introduced. The synchronverter was improved to realize self-synchronization by removing PLL in [31]. Five modifications, like virtual inductors, virtual capacitors and anti-windup, were proposed to improve the overall stability and performance [32,33]. A bounded controller is used for the frequency loop and excitation current loop to guarantee given bounds for both frequency and voltage [34,35].

![Figure 3 Synchronverter. Reproduced from [29].](image)

2.4. Others
Apart from the three VSM control schemes mentioned above, there are also some schemes proposed by other researchers worldwide. Osaka University in Japan proposed a scheme based on the swing equation including governor function in [36–39]. An algebraic type of VSM control by Kawasaki Technology Co., Ltd. and Kawasaki Heavy Industries, Ltd. in Japan was introduced in [40]. University of Tennessee in US also presented their VSM control scheme in [41], which includes modeling of the governor, automatic generation control (AGC), power system stabilizer (PSS) and automatic voltage regulator (AVR).

Of course, contributions kept coming out on improving the VSM control schemes in recent five years. Variations of different schemes lie in many aspects, for instance, differences of SG models utilized, different expressions of SG models in different frames, different parameter designs and tuning, and improvements in terms of stability or performance in various grid conditions, etc. Due to space limitation, details are not included here.
3. Application of VSM control on WTs
This section only includes the work that focuses on the application of VSM control on WTs. The content is arranged by topics of interest.

3.1. WT type
Obviously only type-3 and type-4 WTs are relevant for this topic as VSM control is applied to converters. Papers working on type-3 WTs are [42–47], while those on type-4 WTs are [48–54].

3.2. Energy storage (ES)
One VSM control scheme for type-3 WTs without an ES was presented in [42]. The kinetic energy kept in the rotating mass of a WT was observed to give the inertial support for momentary active power extraction. During super-synchronous mode, the power will not be delivered by the rotor until the speed has reached a threshold value above synchronous speed, to account for the rotor losses. Rotor and stator power sharing is controlled by the variation of power angle between rotor voltage and inverter voltage. The rotor-induced voltage was found to reverse its phase when operation changed from super-synchronous to sub-synchronous mode.

Some results on the inertial response process of a VSM-controlled type-4 WT without an ES were presented in [48]. When there is no ES equipped with the WT, extra energy needs to be obtained from the rotor kinetic energy in case of a system frequency drop. As a result, the rotor speed will decrease during the inertial response process, which leads to the change of active power reference in the VSM control. This is different from traditional VSM control schemes with an ES, in which active power references keep unchanged during the inertial response period. Due to this phenomenon, this paper finds that a VSM-controlled type-4 WT without an ES has worse inertial response performance compared to those with an ES. This paper shows the advantage of ES for VSM control from a new aspect. However, the wind speed was assumed to be constant in the inertial response period. Further work is needed to compare the different influences from change of rotor speed and change of wind speed, on the active power reference of VSM control.

One VSM control strategy for type-4 WTs with a minute-level ES in the DC link as energy buffer was proposed in [49]. The ES is connected to the DC link via a DC-DC converter, named storage side converter (SSC), which keeps the DC link voltage constant by charging or discharging the ES. The VSM control is divided into three different operation modes in terms of the different state of charge (SoC) of the ES. In VSM normal operation, the SoC will be controlled around SoC_setpoint. When SoC drops too low, the control will change to VSM MPPT mode, in which machine side converter (MSC) generates the maximum available power and grid side converter (GSC) will output all the generated power from MSC. On the other hand, when SoC is too high, pitch control will be enabled to reduce the power intake. The operation diagram is shown in Figure 4 below. Sizing of the ES is also discussed in the paper. That is, in Figure 4, the four energy capacities $E_1 \sim E_4$ are designed separately considering different amounts of energy needed in different operation conditions.

![Figure 4 SoC and VSM mode. Reproduced from [49].](image-url)
3.3. Control schemes

Research on a type of VSM control, named virtual synchronous control (VSynC), for type-3 WTs was presented in [44–46]. This control scheme includes four parts: active power control, alternating-voltage/reactive power control, supplementary damping control, and current limitation control. The active power control and supplementary damping control combine together to work in the same way as the corresponding part, which realizes the swing equation of a SG model, in a traditional VSM control scheme. The current limitation control is something new in which a virtual resistance is included to suppress current transients due to the absence of inner current limiter, however, its effectiveness needs to be verified with further details.

Another contribution is to consider the different inertial response characteristics of WTs from SGs. The reason for the difference is that the input mechanical power captured from wind varies during inertial response process with changes of rotor speed and pitch angle, which differs from SGs of which input mechanical power can be regarded constant. An approach dealing with this is proposed by dividing the mechanical power into two parts: $P_{m0}$ as a constant power injection pre-disturbance (part one), and $\Delta P_{m}$ as variations caused by rotor speed or pitch angle (part two), as shown in the green dashed boxes in Figure 5.

![Figure 5 VSynC for type-3 WT. Reproduced from [44].](image)

A comparative study of the principle and dynamic process of different inertia releasing methods on type-3 WTs was presented in [55]. VSynC was compared with $df/dt$ inertial control [56][57] and PLL-tuning control [58,59] considering the motion of internal voltage. The inner link among them is that they all emulate the inertial response behaviour of SGs from different aspects. Simulations showed that WTs with all of these methods contributed effective and similar inertial responses.

A type of VSM control, also named virtual synchronous control, for type-3 WTs was proposed in [47]. Electromagnetic equations of the WT model under d-q axis virtual synchronous rotating coordinates were firstly established. Then the electromechanical model of the WT was realized through the proposed virtual synchronous shaft with due rotor inertia. $P-f$ and $Q-V$ droop controllers were added to emulate the governor and exciter of SGs. The basic structure of the control strategy is shown in Figure 6 below. Last but not the least, an adaptive droop control is applied to achieve MPPT in steady state and realize short-term power support in dynamic state, by changing the droop coefficient of $P-f$ curve.

This virtual synchronous control strategy can be classified as VSM control because it is also based on a simplified model of a SG. Apart from the route from excitation current reference $i_{rm}$ to excitation electromotive force $e_0$, in this control strategy, the $P-\delta$ part works quite similarly to the swing equation part of a classical VSM control, but here it is a bit more complex. The functions of $P-f$ droop and virtual axis are overlapping somehow, and there is no clear damping loop in this strategy.
Some results of VSM control for type-4 WTs with an ES were provided in [49, 50]. The control scheme utilized is introduced in [41].

The VSM control scheme proposed in [54] combines the classical swing equation with the feedforward damping introduced in [60]. This combination offers a unique new feature: the contribution to primary frequency control can be disabled while oscillation damping is preserved. The control diagram is shown in Figure 7 below. Besides, an adaptive inertia power limitation scheme was designed in the paper to address one major restriction of VSM-controlled converters: a reduced capability to deal with short-term peak currents.

A control strategy based on the synchronverter type of VSM control for type-4 WTs was explained in [52, 53]. The MSC is operated as a synchronous motor, since it receives power from the permanent magnetic synchronous generator (PMSG) at the AC side and injects it to the DC link. The main tasks of the MSC are to regulate the DC link voltage to the desired value and to achieve unity power factor operation at the AC side. The GSC is operated as a synchronous generator, since it injects active and reactive power to the grid. The main tasks of the GSC are to achieve MPPT, i.e. maximum power extraction from the wind, and also regulate the reactive power. The control diagrams of these two converters are shown in Figure 8 and Figure 9 below.

Figure 6: Virtual Synchronous Control for type-3 WT. Reproduced from [47].

Figure 7: VSM control with feedforward damping. Reproduced from [54].
The synchronized control (SYNC) for type-3 WTs in microgrids and weak grids was introduced in [61], which applies $P-f$ droop control in MSC to achieve grid synchronization instead of PLL, and SYNC enables WTs to provide active power output under frequency disturbances. Increasing the $P-f$ droop coefficient will improve the synchronous stability but deteriorate the small signal stability. To solve this problem, a modified SYNC scheme is proposed in the paper by adding an assistant damping component to improve the synchronous stability and small signal stability simultaneously.

This modified method was inspired by SG’s swing equation. Hence, to some extent, it has some characteristics in common with VSM control. However, we do not consider this $P-f$ droop-controlled SYNC as VSM control because they have different development sources and routes. $P-f$ droop control [62][63], together with VC-based $df/dt$ control [64][56], are two different methods to equip WTs with virtual inertia (VI) to have frequency control capabilities like SGs under frequency disturbances. The VI designs are derived with initial focus more on realizing frequency regulating capability. Slightly differently, VSM control focuses more on realizing SG models within converter controls, while frequency control capability comes true as one of the consequences. However, it has been demonstrated that there are equivalence links into a single theoretical frame for VSM control and droop control, these two well established concepts that have been developed in separate contexts [65].

### 3.4. Grid conditions

#### 3.4.1. System rating at PCC.

VSM control is deemed to enable WTs to work properly in weak grids and islanded power systems. This subsection presents some work about this.

Results from preliminary tests of a VSM grid-forming algorithm were presented in [66]. The capabilities of the algorithm are demonstrated in a strong AC power system, a very weak one and an islanded one. When a WT with VSM control was connected to a strong AC power grid, its steady state performance was compared to an adjacent WT operating with classical current control. Comparison over several months shows that there is little difference in the average frequency content between VSM control and current control and the dynamic power changes on the generator side is not altered by the VSM control. For weak power grid integration, RTDS simulations show that VSM control can operate in power grids of lower SCR compared to conventional current control. The comparison is shown in Table 1. In an islanded system, different WTs shared the dynamic load change by the droop control of frequency and reactive power was shared by the droop control of voltage.
Table 1. Minimum SCR of power grid.

|                      | WT power output percentage |
|----------------------|---------------------------|
|                      | 0%                        | 100%                      |
| VSM control          | 0.00005                   | 1.1                       |
| Current control      | 1.7                       | 2.2                       |

Some simulation results were presented in [49] of a stand-alone working scenario, in which a load was only supplied by a type-4 WT, in the two-area power system model [67]. In VSM normal operation, the WT could adjust the rotor speed and pitch angle according to the load, even if the load was larger than the available wind power. When SoC dropped below the threshold, the power limit block was enabled and system frequency dropped rapidly. The under frequency load shedding (UFLS) protection was triggered to reduce the load until reaching a new balance. If there were no UFLS, the frequency would keep dropping until the event was considered as an internal fault and the WT was tripped.

3.4.2. Unbalanced voltage. A collaborative control strategy based on VSM for the MSC and GSC of type-3 WTs under unbalanced grid voltage was proposed in [43]. In the control strategy, the MSC is controlled to achieve smooth electromagnetic torque, while the GSC is controlled to reduce the oscillation of output power. To realize this, reduced-order generalized integrator (ROGI) is employed. The voltage reference for MSC contains two parts: one is the output of VSM that controls the output power of stator; another is the output of ROGI to get smooth electromagnetic torque. There are also two parts in the voltage reference for GSC. One is the output of PI controller based on vector control (VC) which keeps stable the voltage of DC link. The other one is the output of ROGI to reduce the oscillation of the total output power of WT. The control scheme is shown in Figure 10 below.

Simulations in MATLAB/Simulink were carried out to test the proposed control strategy under 5% unbalanced grid voltage. This scheme successfully decreased the oscillation of electromagnetic torque from 14.5% to 3.41% and output active power from 15.44% to 1.17% separately.

3.5. Fault ride-through (FRT)
In order to verify the FRT capability of the proposed control strategy, real-time simulations using an OPAL RT digital simulation system were carried out in [52]. A 50% grid voltage drop was initiated and lasted for 0.1 s. A peak was observed of the grid current when the voltage dropped, but it quickly settled down. The peak value was about five times of the normal value. Additionally, there was no noticeable change in the torque and rotor speed, which meant that the WT worked properly during the grid voltage fault.
The electromagnetic transient behavior of VSynC-based type-3 WTs was investigated in [68] and a voltage compensation strategy was proposed to ride through asymmetric grid faults. Through compensation of fault components of WT rotor voltage, overcurrent no longer exists under mild asymmetric faults and its amplitude is significantly suppressed under severe asymmetric faults. Meanwhile, electromagnetic torque oscillations are obviously limited during electromagnetic transient process as well as fault steady state. The proposed strategy improves the FRT capability of VSynC-based type-3 WTs, without complex control switches between normal and fault operations.

3.6. Frequency control

The effectiveness of proposed VSM control scheme for type-3 WTs was validated in [43] through simulations in MATLAB/Simulink. Compared to traditional vector control (VC), VSM control improves the frequency nadir and smooths frequency changing. Furthermore, influence of different parameters in VSM control was also investigated. In summary, a larger damping constant can damp the frequency changing better and increase the time of transition process. A larger active power coefficient will speed up the active power response, however, the damping for frequency changing becomes weaker.

Simulations were carried out to study the impacts of controller parameters and initial operation conditions on frequency response of a single WT in [44]. In addition, there were simulations that compared the different inertial responses of proposed VSynC control and traditional VC-based \(df/dt\) control with PLL. Results verified the better frequency control capability from VSynC control. Furthermore, VSynC control also shows better operation stability especially in weak power grids than VC-based \(df/dt\) control, which easily has oscillations because of the dynamics of PLL. It is pointed out in [45] that the power transfer capability of type-3 WTs with VSynC control is not limited, which means the maximum transmittable power, viz., the rated power can be achieved even when SCR is decreased to 1. However, the maximum transmittable power of VC-based type-3 WT is highly limited, approximately down to 0.84 pu.

The VSM control scheme for type-4 WTs in [49] was verified in the two-area power system model in real-time simulations. Firstly, transitions between different VSM operation modes were tested under variable wind conditions. The time sequence of the wind speed was generated by NREL TurbSim [69]. Secondly, dynamic performance of the VSM control was tested and compared with traditional MPPT control of WT. Results show that when there is large power imbalance in the grid, traditional MPPT control will not change its power output, while VSM normal mode and VSM MPPT mode provide active power injections at the beginning of the frequency event and guarantees higher frequency nadirs. What is more, VSM normal operation mode gives better frequency control capability compared with VSM MPPT mode.

3.7. Field tests

Some results from field tests were presented in [66]. WTs with VSM control were compared with adjacent ones with current control in steady state operation. WTs with VSM control were tested against dynamic load changes in an islanded system. However, for frequency events, a pseudo frequency disturbance was used rather than a real one, by injecting a frequency disturbance (with varying \(df/dt\)) into the VSM controller’s view of grid frequency. Besides, the research on SCR value of power grid in which VSM control can operate was carried out using RTDS simulation.

4. Further research

From what has been summarized above, we can see there is far from enough work on this topic of VSM control application on WTs. For each of the aspects listed above, the results presented in literature do not cover all the details we are concerned about. Besides, there is also a lack of repeated validations for the results above.

For ES, techno-eco analysis is essential to evaluate the necessity of applying an ES for VSM control of WTs. The advantage of VSM control with an ES for guaranteeing MPPT and frequency control simultaneously should be evaluated correctly. Different types of ES need to be evaluated individually to
find the most suitable type for VSM-controlled WT application. Besides, different locations of the ES also need to be compared, especially for VSM-controlled wind power plant (WPP) applications in the future. The control strategy for the SoC of ES needs to be optimized further, considering the difference of WT's from PV arrays, and it should be better coordinated with VSM control design and different WT operation conditions.

For VSM control schemes, although there are several different control schemes applied to different kinds of WT's, only availability of each control scheme is considered. There is no verified comparisons between different schemes, in terms of stability and performance in frequency control at least. Besides, special requirements for WT applications, like parameter design and tuning, need to be emphasized.

For grid conditions, VSM control can be considered to coordinate with black start methods in islanded systems. Improvements of VSM control need to be developed and compared for WT's under unbalanced voltages. It is also possible to combine FRT capability with VSM control.

For frequency control capability, characteristics of the converters with VSM control need to be defined quantitatively and methods for assessing these characteristics need to be developed. Besides, a lot of work can be done when considering this frequency control capability from a WPP with VSM control.

For voltage control capability, at present there is not much verified and credible work on this. Validation of voltage control capability of WT's with VSM control needs to be carried out in various scenarios, especially during different faults and asymmetric voltage sags.

5. Conclusion
VSM control will play an important role in equipping WT's with frequency control capability and helping to increase wind power integration proportion. To understand better the state-of-art research status in this field, this paper gives a complete review on current achievements of VSM control application on WT's. Available control schemes and their special modifications for this application are summarized in detail. Especially, scenarios like weak power grids and unbalanced voltages are discussed. Based on what has been done on this topic summarized in this paper, further research needs are put forward as suggestions for future work. It still requires a lot of work to develop VSM control to a stage where it can be deployed as vector control today.

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