Transient Modeling and Comparison of Wind Generator Topologies

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Abstract--There currently exist various competing technologies for wind generator systems, whose differences lie in the complexity, cost, and degree of control over the system characteristics. This paper presents the full transient models in EMTP-RV for two of the most popular topologies, namely the doubly-fed induction generator (DFIG) and the directly connected induction generator (IG). In addition, the system characteristics of these two generator designs are compared by simulation of two wind parks, one composed of each of the designs. As the reactive power control is much greater in the case of the DFIG, a static compensator (STATCOM) of identical reactive power rating as the combined DFIGs is added to the IG wind park design. In this way, the two systems are similar in reactive power capability as well as cost and complexity and a comparison of the different operating characteristics is obtained. The modeling of the various components is presented and the system characteristics of the two wind parks are contrasted.

Keywords: wind energy, induction generator, doubly-fed induction generator, STATCOM, voltage stability

I. INTRODUCTION

WIND energy has grown dramatically over the past decade and while government policy has helped to fuel this growth, increasing utility interconnection requirements has resulted in a number of emerging wind generator technologies. Stricter requirements demanding accurate reactive power control and voltage regulation capability has led to the integration of power electronic converter in many of the wind generator designs. This allows better overall control of the generator, both in terms of reactive power control but also limited control of real power characteristics as well.

Due to the inherent nature of wind, electrical power based on this energy source possesses similar characteristics. Furthermore, wind farms are usually interconnected at remote locations, far from central loads or conventional generation. This imposes stricter requirements on the reactive power control of the system. The majority of wind generator topologies are based upon asynchronous machines, which only tends to further aggravate the situation.

Various studies have been performed to compare the performance of fixed speed and variable speed machines, [1][2], however, these studies have neglected to match the reactive power capabilities of the two topologies. Through comparison of a fixed speed induction generator complemented with a static compensator, with the variable speed machine, the differences between variable speed and fixed speed machines can be highlighted.

The need to accurately model these new forms of generation and investigate their interaction with the network becomes increasingly important as the penetration of wind in certain areas reaches significant levels. This paper presents the transient modeling of two competing wind generation technologies and contrasts their operating characteristics, both under an intact network and in response to transients.

II. BACKGROUND

Wind energy is one of the fastest growing industries at present and will continue to grow worldwide, as many countries have planned future development. Following recent growth of wind, utilities have responded by developing various interconnection requirements to which new wind generators must abide.

Many wind generators are based on asynchronous machines, with a great number being of the directly connected squirrel cage machine variety. Therefore, reactive power is a major concern, not only to compensate for the reactive power requirements of the wind park itself but also to help support the system voltage. Most of the requirements define a typical power factor range that the wind park should be at least able to maintain. The methods of reactive power control are left up to the designers and may come in the form of capacitor banks, static power converter based devices (SVC, TSC, or STATCOM) or by employing machines capable of reactive power control, such as the doubly-fed induction machine topology.

Low voltage ride-through is seen to be particularly important in terms of maintaining voltage stability,

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especially when there is a high local concentration of wind generation. Premature tripping of numerous wind generators due to local disturbances can further risk the stability of the system, contributing to amplification of the effect of the disturbance. This reflects the concern on maintaining stability of the wind farm and the associated system during normally occurring power system disturbances.

The issue of power management of wind farms is becoming more important and the trend is such that utilities may eventually demand that wind generators behave in a manner analogous to conventional types of generation. This is a requirement that is subject to much debate since wind is often looked at, perhaps unfairly, as being unreliable from a power production stand-point and that a large spinning reserve, almost equivalent to the installed capacity needs to be maintained. However, much of the work in Europe has been attempting to prove otherwise, perhaps resulting from stringent standards imposed upon the power control requirements of wind turbines there [3][4].

A. Generator topologies

Variable speed wind generators are increasingly used, as they present higher energy capture, lower mechanical stresses, more constant output power, and reduced noise compared with fixed speed machines, [4][5]. Direct drive technology using high pole permanent magnet synchronous generators are capable of variable speed operation, where the generator is connected to the system using a back-to-back voltage source converter (VSC). The doubly-fed induction generator (DFIG) is another common variable speed topology which utilizes wound-rotor induction machines with an ac-dc-ac converter between the stator and rotor terminals. The most common wind generator arrangements are shown in Fig. 1

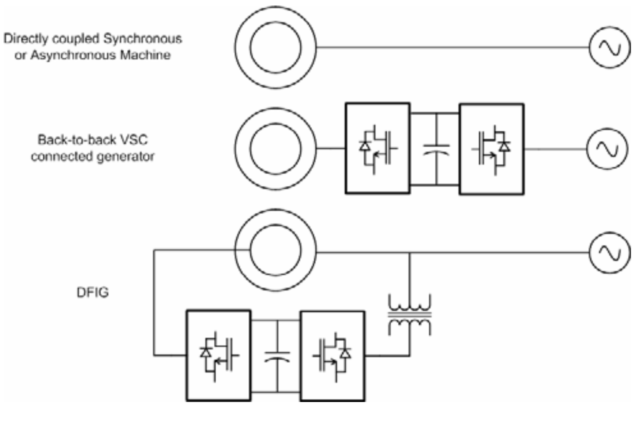

Fig. 1. Wind generator technologies

The three main wind generator topologies each differ in terms of overall cost, component count, complexity, control potential, protection, and integration costs. The requirements placed upon the wind park installation by the utility will to a large extent determine additional equipment that is required or whether the purchase of ancillary services will be necessary. For instance, reactive power control is almost without exception required as previously mentioned. Therefore, directly coupled induction machines require at the very least switched capacitors, while some are moving to reactive compensation device based upon solid-state devices.

III. SYSTEM MODELS

The development of full transient models of the various wind turbine topologies is of interest in order to investigate the effect of an intermittent source on power quality, harmonic injection by power electronic converters, voltage control characteristics, and their response to disturbances and short circuit behavior. Here, the fixed speed topology is presented and compared with the doubly-fed induction generator (DFIG), one of the popular variable speed generators, followed by their operating characteristics.

A. Wind models

For the sake of determining the effect of wind generation on the electrical characteristics, it is only necessary to translate the input wind speed into a mechanical torque, which is then applied to the blades of the generator. The relationship is one that depends not on only the wind speed but also the speed of the generator and naturally the aerodynamics of the turbine in question. Wind speed measurements available from [6] were used in the study to model the wind itself. The input torque is most simply represented by the following equation:

$$T_m = \frac{1}{2}\pi\rho C_p(\lambda,\ \beta)R^2 v_w^3 \qquad (1)$$

where $C_p\ (\lambda,\beta)$ is the characteristic curve which depends on the generator in question, ρ is the air density, R is the radius of the blades, v_w is the wind speed, β is the blade angle, and λ is the tip-speed ratio, i.e. the ratio of the speed at the tip of the blades to the speed of the wind, otherwise:

$$\lambda = \frac{\omega_m R}{v_w} \qquad (2)$$

Upon calculation of the input torque of the generator, it is applied to the two mass model of the machine. The model was developed for a 1 MVA generator with blade radius of 60 m with an optimum $C_p = 0.4$ at zero pitch angle for tip-speed ratio, $\lambda_{opt} = 7.5$.

B. Induction Generator

The induction generator (IG) is represented using the wind torque model, applied to the shaft of the induction machine model as shown in Fig. 2. The model also incorporates a pitch control block, which changes the angle of the blades of the machine at high wind speeds in order to modify the torque characteristic and thus limit the output power to the rating of the machine. Since induction machines need to be operating at supersynchronous speed in order to generate power, the model is initialized to -1% slip. This prevents simulation of the start-up transient of the machine.

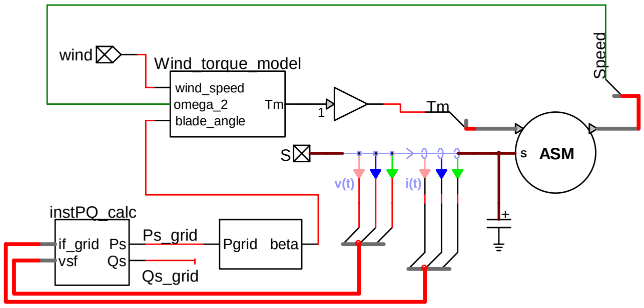

Fig. 2. Direct connected induction generator model in EMTP-RV

The uncompensated machine consumes reactive power under all modes of operation and therefore, the magnetizing branch is compensated using shunt capacitors. However, this provides only constant reactive power and therefore, a controllable reactive power source may be added in order to limit voltage fluctuations resulting from variable output power, while at the same time can be used to improve voltage recovery following sags.

C. Static Compensator (STATCOM)

In the present case, a three-level STATCOM was modeled and connected at the high side of the transformer in order to provide voltage support for the IG. The STATCOM uses insulated gate bipolar transistor (IGBT) based technology and shifted pulse width modulation (PWM) for generation of the gating signals. The outline of the control is given in Fig. 3 and follows that detailed in [7].

D. Doubly-fed induction generator (DFIG)

The doubly-fed induction machine was modeled using control schemes as developed in [8][9]. The power circuit of the model is shown in Fig. 4. The control strategy for the rotor side converter is well documented in the literature and will not be presented here. The control of the supply side converter is much the same as that of the STATCOM control, whereby the converter serves primarily as a dc voltage regulator with the ability to also exchange real power with the system.

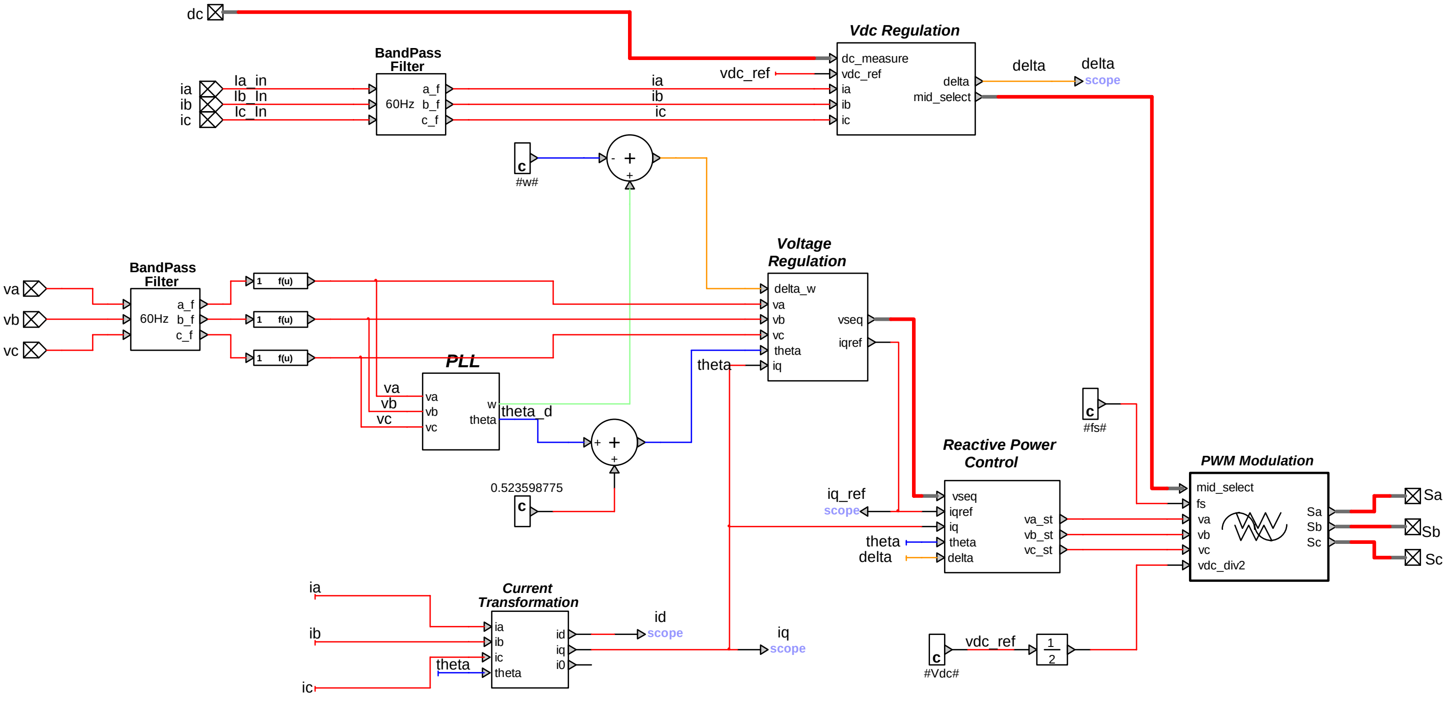

Fig. 3. EMTP-RV representation of STATCOM control algorithm

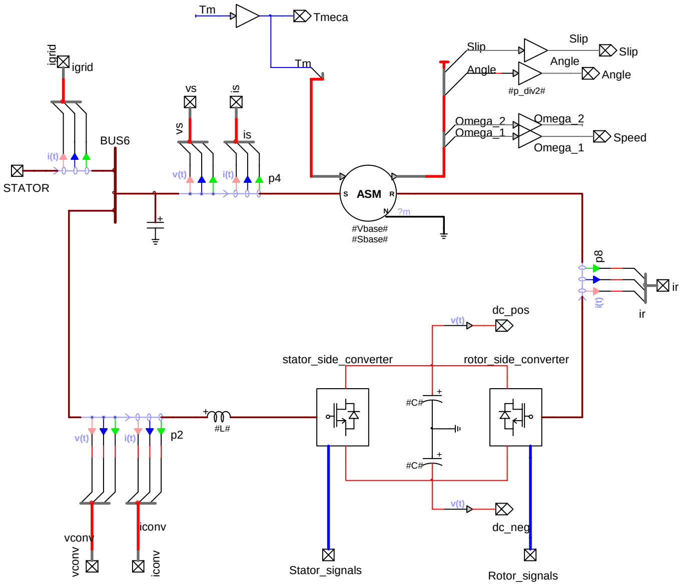

Fig. 4. EMTP-RV representation of DFIG power circuit

E. *EMTP-RV Solver*

The transient analysis software program [10] used in this paper allows for the representation of very large systems and produces very accurate results, enabling simulation of numerous cycles to even multiple seconds, with relatively short execution times. The ability of the software to model large systems with multiple machines, power electronics, and control makes it ideal for modeling wind energy systems and studying the interconnection characteristics.

The complete design is based on hierarchical (subnetworks containing subnetworks) blocks with masking. Hierarchy is essential for designing large and complex systems. The assembly of control block-diagrams is straightforward and does not require extra artificial blocks to eliminate numerical problems [11].

The asynchronous machine model is a hard-coded model. It is based on an iterative method and is capable of obtaining a simultaneous solution with network equations at each simulation time-point. Automatic steady-state conditions are found from the initially given slip data. This is particularly important for weak systems. This is used to minimize startup transients and decrease computer time.

IV. SYSTEM CHARACTERISTICS

Following verification of the control algorithms of the two systems, the system characteristics were compared. The two generator designs were compared using a typical network connection, where both normal operating characteristics as well as their response to voltage dips were investigated. Here the capacity was set to 10 MVA accomplish by aggregation of the 1 MVA model but neglecting the effect associated with geographical distribution. This becomes a more conservative approach since the averaging effect due to different wind conditions was ignored and therefore power fluctuations at the point of common coupling are proportional to the fluctuations at each of the generators.

A. *Network*

There are a number of possible interconnection structures for wind parks and thus it is not possible to cover every type of network configuration, load, and interconnection point of the wind park. Frequently wind parks are connected to weak systems, as they are typically located far from major load centers and central generation. This is reflected in the short circuit ratio (SCR) of the interconnection, given by:

$$SCR = \frac{SCC}{S_{base}} \qquad (3)$$

Where SCC or short circuit capacity is the short circuit power delivered from the grid for a three-phase fault at the wind park:

$$SCC = \frac{{V_{base}}^{2}}{|Z_{line}|} \qquad \mathbf{(4)}$$

For weak systems the SCR will usually be less than 6 and in some cases may be as low as 2. Fig. 5 shows the network under investigation where the wind park is connected at 69 kV to a system with short circuit ratio (SCR) of 6. The two wind generator systems have matched capacities in terms of real and reactive power, whereby reactive power support is supplied from the generator itself and from the STATCOM for the variable and fixed speed machines, respectively.

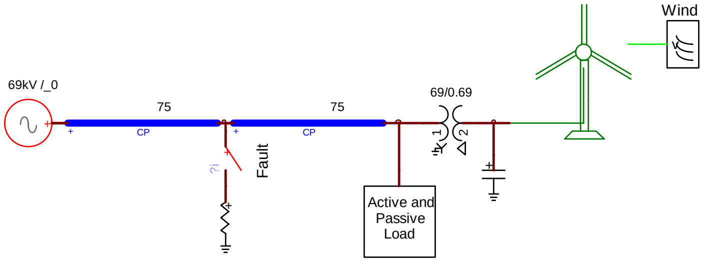

Fig. 5. Interconnection of wind park to power system (EMTP-RV schematic)

B. *Steady-state*

The wind speed, output power, and ac voltage magnitude are given for the two generators for an intact network with wind speeds around 13 m/s. As can be noted, the voltage remains more or less constant for the two machines while the output powers fluctuates with the wind speed. Also, there is a certain delay between the peak of the wind speed and that of the power, due to the mechanical time constant of the system. Finally one can note that the DFIG is able to extract more energy from the wind over interval considered due to its variable speed capability and maximum power point tracking algorithm.

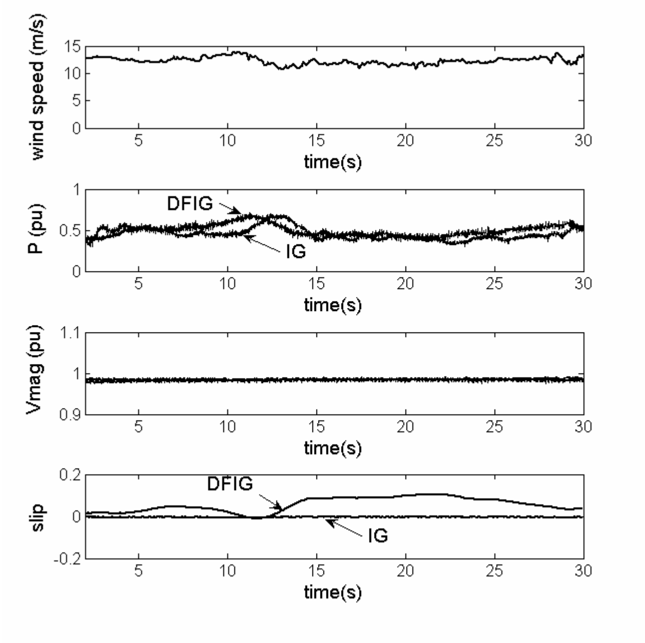

Fig. 6. Wind speed, output power and rms ac voltage at PCC for fixed speed (with STATCOM) and variable speed topologies

C. Response to Disturbances

Each of the systems is subjected to identical two-phase to ground faults. Fig. 7 and 8 show the response of the ac voltage magnitudes and machine slips, respectively. The variable speed recovers well, while it can be noted that the fast controllable reactive power provided by the addition of the STATCOM definitely improves the speed of response of the voltage magnitude in the case of the fixed speed machines.

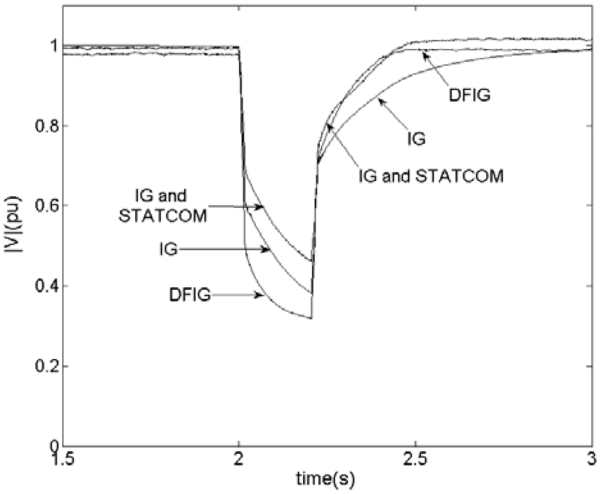

Fig. 7. Rms voltage at PCC for fixed speed (with and without STATCOM) and variable speed wind generators, during 12 cycle two-phase fault, SCR = 6.

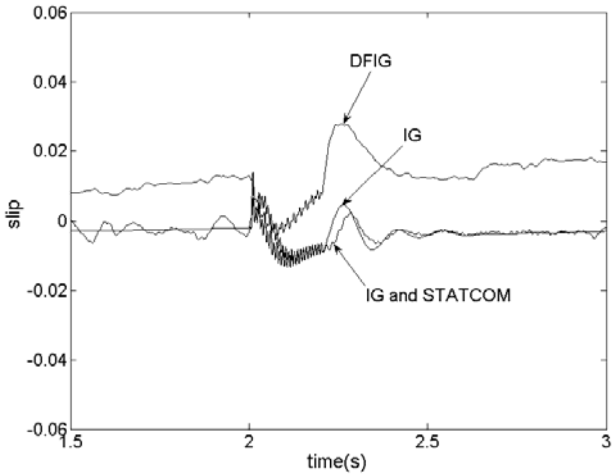

Fig. 8. Slips of induction machines for fixed speed (with and without STATCOM) and variable speed wind generators, during 12 cycle two-phase fault, SCR = 6.

V. CONCLUSIONS

The detailed transient models for variable speed wind turbines and fixed speed technologies were developed in EMTP-RV. The development of transient models is increasingly important in order to investigate many of the interconnection issues associated with wind energy. The two systems were compared in terms of their steady-state behavior as well as their response to disturbances in the local network. The variable speed topology is capable of greater energy capture when considering a wide range of wind speeds. Results show that as long as the fixed speed machine is complemented with sufficient reactive power control, such as a STATCOM, the transient performance is comparable to that of the variable speed design.

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VII. BIOGRAPHIES

Chad Abbey (S’01) received his degree in electrical engineering from the University of Alberta in 2002. In 2004, he graduated with an M. Eng degree from McGill University, Montréal where he is currently pursuing his Ph.D. He is presently working with CANMET Energy Technology Centre, in Varennes, Québec where he is a Research Engineer and helps to coordinate a joint research program on the modeling and integration of distributed generation. His current research interests include power electronics, control, distributed generation, wind energy, microgrids and planned islanding.

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