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Transient Modeling and Simulation of Wind Turbine Generator and Storage Systems

C. ABBEY[*], J. CHAHWAN[**], M GATTRELL[***], G. JOOS**

*** CANMET Energy Technology Centre**
****McGill University**
*****National Research Council of Canada**

Canada

SUMMARY

Although many of the issues related to wind integration are related to longer term dynamics, accurate transient models are becoming increasingly important—for testing of controls, study of short-term dynamics, and validation of reduced order models. Furthermore, accurate transient models of complementary technologies, such as energy storage, are required in order to investigate how one might mitigate some of the negative characteristics of wind energy. Transient models thus serve as a means of investigating the merits of these technologies, before actual field demonstration. This paper discusses the development of transient models for wind turbine generators and various promising storage technologies. The detailed models of the most common variable wind turbine generators are presented, together with a Vanadium Redox flow battery model. Operation of the two is given for both normal conditions and in response to transient phenomenon, namely three phase faults.

cabbey@nrcan.gc.ca

SOMMAIRE

Bien que plusieurs questions liées à l'intégration des éoliennes soient associées aux dynamiques à plus long terme, les modèles transitoires précis deviennent de plus en plus importants—pour l'essai des commandes, l'étude de la dynamique à court terme et la validation des modèles approximatifs. En outre, des modèles transitoires des technologies complémentaires, telles que le stockage d'énergie, sont exigés afin d'étudier comment on pourrait atténuer certaines caractéristiques négatives de l'énergie éolienne. Les modèles transitoires servent ainsi de moyen d'étudier les mérites de ces technologies, avant leur démonstration formelle dans l'industrie. Cet article discute du développement des modèles transitoires d'éolienne et de diverses technologies de stockage d'énergie. Les modèles détaillés d'éoliennes à vitesse variable sont présentés, ainsi qu'un accumulateur électrique (de type vanadium redox). L'opération des deux composants est présentée, pour les conditions normales et suite à un défaut triphasé."

KEYWORDS

Wind energy, energy storage, transient modeling, Vanadium redox.

cabbey@nrcan.gc.ca

1. INTRODUCTION

A unique relationship is unfolding between two technologies that have traditionally occupied but niche positions in the power systems industry—wind energy and energy storage. With the heightened growth of the former technology and the benefits associated with its pairing with the latter, people are now turning to the question of whether or not the combined system now makes sense. The main detractor to energy storage is that which has until now kept it on the side line—cost. However, the additional costs associated with large amounts of wind generation may soon help to tip the scales in the favour of a technology that fundamentally makes a great deal of sense.

The additional factor that accompanies the financial uncertainty of novel technologies is that associated with its behaviour and interaction with the existing system. There has been a substantial amount of effort invested in grid codes, modelling, and control of wind energy, [1]-[4]. Although for storage technologies modeling and applications have begun, the focus has been for the most part in controlled environments or on scheduling, [5]-[9]. Much less experience exists with its actual operation in power systems. These concerns fuel the need for better defined transient models and control of these systems, which will help in its acceptance as a viable technology of the future.

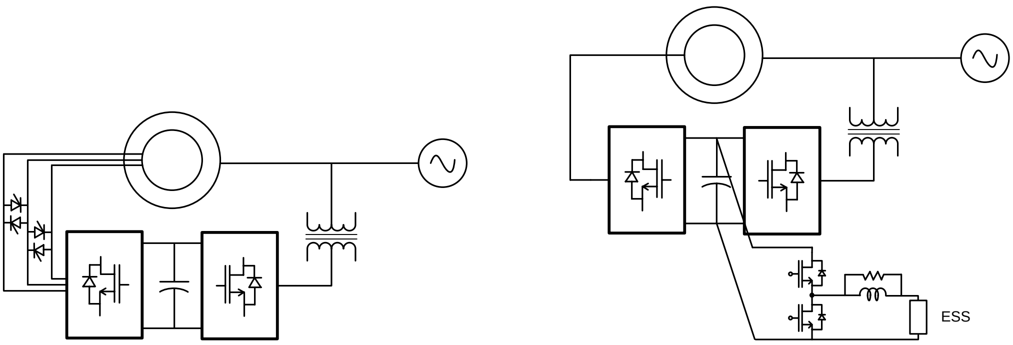
This paper considers the modeling of modern wind turbine generators and energy storage systems using the most sophisticated power system analysis software—EMTP. The different technologies and modeling approaches are discussed. The operation of the two systems is then demonstrated using illustrative applications examples. The main characteristics of these technologies are summarized and we reflect on the important role of transient modeling tools in facilitating the introduction of these technologies into the industry.

2. WIND TURBINE MODELS

The main wind turbine generators (WTGs) can be grouped into two classes: fixed and variable speed. The main difference is the use of power electronics in the second of the two, enabling control of the generator's speed and reactive power. Fixed speed machine—essentially a directly coupled induction machine—are now virtually unknown at high power levels, yet still occupy an important place for smaller wind parks connected to the distribution system and in remote applications. For the present discussion, we focus our attention solely on the variable speed topologies.

2.1 Doubly-fed induction generator

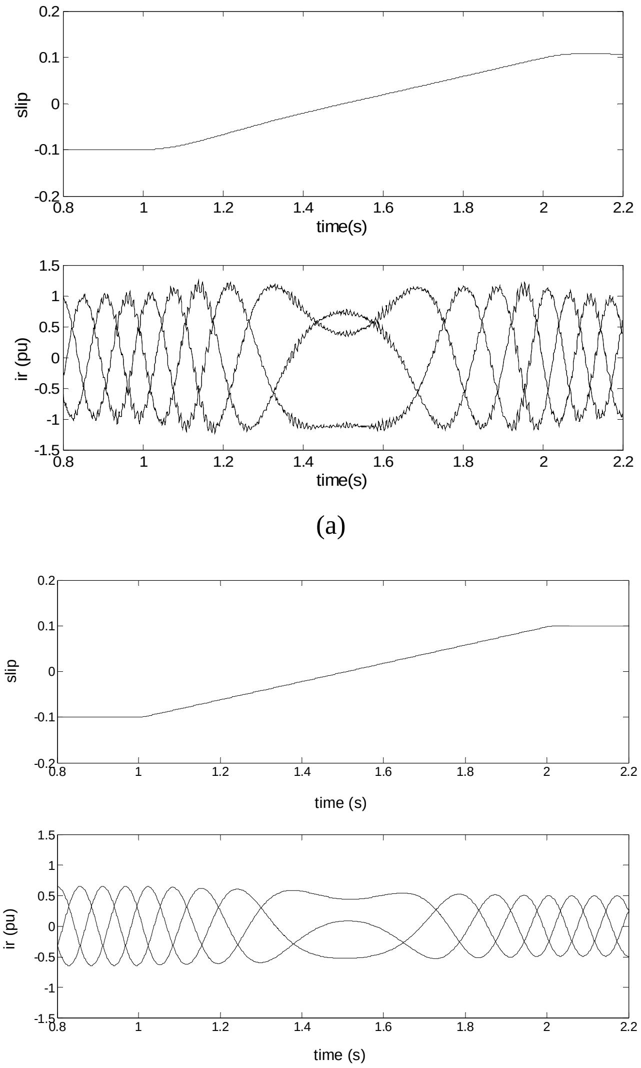
The doubly-fed induction generator (DFIG) is, at present, the more common of the variable speed machines. It consists of a wound rotor induction with a full bridge voltage sourced converter, connecting the rotor windings to the source, Figure 1. The machine's speed and stator reactive power are controlled by the converter feeding the rotor winding. The supply side serves as a dc bus voltage regulator in most cases. One potential variation on this topology is the connection of an energy storage system (ESS) on the dc bus. This can be used to exchange power with the system and also represents an alternative to the crowbar circuit that is used in the conventional DFIG for protection during short-circuits on the mains.



(a) (b)

Figure 1. Doubly-fed induction models: (a) conventional system and (b) with ESS.

Its model was developed in EMTP-RV™ and was compared with a fundamental frequency model of this topology existing in the MATLAB-SimPowerSystems™ library. Figure 2 shows the validation of the generator speed control using the two models. As can be noted the main difference are related to the absence of the high-frequency switching noise in the MATLAB average models.



(a)

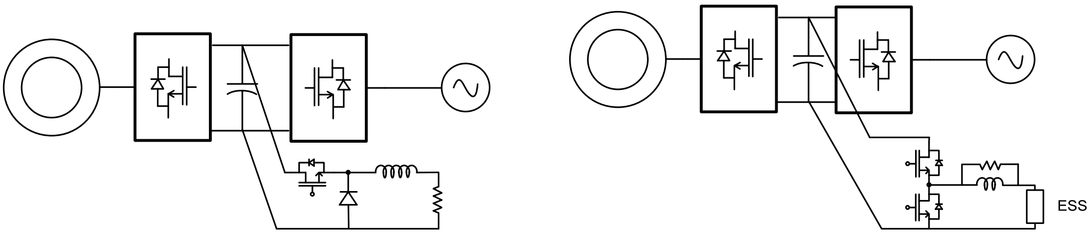
(b)

Figure 2. Validation of speed control for (a) EMTP-RV full transient model (b) MATLAB SimPowerSystems average model.

2.2 Full converter interfaced topology

While the DFIG does have various merits, it would not be unreasonable to expect that it will be soon displaced of its position of preferred WTG topology by the full converter integrated machine. Although the converter does need to carry the full rating of the machine, the decoupling between machine and grid dynamics, and the elimination of the gearbox (when using machines of sufficient number of poles to be directly coupled to the turbine) make the argument for full converter topologies quite convincing. Particularly when one considers the maintenance and unavailability costs associated with gearbox repair, the move away from the DFIG seems inevitable.

Again, as in the DFIG, there are a couple of varieties when considering management of energy during low voltage events—either power dissipation or energy storage. Likewise, the line side converter is controlled to regulate the dc bus while the converter coupled to the machine essentially controls its speed, as dictated by the wind speed and corresponding maximum power point.



(a) (b)

Figure 3. Full converter interfaced system: (a) conventional system and (b) with ESS.

3. ENERGY STORAGE MODELS

As in all fields of engineering, the detail required in the models of energy storage is dictated by the study of interest. There exist incredibly complicated models of storage but which are likely not appropriate for certain studies. Likewise, oversimplifications can result in simulations that are at best rough estimates of the system's behaviour. Here we present two different approaches in order of complexity and time spent in implementation.

3.1 Generic storage modeling

A fairly rudimentary approach to the storage modeling problem is to simply represent the system as an equivalent inductance or capacitance, depending on whether the system is current or voltage based storage. Although other types do exist, for the purpose investigating general behaviour and control using power electronics, this approach will suffice. The energy state is then given by:

$$E(T) = E_0 + \sum_{k=1}^{T} P_{ek} \Delta t \tag{1}$$

Or expressed in continuous time as:

$$E(t) = \int_0^t P_e(s) ds \tag{2}$$

Where the energy for the voltage and current based storage are given by:

$$E_V = \frac{1}{2} C V^2 \tag{3}$$

and,

$$E_I = \frac{1}{2} L I^2 \tag{4}$$

respectively. As the solver in EMTP automatically computes relation (1), it is then only necessary to represent the storage device by the necessary capacitance or inductance, which corresponds to the rating of the device. These representations then lead to various power electronic converter variations—both dc/dc and inverter—that can be used to study the charging and discharging of the storage device.

3.2 Vanadium Redox flow battery

For more detailed studies, where the intent may be focused on efficiency, or simply comparison with higher levels models, a greater understanding of a specific technology is required. Here, we consider developments towards a detailed model of the vanadium redox flow battery, which consists of the internal voltage, the losses (of both the device itself and the pump system), and electrodes capacitance, Figure 4.

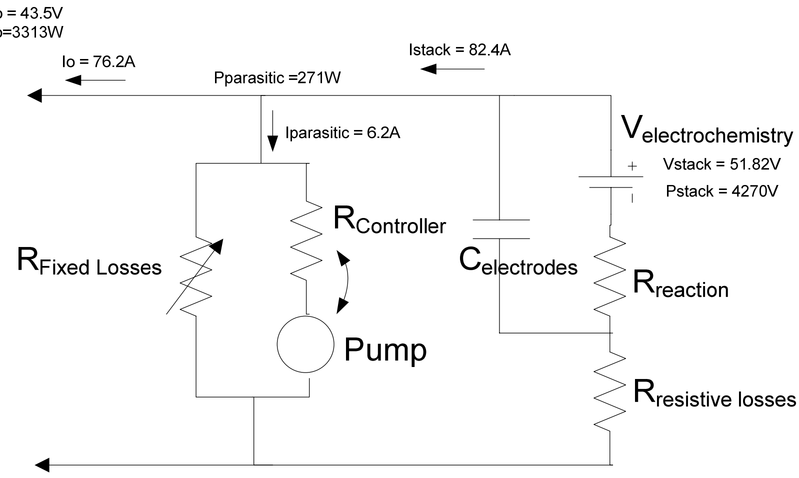


Figure 4. Vanadium Redox Flow model and discharging operation at 20 % state-of-charge

The internal voltage is given by the state of charge and is given by:

$$V_{cell} = V_{equilibrium} + 2\frac{RT}{F}\ln\left(\frac{SOC}{1-SOC}\right) \tag{4}$$

This model can be used in conjunction with simplified models of the power electronic converter or can be implemented with the detailed model. Validation of the model with experimental measurements is underway at this time.

4. ENERGY STORAGE AND WIND CHARACTERISTICS

The aforementioned models were developed with the underlying intention of combining them to simulate the pairing of wind and storage systems. Here we present the operation of these models for various cases: normal operation for longer term dynamic; and the effect of storage on the behaviour of the wind energy system following disturbances.

4.1 Storage scheduling for dispatchable power

In the following cases the storage device is separated into two distinct levels. The short-term storage is used to regulate the fast changes in wind energy while the medium-term storage handles the slow variations around the norm. Together, the two levels are able to completely damp the fluctuations and deliver a constant power, which is equal to the average value over the period in question. Figure 5 shows the evolution of the different powers and energy states of the two storage levels.

4.2 Machine transients and merits of energy storage

Finally, we consider the impact of a 100 ms low voltage event on various WTG topologies, while the generator is operating above rated wind speed, and thus, is delivering rated power. Here, both the DFIG and PMSM are considered, in part to demonstrate the differences in response of the two to grid disturbances—the PMSM is completely impervious to the event, whereas the DFIG requires a certain period before settling to the pre-fault operating point, Figures 6.

The integration of storage to the dc bus of the DFIG greatly alters its response. The transients in the generator speed are nearly undetectable and the power fluctuations are greatly smoothed. Although the PMSM remains superior in terms of performance, storage is able to enhance to recovery of the DFIG, such that it exudes characteristics very similar to the favored topology.

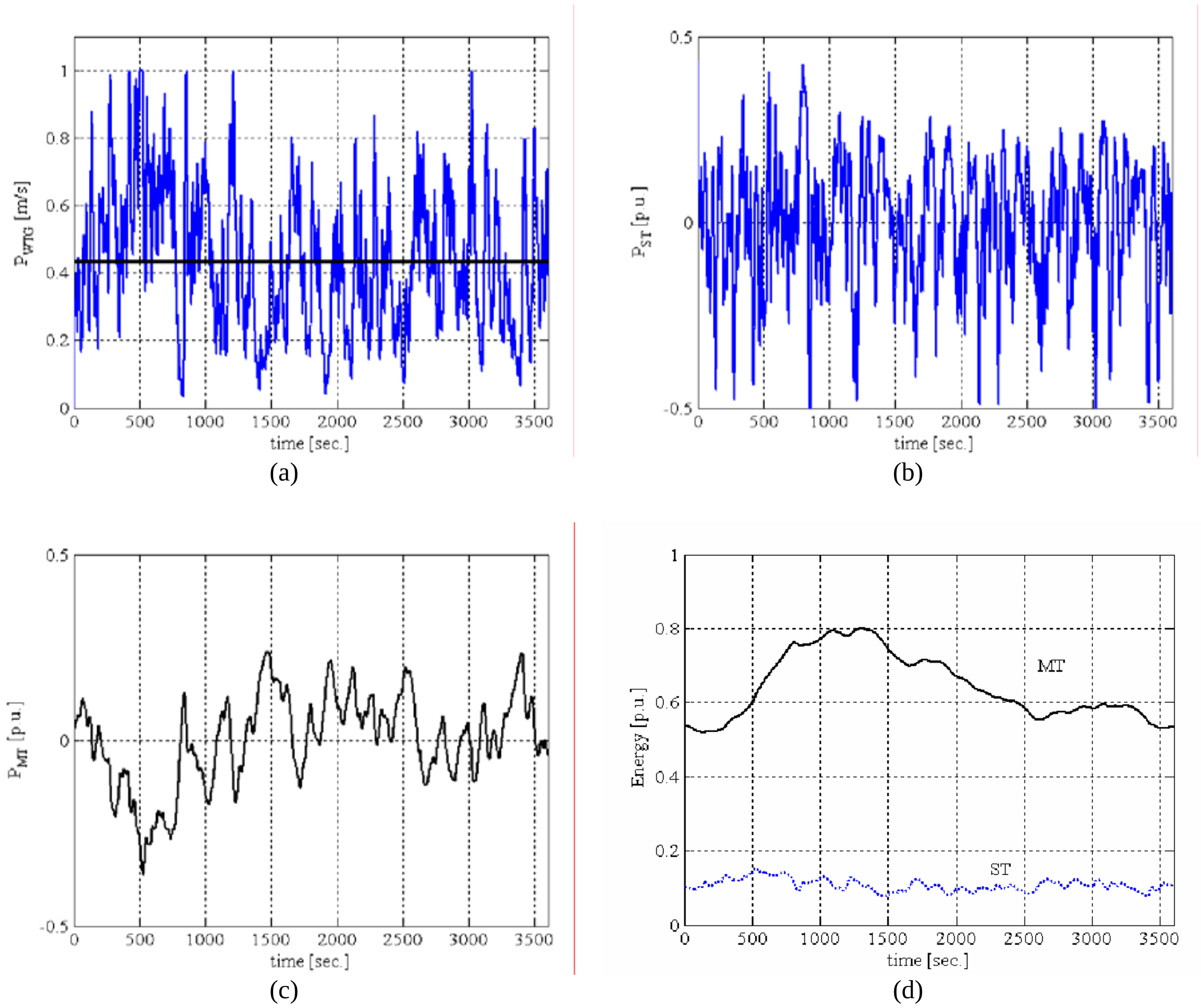


Figure 5. Performance characteristics of storage-wind system: (a) WTG power and total system power; (b) short-term storage power; (c) medium-term storage power; and (d) change in energies for short and medium-term storage devices.

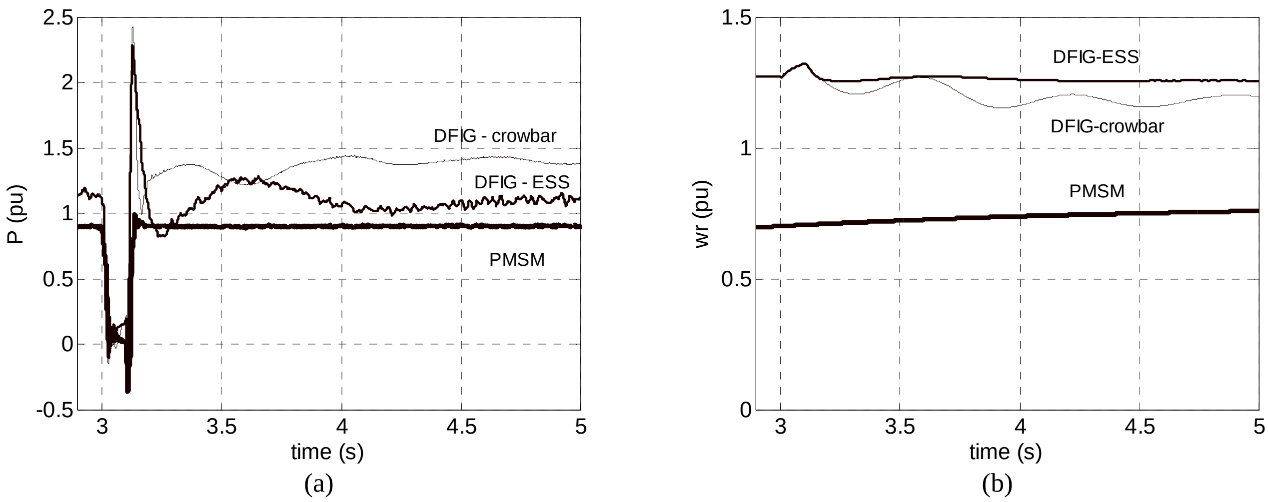


Figure 6. Response of the generator (a) output power, and (b) speed to a 6 cycle, 0.33 p.u. voltage depression, above rated wind speed.

5. CONCLUSIONS

This paper has presented the transient models for the most prominent wind turbine generators, and the merits of each were discussed. Furthermore, different approaches to modeling of storage devices were elaborated upon. The detailed components of a Vanadium redox flow battery model were given as an extension of generic models. Finally the combined operation of wind and energy storage was demonstrated for both normal conditions and contingencies. Many desirable benefits from their pairing could be extracted from analysis of the results. This analysis has demonstrated that EMTP-RV is a powerful tool that can be used to model and study the operation of two complex technologies and their interaction with the power system. It will be undoubtedly be an important tool to aid in the study of the integration of these technologies.

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