

Dynamic Analysis of Parallel Operation of Doubly-fed and Synchronous Machine

Valentin Azbe¹, Rafael Mihalic¹

Abstract

Dynamic analysis of doubly-fed induction machine (DFIM) in hydro pumped storage plant is analyzed and compared with synchronous machine in this paper. Since DFIM is relatively new technology, models of turbine governor and models of voltage control for DFIM were presented in literature just recently. In this paper the model of turbine governor and the model of control of converter are presented and applied in computer software for dynamic analyses of electric-power system. The behavior of DFIM during large and small transients is compared with the behavior of synchronous machine and described from the power-system-engineer point-of-view.

In the case of large faults crow-bar protection convert DFIM to a classical asynchronous machine, so transient stability of DFIM is analyzed as transient stability of asynchronous machine. Due to variable speed of DFIM better transient stability of this machine was determined compared to a synchronous machine. Results of dynamic simulations show that smaller and shorter oscillations of speed and active power are present by DFIM. Besides longer critical clearing times can be achieved by DFIM

Keywords

Doubly-fed induction machine, Dynamic analyses, Modelling, Simulation

1 Introduction

Hydro pumped storage plants (PSP) have an important role in electric-power systems, especially when a large amount of unpredictable renewable sources like wind or solar are present. In older PSPs usually synchronous machines are used, while in recent time a new technology with doubly-fed induction machine (DFIM) became available. This is a mature technology for wind turbines, while in the field of PSPs the technology is relatively new. The main advantage of using a DFIM is in achieving better efficiency, because rotating speed can be optimized according to the head and the required power. A technology of a DFIM is—in the field of power engineering—relatively new and with little experiences. That is why the modelling of these devices and the modelling of their controls is not a trivial task and references—in the field of PSP—are few. A majority of simulation programs for dynamic analysis of electric-power systems do not enable direct use of such an element. That is the reason why the understanding of the operation is important for proper modelling of this device for dynamic studies. Important part of a PSP is also a long pipeline that has a large influence on the dynamic characteristic within some electro-mechanical phenomenon, so proper model of turbine and pipeline should be considered. The control of a DFIM can be—due to the application of power electronics—very rapid, comparable to the control of FACTS devices.

In Slovenian electric-power system (EPS) one PSP that includes a DFIM is in operation since 2009. Another one is planned to be built and according to plans it will include one synchronous machine and one DFIM. Because generating units in PSPs are relatively big—the

¹Faculty of Electrical Engineering,
University of Ljubljana
Trzaska 25, 1000 Ljubljana
(e-mail: valentin.azbe@fe.uni-lj.si)

nominal power of PSPs will be in the range of 1/4 of installed generating capacity in Slovenia—their behavior is very important for the stability and security of the EPS.

An intensive research on large DFIM in PSPs was performed in order to provide proper models of this machine and some general principles of controls have been reported recently [1]. Prior to this only models of DFIM for wind turbines were described in literature [2]–[5]. Mathematical model of DFIM and a simplified control for application in PSP were presented in [6]. Various control strategies of DFIM in PSP were investigated in [7].

This paper analyzes the dynamic behavior of a DFIM and compares it to a synchronous machine. After the introduction basic characteristics of DFIM are presented, then modeling of control of active and reactive power and turbine governor is presented. An option for frequency and voltage control is also described. Then transient stability of both machines are described and compared. Finally the differences between two machines are presented with the help of results of dynamic simulations.

2 BASIC PRINCIPLES OF OPERATION OF A DFIM

In this section basic principles of DFIM are presented. Rotor of DFIM is connected to the turbine by the common shaft. Stator is directly connected to the grid, while rotor is connected to the grid via slip-rings and converter that controls the voltage on the rotor and in this way enables the control of active and reactive power. A basic scheme of a DFIM is presented in Fig. 1.

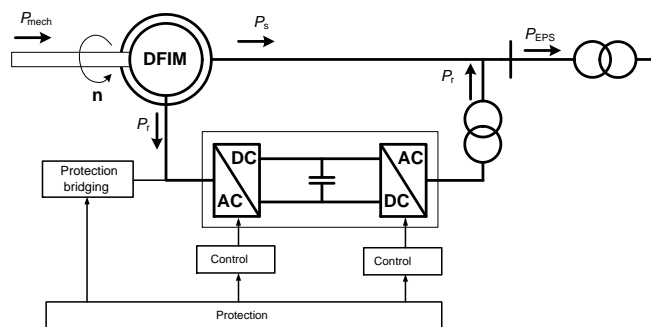


Fig. 1 A basic scheme of a DFIM

The active power through the rotor is approximately equal to:

$$P_r \approx \text{slip} * P_s \quad (1)$$

According to (1) in the vicinity of synchronous speed the active power through the converter is small. Generally, a DFIM can generate or consume various active and reactive powers by various slip (within the operational range) as long as the mechanical torque is

equal to the electrical torque.

3 Modelling of DFIM in computer programs for dynamic analyses

To analyse the dynamic behaviour of an EPS usually numerical simulations are applied. To analyse EPS that includes DFIMs, applied computer programs for this task should have a proper model of a DFIM. Some general principles of controls have been reported recently [1]. However, models of turbine control and models of control of the converter are not included in computer programs yet and users must make proper models.

3.1 Active and reactive power control

In contrast to synchronous machines active power of DFIM is not controlled by turbine governor. Instead of that it is controlled by the converter that supplies rotor windings. This converter consists of two parts that are coupled by a DC link, as it is presented in Fig. 1. The first part is a bi-directional AC/DC converter that is connected to the grid. This part controls proper voltage of a DC link by controlling proper active power exchange between the grid and the converter. Reactive power exchange between the grid and the converter is usually set to 0. The second part is a bi-directional DC/AC converter that supplies rotor windings. This part provides proper magnitude and phase of an AC voltage at the rotor windings that provides proper active and reactive power of stator windings. The frequency of this voltage is proportional to the slip and it is controlled in such a way that the control of electro-mechanical torque (i.e. active power) and voltage (i.e. reactive power) are decoupled.

The control of rotor-side converter is modelled in two stages, as it is presented in Fig. 2. The first (outer) stage is “P, Q control” that according to the difference between actual and reference active and reactive power provides reference currents in d and q axis for the second stage. The second (inner) stage is “voltage control” that controls rotor voltage (i.e., d and q component of rotor voltage in stator reference frame) according to the difference between actual and reference currents in d and q axis. Control blocks applied in both stages are PI controllers with limiters. The second (inner) stage is in some of the computer programs (e.g. NETOMAC) already internally modelled and also sophisticated to smooth transients, so only the first stage should be modelled by the user. In some other programs (e.g. NEPLAN) both stages should be modelled by the user.

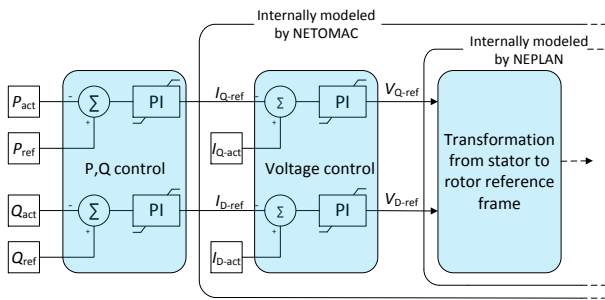


Fig. 2 A model of control of rotor-side converter

In order to keep the frequency of the network constant (i.e., to adjust the production to the consumption), synchronous generators have a so called “permanent droop” control loop in turbine control. As active power in DFIM is controlled by converter, permanent droop should be included in this control. It can be modelled as an additional signal that is added to the reference active power P_{ref} in Fig. 2. A possible solution for this signal—like it is applied in this paper—is presented in Fig. 3.

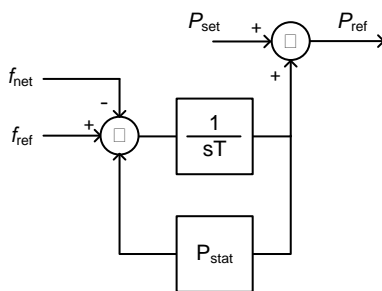


Fig. 3 Permanent droop added to a reference active power of converter control

According to Fig. 3 the difference between actual and reference frequency is forwarded to an integrator with a backward loop that defines permanent droop. Output of integrator is added to the signal of the active power P_{set} that is set by operator of a PSP and the sum of both signals presents the reference active power P_{ref} for the converter control.

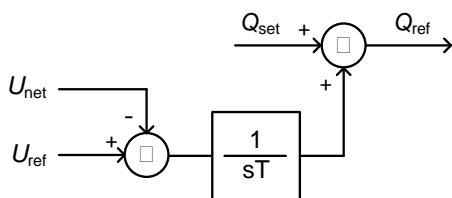


Fig. 4 Network voltage control added to a reference reactive power of converter control.

Considering the voltage of the network, the reactive power of the DFIM can be controlled in order to provide proper voltage. This control can be accomplished as it is presented in Fig. 4. According to this figure, the difference between actual network voltage U_{net} and reference voltage U_{ref} is integrated and added to the signal

of reactive power Q_{set} that is set by operator of a PSP and the sum of both signals presents reference reactive power Q_{ref} for the converter control.

3.2 Turbine governor

In contrast to the turbine governor of synchronous machine that controls both power and speed, the turbine governor of a DFIM is responsible only for the proper speed of DFIM. The optimum speed of DFIM depends on the power and on the water head (i.e., the height of the water in upper reservoir of PSP). Maximum possible variation of speed depends on the size of converter that supplies rotor and by DFIM in PSPs it is usually in the range of $\pm 4\%$, i.e., much less than by DFIMs applied in wind turbines. Examples of optimal speed at nominal head for generator-mode of operation and for motor-mode of operation are presented in Fig. 5 and Fig. 6, respectively.

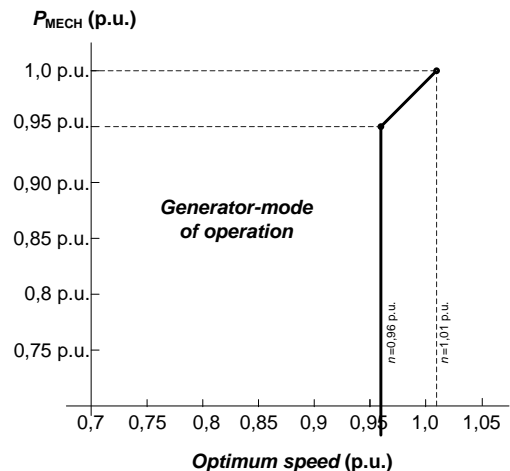


Fig. 5 Optimum speed at nominal water head for generator-mode of operation.

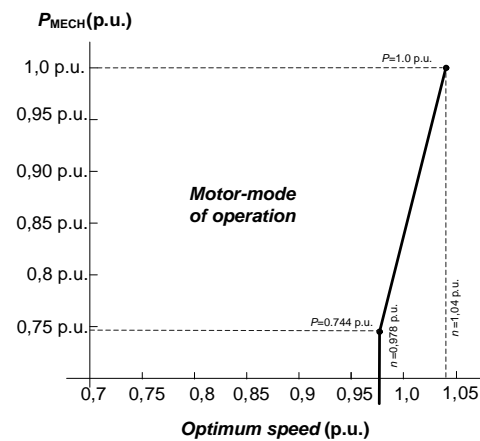


Fig. 6 Optimum speed at nominal water head for motor-mode of operation.

As DFIM is relatively new technology in PSP, the first model of turbine governor was proposed in literature just recently [1]. According to [1] the turbine governor can be constructed as it is presented in Fig. 7. Reference speed ω_{ref} is set according to Fig. 5 and Fig. 6. The difference between actual and reference speed is forwarded to a PID controller and further to an integrator with backward loop. The output of turbine governor G is then forwarded to a model of turbine and penstock that is identical to the one applied for synchronous machine.

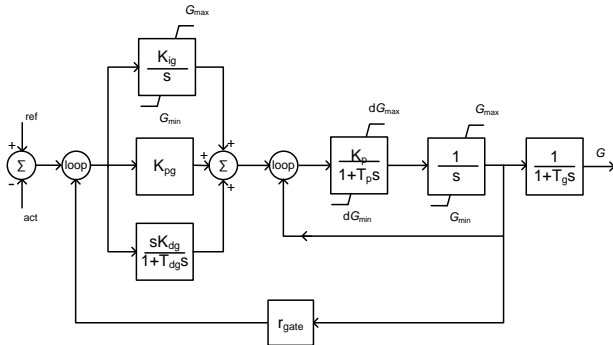


Fig. 7 Model of turbine governor.

4 Transient stability of DFIM and synchronous machine

Speed of synchronous machine is closely linked with the frequency of the network. During transients load angle δ —that is physically correlated with the rotor angle—swings. According to the P- δ characteristic presented in Fig. 8 also the active power swings – it is a sine function of the load angle δ .

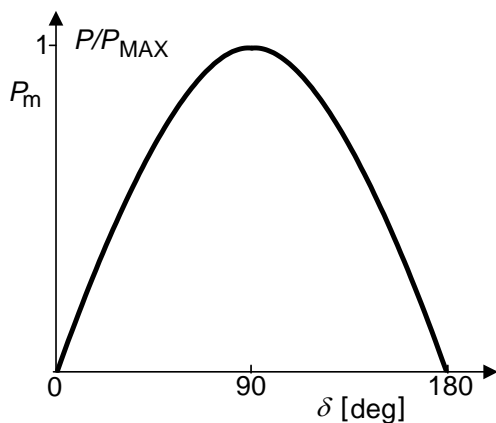


Fig. 8 Typical P- δ characteristic of synchronous machine.

On the other hand the speed of DFIM is variable and it is not linked with the frequency of the network. Consequently larger deviations of rotor speed are possible without large changes in active power—only minor changes of active power are present due to the control

algorithm of active power. To compare DFIM to a synchronous machine, a P- δ characteristic can be presented as a P- δ characteristic with a variable origin that can be set by DFIM's control as it is presented in Fig. 9. In the case of large faults like short circuits in the vicinity of DFIM, rotor currents become too high, consequently a crow-bar protection disconnects rotor from converter and inserts ohmic “crow-bar” resistance in rotor circuit.

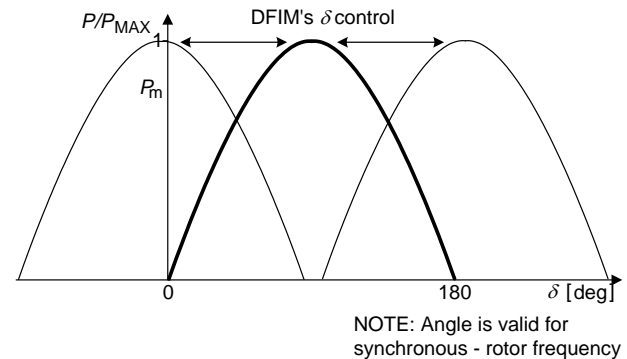


Fig. 9 Variable P- δ characteristic of DFIM.

In this way DFIM is converted to a classical asynchronous machine until rotor currents decrease and a crow-bar protection deactivates ohmic resistance and re-connects rotor windings to the converter. During the crow-bar activation DFIM's power is defined by Kloss equation that is in Fig. 10 presented as a “static power/speed characteristic”. This characteristic is valid in steady state, while during transients the active power swings around this characteristic. This characteristic is also greatly affected by saturation and by voltage reduction due to big reactive power consumption of asynchronous machine. In Fig. 10 trajectory of a DFIM operating point after the fault with crow-bar resistors in rotor circuit is presented. This trajectory starts in point “0” that represents a pre-fault state, at the time of the fault it moves to point “1” and during the fault it travels to point “2”. After fault clearance it jumps to point “3” and then oscillates around static power/speed characteristic toward the point “4”.

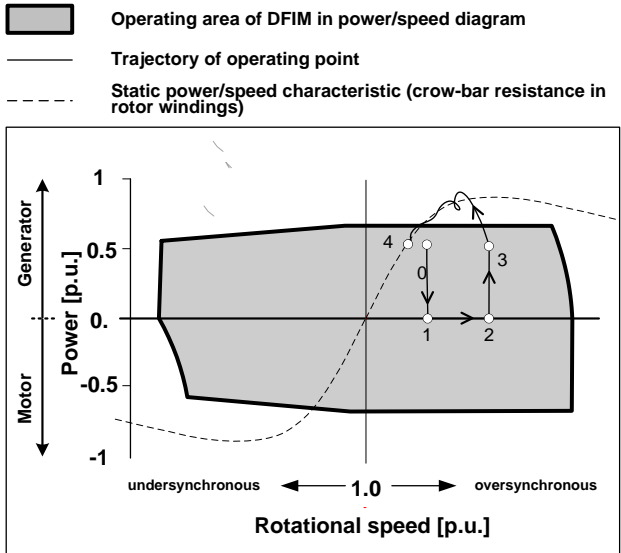


Fig. 10 Trajectory of a DFIM operating point after the fault with crow-bar resistors in rotor circuit.

5 Results of numerical simulations

Parallel operation of synchronous machine and DFIM were tested on simple longitudinal model presented in Fig. 11. Both machines were connected to a common bus that was connected to an infinite bus via short 1 km 2x110 kV overhead line. Additional no-loaded line is added to provide the point of the fault in the system.

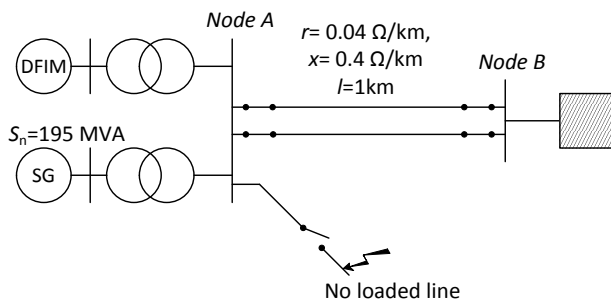


Fig. 11 Test system of parallel operation of DFIM and synchronous machine

Two cases of a 3-phase short-circuit on no loaded line were analyzed. In the first case the fault was near the machines, consequently crow-bar protection was activated for 1 s and then de-activated. During this period DFIM operates as a classical asynchronous machine. Active and reactive power, network voltage, speed and trajectory of operating point in the “active-power versus speed” diagram for this case are presented in Fig. 12. From results it can be seen that larger and longer oscillations are present by synchronous machine. 1 s after the fault the crow-bar protection is deactivated, consequently active and reactive power is rapidly set to pre-fault values. Large

difference between these machines is also in critical clearing time, for synchronous machine it is 367 ms, while for DFIM it is longer than 1.5 s.

In the second case a fault that was far from machines was analyzed. In this case small transients are present and consequently the crow-bar protection is not activated. The difference between DFIM and synchronous machine is still noticeable. Results of dynamic simulations are presented in Fig. 13. During and after the fault DFIM can keep both active and reactive power constant with only short and small oscillations of power and speed.

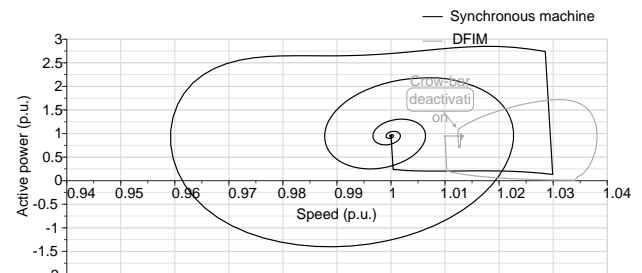
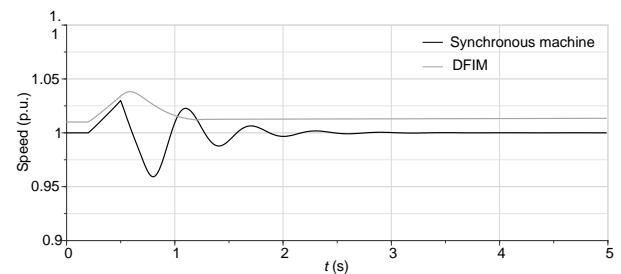
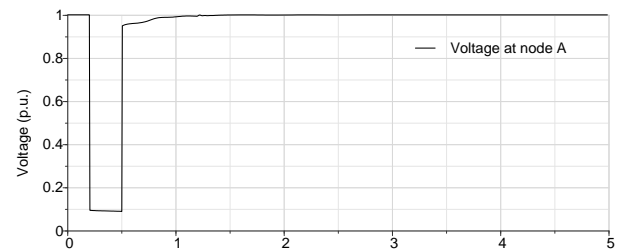
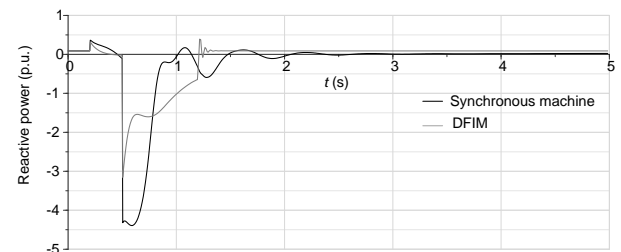
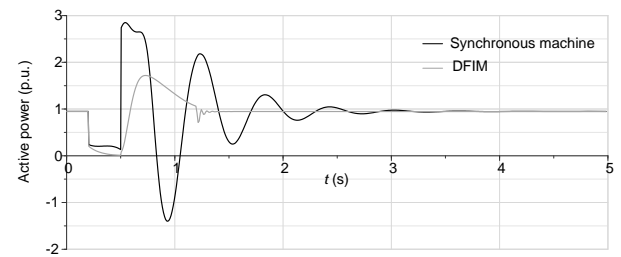


Fig. 12 Dynamic analyses – fault near to machines

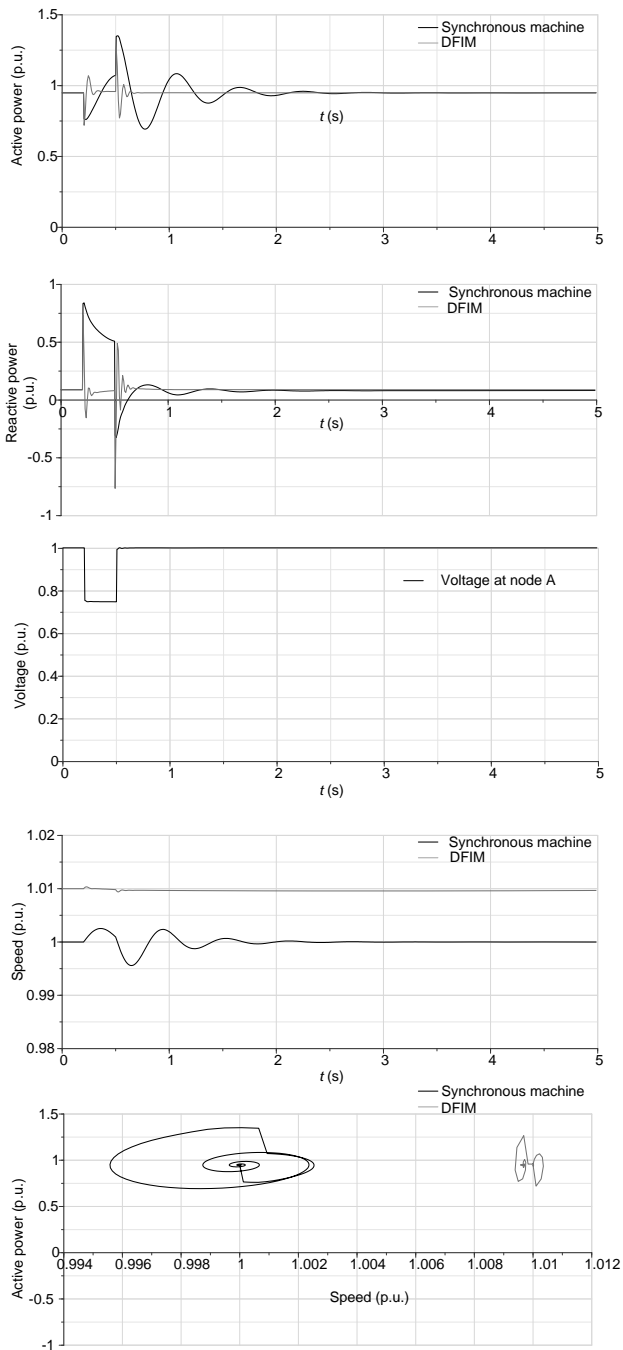


Fig. 12 Dynamic analyses – fault far from machines

Oscillations of DFIM's active and reactive power are rapidly cleared (in ~ 0.2 s) due to fast control of rotor converter while oscillations of synchronous machine are larger and they last for about 2 s.

5 Conclusion

Although the principle of operation of DFIM is quite different from synchronous machine, we try to present its stability in the same way as it is usually presented for synchronous machine. Analyses show that DFIM and synchronous machines have different dynamic behavior. Models of converter control and turbine control are proposed in the paper and applied in numerical simulations of transient stability. A simple two-machine infinite-bus test system was applied to compare the behavior of synchronous machine and DFIM. In case of a fault near machines a crow-bar protection converts DFIM temporarily into a classical asynchronous machine while in the case of a fault far from machines crow-bar protection is not activated and consequently DFIM's active power has only minor oscillations during and after the fault. Possible interactions between DFIM and synchronous machine might be the matter of the future work.

References

- [1] J. Feltes and Y. Kazachkov, "PSSE Dynamic Simulation Models for Different Types of Advanced Pumped Storage Hydropower Units," *Siemens Power Technology*, Issue 115, Nov. 2013.
- [2] P. Ledesma, J. Usaola, "Doubly Fed Induction Generator Model for Transient Stability Analysis", *IEEE trans. energy conversion*, vol. 20, , pp. 388-397, June 2005.
- [3] M. A. Pöller, "Doubly-Fed Induction Machine Models for Stability Assessment of Wind Farms", *2003 IEEE Bologna PowerTech Conf.*, June 2003.
- [4] J. B. Ekanayake, L. Holdsworth, X. Wu, N. Jenkins, "Dynamic modelling of Doubly Fed Induction Generator Wind Turbines", *IEEE trans. power systems*, vol. 18, pp. 803-809, May 2003.
- [5] DiGSILENT, "Dynamic Modelling of Doubly-Fed Induction Machine Wind-Generators", Technical Documentation, Aug. 2003.
- [6] J.K. Lung, Y. Lu, W.L. Hung, and W. S. Kao, "Modeling and Dynamic Simulations of Doubly Fed Adjustable-Speed Pumped Storage Units," *IEEE trans. energy conversion*, vol. 22, pp 250-280, June 2007.
- [7] Y. Pannatier, B. Kawkabani, C. Nicolet, J.J. Simond, A. Schwery and P. Allenbach, "Investigation of Control Strategies for Variable-Speed Pump-Turbine Units by Using a Simplified Model of the Converters," *IEEE trans. Industrial electronics*, vol. 57, pp 3039-3049, Sept. 2010.