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Modifying the aggregated wind farm model with a controller

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Abstract. A large wind farm can be simplified by the aggregated wind farm models for load flow, steady and transient stability studies. When a fault (such as a short circuit) happens in a large wind farm, some of wind turbines trip while others do not. This paper is to design a controller to modify the aggregated wind farm model in the case of one or more unit removed or added from the complete model. This is without stopping the simulation process during performing the steady state and transient analysis of the whole system. This controller can modulate the status of the wind turbines in the aggregated model in a given farm according to any change in this farm. By this controller, we save effort and time to change the status of wind turbines in the aggregated model. The proposed wind farm is composed of some smaller farms of permanent magnet synchronous generators (PMSGs) and others of squirrel cage induction generators (SCIGs).

Keywords: wind farm aggregation model; controller; PMSG and SCIG

1. Introduction

Wind is considered as one of the important sources of electrical energy production, where it is considered a clean source of energy production. With increasing in output power of wind energy, wind farms have a great effect on the electrical power systems, so the network integration of wind farms to the grid studies becomes very important in our field of research. Wind energy has the potential to play an important role in future energy supply in many areas of the world. The growing worldwide market will lead to further improvements, such as larger wind turbines and offshore wind farms. These improvements will lead to further cost reductions mentioned in Ackermann (2012).

Wind farms are represented by modeling each of wind turbines. With increasing number of wind turbines in a wind farm, the modeling of these wind turbines becomes more difficult because it is considered complicated and takes time in the implementation. Therefore, most of the studies and researches were interested in simplifying these wind farms so as to reduce the size of the power system model, the computation time and implementation described by Rudion (2008). They simplified complete wind farm model by using an aggregated wind farm (AWF) model, which

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represents active and reactive power exchanged with the grid during transient and steady state analysis.

Many researchers have studied different aggregated techniques described by (Ackermann 2012, Rudion 2008, Zhao, Bao, Yang, Yan and Zhang 2013, Yang *et al.* 2012, Xue *et al.* 2013, Hayes *et al*. 2011, García *et al.* 2015, Ali *et al.* 2013, Hayes and Djokic 2013, Chowdhury *et al.* 2013, Conroy and Watson 2009, Fernandez *et al.* 2006, Fernandez *et al.* 2009, Muljadi *et al*. 2008, Meng and Xue 2011, Fernández *et al*. 2008). Most of them found that the full aggregated model using equivalent wind speed (FAM_EWS) is the closest one to the actual complete model as in (Fernandez *et al.* 2006). This technique operates on identical wind turbines in a wind farm (the same type turbine, the same parameters and operational conditions). It aggregates wind turbines and replaces the entire wind farm with a single equivalent wind turbine using equivalent wind speed as depicted in the following equation described in (Fernandez *et al*. 2009)

$$S_{eq} = \sum_{i=1}^{n} S_i \tag{1}$$

where n is the number of wind turbines in a wind farm, S_i is the apparent power of each wind turbines and S_{eq} is the rated apparent power of the equivalent wind turbine of the farm.

The equivalent wind speed is derived from the power curve of the wind turbine as proposed in (Fernandez *et al*. 2009).

For a wind farm consisting of different types of wind turbines, most researchers concluded that multi full aggregated model using equivalent wind speed (MFAM_EWS) gives a better approximation to the complete model as proposed in (García *et al*. 2015, Ali *et al*. 2013). This technique presents a wind farm with many equivalent wind turbines, where each equivalent wind turbine aggregates wind turbines that have similar operational points and similar rated power. This means that the wind farm divide in to several clusters as depicted in the following equation

$$S_{M,eq} = \sum_{j=1}^{c} \sum_{i=1}^{n} S_{j,i} \tag{2}$$

where c is the number of clusters in a wind farm, $S_{M,eg}$ is the apparent power of the all wind farm.

But most studies and researches have focused on compiling all the wind turbines in a wind farm considering that all turbines are in service. For example, if the wind farm consists of 100 wind turbines, they aggregate the 100 wind turbines without taking in mind that some of these turbines may be out of service due to high incoming wind speed, three phase short circuit, one or more units in maintenance and etc. No studies have been prepared in case of any number of turbines was shut down during the operation, which means that off wind turbine(s) should be taken off from the aggregated system, where every turbine taken off from the whole system should be subtracted from the aggregated model using its speed and power curve. This means that they have to stop the operation (simulation) and take off the separated wind turbine from the AWF model (separate its speed and power curve). Suppose also that some wind turbines became out of service at a certain time and after time some of these wind turbines are returned in service. This leads to stop the running simulation every period to update the status (on/off duty) of wind turbines in the aggregated wind farm model.

This paper works on linking the whole wind farm and the AWF model by a controller as depicted in the following section.

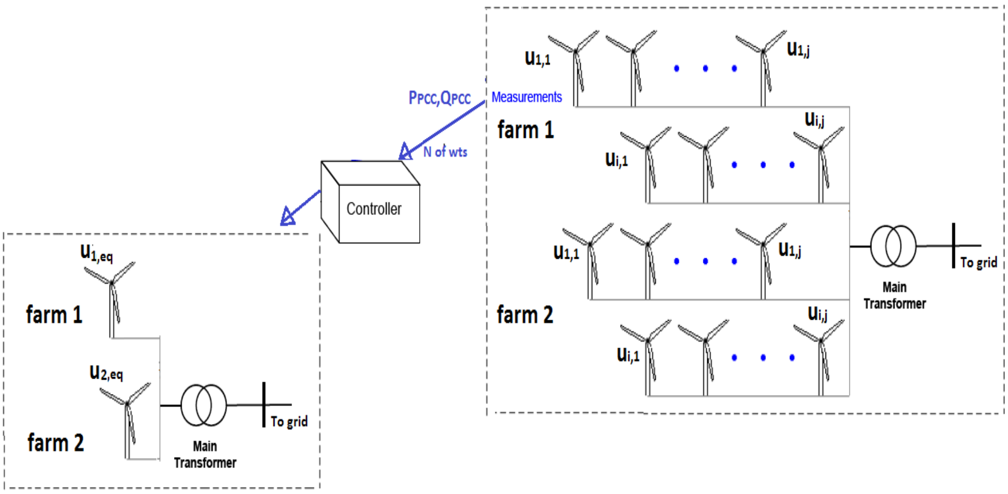

Fig. 1 The function of the controller

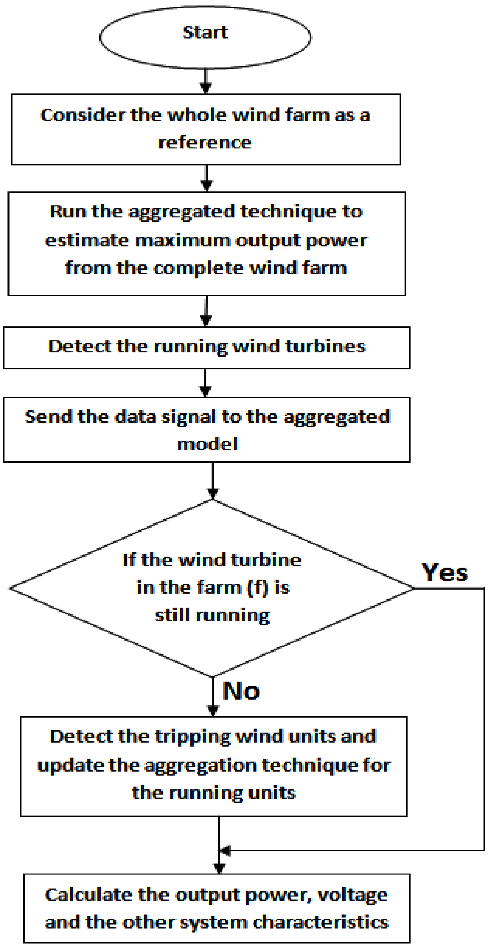

Fig. 2 Flowchart of the proposed controller

2. The proposed controller

As shown in Fig. 1 the wind farm is laid out on a matrix with *i* rows and *j* columns. The controller detects the running wind turbines in wind farms and resurrected this information to the AWF model. If any wind turbine in a wind farm is separated for high incoming wind speed (exceed cut off wind speed), it detect the position of this turbine in which rows and columns and sends a signal to the AWF model to separate the same wind turbines speed and power curve in the AWF model. In this way, we are saving time and effort to stop the execution (simulation) and change the status of wind turbines in the AWF model and separate the turbine, which was off duty and taken out during operation. With this controller, we can simulate the whole wind farm without the off units or with the units that returned back on service.

If $u_{f,i,j}$ for one of the farms changed there is a change in $u_{f,i,j}$ to $u'_{f,i,j}$. The corresponding output power $P_{f,i,j}$ changes to $P'_{f,i,j}$ where $P'_{f,i,j}$ can be zero for $u'_{f,i,j} < u_{f\ cut\ in}$ or $u'_{f,i,j} > u_{f\ cut\ off}$, where f refers to number of farm, *i* refers to the rows and j refers to the column in the farm. The controller scans wind turbine matrix if the output of the scanned is zero, then nothing changes. During the scan, if one wind unit or more have changed its status, then the controller should enter the changed speed to the aggregated model to find a new aggregated system by disconnecting the speed and power curve of the tripped wind turbines. Fig. 2 presents a flowchart of the proposed controller.

This paper considers two wind farms, which operates by the systems PMSG and SCIG wind turbines using the data in both of the two farms (Data on wind turbines Goldwind and Vestas) as described in website link. The system composed of ten of wind turbines of the type Goldwind (PMSG) and ten of wind turbines of the type Vestas (SCIG). Fig. 3 shows the connected schematic of this wind farm.

3. Simulation studies

Now we are modeling these wind turbines in a wind farm by MATLAB/SIMULINK. This large

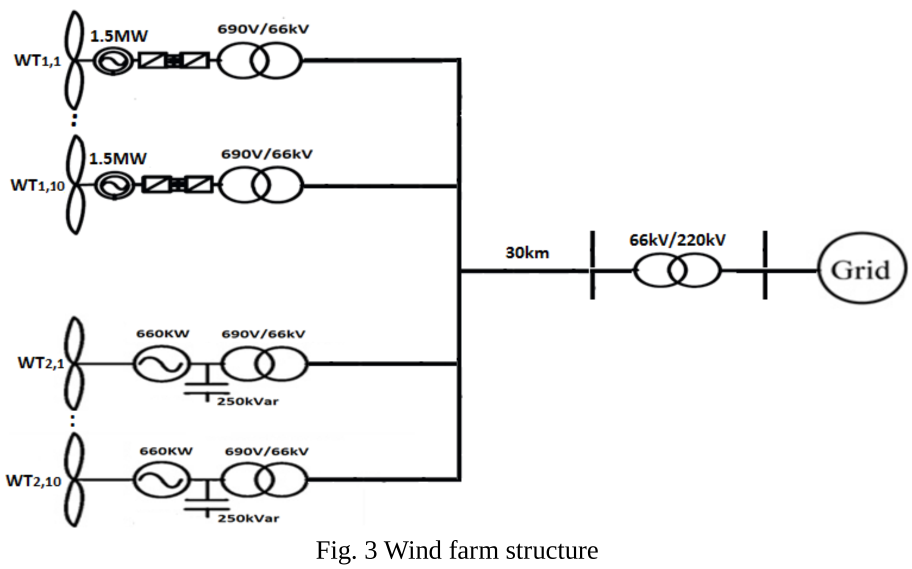

Fig. 3 Wind farm structure

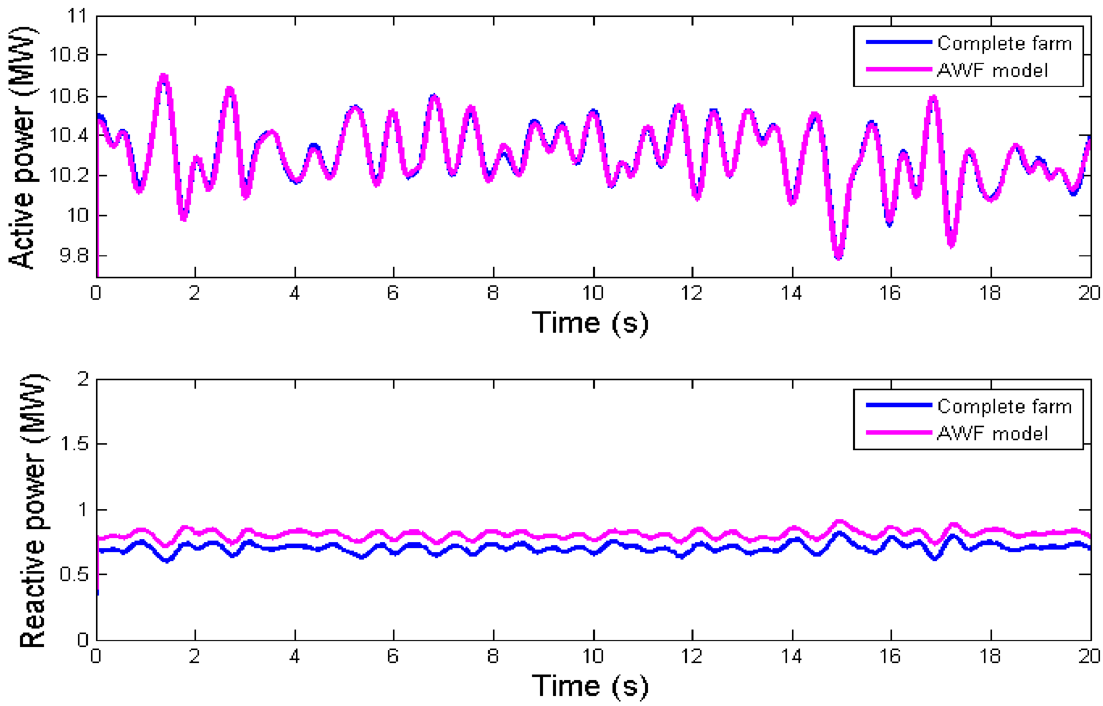

Fig. 6 Comparison during all running wind turbines at the PCC

farm is composed of smaller wind farms with different types of wind turbines as shown in Fig. 3. The capacity of this farm is 21.6 MW consisting of 10*1.5 MW PMSG and 10*660 KW SCIG wind turbines. The rated speed of each PMSG wind turbine is 11 m/s with *wr*=1 and the rated speed of each SCIG wind turbine is 15 m/s with *wr*=1. These smaller farms are connected to a 60 kV distribution system exporting power to a 220 kV grid through a 30 km 60 kV feeder. We compare between the whole wind farm and MFAM_EWS, which is used due to the farm consisting of different wind turbines as mentioned before. The variables considered in the comparison are the active (P_e) and reactive power (Q_e) exchange between the wind farm and power system. The speeds of the wind received by the PMSG and SCIG wind turbines are depicted in Appendix A. This paper is working in four cases.

3.1 case 1

If all wind turbines in the complete wind farm are running. Comparison between the complete wind farm and the MFAM_EWS (kind of AWF model) during operation (running all wind turbines) are shown in Fig. 6. The wind speed incident in each wind turbines are depicted in Appendix A.

Fig. 6 compares between the complete wind farm and MFAM_EWS in active and reactive power at the point of common coupling. The figure depicted that MFAM_EWS has a better approximation to the complete model. This aggregated model can represent the whole system with a reasonable accuracy and reducing computation time. Where the whole wind farm executes with 540 sec and aggregated model executes with 26 sec.

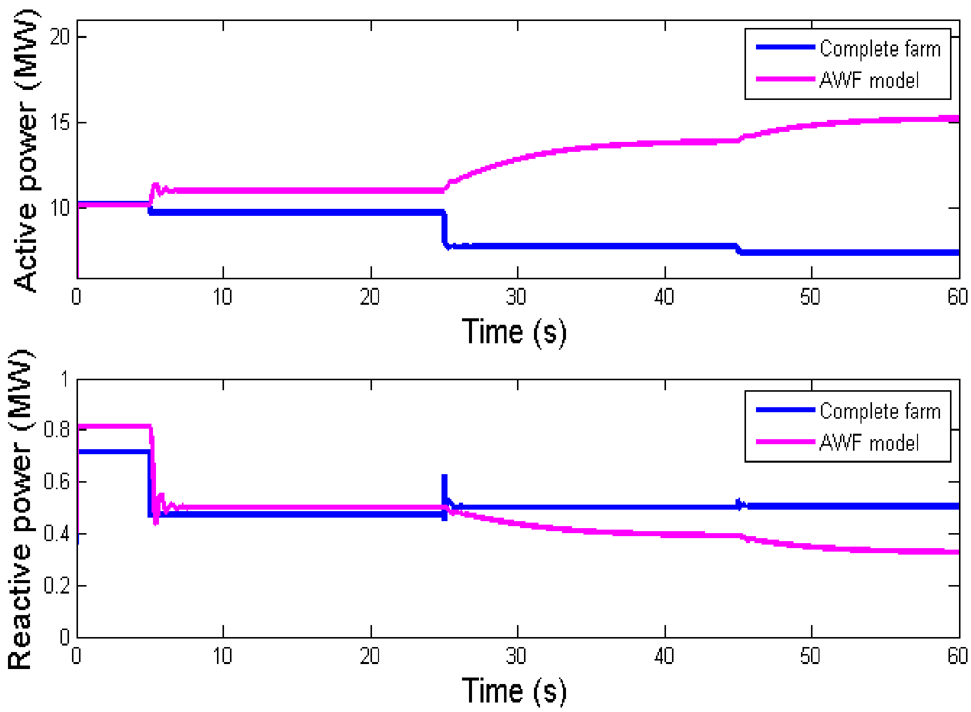

Fig. 7 Comparison at PCC without controller

3.2 case 2

Now we suppose that the wind speeds incident on each wind turbine without fluctuations and during the simulation two of SCIG wind turbines become out of service due to high incoming wind speed (exceed the cut off wind speed) at *t*=5 sec and three of PMSG wind turbines become also out of service at *t*=25 sec, then one PMSG wind turbine becomes off duty at *t*=45 sec. Fig 7 shows a comparison between complete wind farm and AWF model.

From the previous figure, it is clear that the AWF model is closer to the whole wind farm, but only during the period of operation of all wind turbines, while when some of wind turbines are shut down, the difference became very clear between the AWF model and the output of the wind farm. This difference is growing with increasing of separated wind turbines.

When the wind speed exceeded its limit (cut off speed) in some turbines, the complete wind farm model could separate these turbines from the farm, as the output power of the complete model decreased as shown in Fig. 7. However, in the AWF model, it could not separate these turbines, as the output power of the AWF model increased with the increase of the speed of these turbines; the energy did not decrease like what happened in the complete model.

3.3 case 3

And that's where the main goal is not to stop simulation from time to time to change the status of wind turbines in the AWF model, because the turbines are separated during seconds. It consumes time to take off the separated turbine from the AWF model. The main objective of this

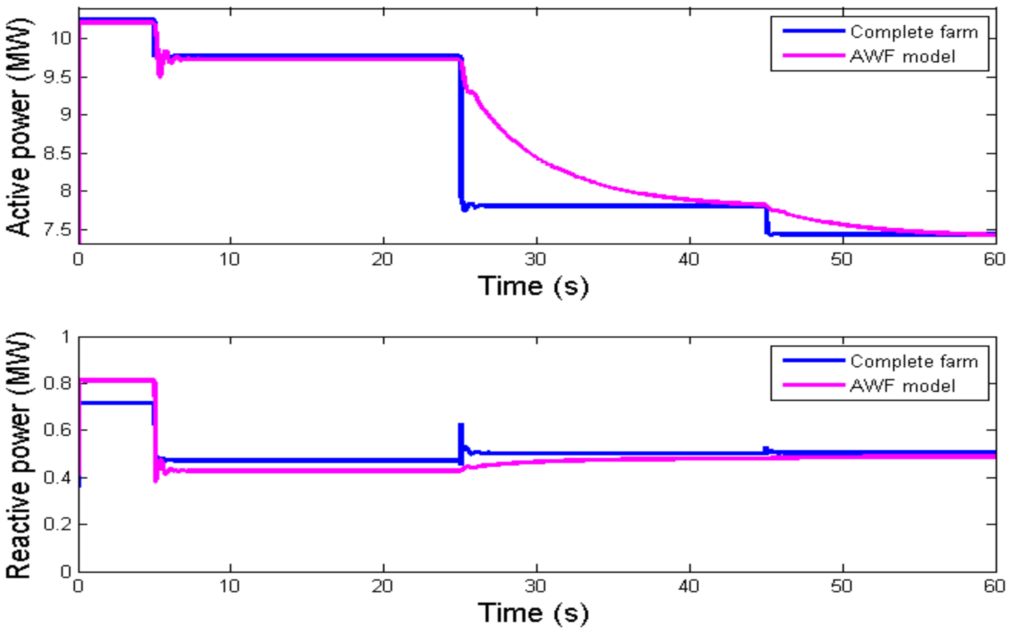

Fig. 8 Comparison at PCC with controller

study is that the operation will continue in the case of all turbines in the operating state, or some of them have been separated. So this paper makes a controller to connect between the whole wind farm and the AWF model. This controller sends numbers and data (wind speed and power speed curve) of all wind turbines in the complete farm, data of separated wind turbines and data of running wind turbines. It can modulate the status of wind turbines in aggregated model without stopping the run simulation. The following figure shows the function of this controller.

Fig. 8 clarifies that the controller may possess the ability to separate the turbines in AWF model that separated during the operation in the whole wind farm, without the need to stop the simulation.

3.4 case 4

From Fig. 7 the output power of the wind farm is about 10.24 MW with all wind turbines running and about 7.4 MW after some of wind turbines are separated as shown in Fig. 8. Now, I suppose that some of these separated wind turbines are coming back to the operating condition again. I want to see the reaction of the controller for these returned wind turbines. Suppose that one of SCIG and PMSG wind turbines are returned to service after six of wind turbines are out of service (2 SCIG and 4 PMSG wind turbines). Fig. 9 shows the ability of the controller in this case.

Fig. 9 shows the response of a controller about the returned turbines to the operation again. It has the ability to retrieve the separated wind turbines in the AWF model according to the data received from the complete wind farm. So the controller will control the status of turbines, whether within the operating range or not, as well as being able to retrieve the turbine into operation again without any need to stop the execution to modify position of wind turbines in the AWF model.

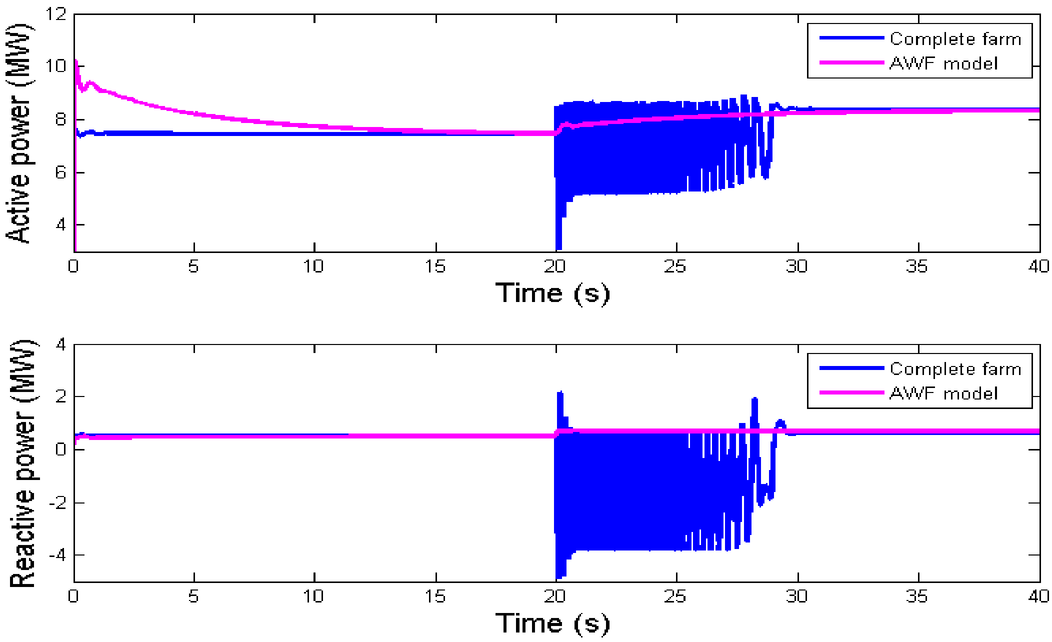

Fig. 9 Comparison at PCC in case 4

4. Conclusions

Most of researchers interested in aggregation techniques of wind farms, but they did not concern whether whole wind turbine is operated or not in the wind farm. This means that they aggregate all the wind turbines in the entire wind farm. If any of wind turbines is out of service due to any reason, they have to stop simulation to modulate the case. It takes time to change the status of wind turbines to separate or add inside the aggregated model, especially the turbines may be separated in milliseconds interval. It is not reasonable to stop the execution to vary the state of turbines every time. So we make a controller to link between the entire wind farm and the AWF model. With this controller, we can simplify and represent the entire complete wind farm in the AWF model all the time whether all wind turbines working or some of them are off duty. With this controller, we can save time and effort to adjust wind turbines status in the AWF model according to the data received from the total wind farm. Simulation results show the response of a controller about separated or retrieved wind turbines in AWF model.

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Appendix A

Wind speeds incident on the PMSG wind turbines

Wind turbine	WT_1	WT_2	WT_3	WT_4	WT_5	WT_6	WT_7	WT_8	WT_9	WT_{10}
Wind speed (m/s)	7.2	9.64	7.98	6.95	8.87	9.45	9.13	8.78	7.58	9.05

Wind speeds incident on the SCIG wind turbines

Wind turbine	WT_1	WT_2	WT_3	WT_4	WT_5	WT_6	WT_7	WT_8	WT_9	WT_{10}
Wind speed (m/s)	11.54	11.98	12.01	12.69	13.2	13.65	14.6	11	12	13