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Published in:
Proceedings of the IEEE Power & Energy Society General Meeting, PES 2015

DOI (link to publication from Publisher):
10.1109/PESGM.2015.7286491

Publication date:
2015

Document Version
Early version, also known as pre-print

A Strategy of Minimizing Wind Power Curtailment by Considering Operation Capacity Credit

Zhou Liu[1], *Member, IEEE,* Chi Su[1], *Member, IEEE,* Jiakun Fang[1], *Member, IEEE,* Weihao Hu[1], *Member, IEEE,* Zhe Chen[1], *Senior Member*, *IEEE*, Yanting Hu[2], *Senior Member*, *IEEE*, Taiyi Zheng[3] and Yong Sun[3]

[1]Department of Energy Technology, Aalborg University, Aalborg, Denmark

[2]Faculty of Science and Engineering, University of Chester, Chester, UK

[3]China Sate Grid Jilin Electric Power Co. Ltd., Changchun, China

zli@et.aau.dk

***Abstract*—An optimal wind power curtailment strategy considering operation capacity credit is proposed in this paper to minimize the uncertain wind power curtailment and minimize the system operation cost. The relevant definitions in capacity credit assessment are applied in the power system operation situation. Based on operation capacity credit prediction, the optimal operation control strategy is defined and implemented for hourly system operation and control. Multi-agent system based control structure is adopted to coordinate the diverse system components to work together and realize the system wide targets of the proposed strategy. The simulation results demonstrate the effectiveness of the proposed strategy.**

***Index Terms*—wind power curtailment, operation capacity credit, optimal control strategy, multi-agent system**

I. Introduction

Owing to the ability to reduce CO2 and substitute the conventional fossil fuels, wind energy, which is an environment-friendly source of energy, now becomes one of major energy contributors for societies. With the help of diverse incentive policies and legislation, the penetration levels of wind power in many countries become higher and higher, such as 33.2% of total electricity production in Denmark (2013) [1], 19% in Portugal, 11% in Germany [2] and etc. However, high level wind power integration is still a big challenge. Many electricity systems have experienced problems that some wind farms are becoming unprofitable, since these units have a very limited operation time and some available wind power has been curtailed due to transmission or operational constraints [3]. Also due to variability and prediction difficulty of wind, a wind farm cannot contribute as much to the generation adequacy as a conventional power plant with equivalent energy generation [4].

So when the high level wind power is integrated and replace those conventional power plants, how to keep the reliability of generation system and reduce the wind power curtailment become urgent issues to be solved.

Many efforts have been made on the research of the capacity credit of wind power recently [4-7]. In [5], the capacity credit of renewable sources is defined as the amount of conventional sources that could be replaced by the renewable power source, without changing system reliability. Also in this paper, two kinds of calculation methods for capacity credit, chronological method and probabilistic methods, are discussed and compared. More relevant definitions of capacity credit for wind power, such as secured capacity, load carrying capability, equivalent firm capacity, have been proposed in many publications, and discussed in [4][6][7]. The most common reliability indices in generation adequacy assessment, such as the Loss of Load Expectation (LOLE), the Loss of Energy Expectation (LOEE) and the Loss of Load Possibility (LOLP), have also been implemented and discussed in the cases of wind power integration [4]. In [7], the capacity credit of wind power was applied and discussed in a system operation context as Operating Capacity Credit (OCC), which has not been limited in the planning level as Planning Capacity Credit (PCC) any more. On the other side, the “uncertain” wind power curtailment problem draws a lot attention in both the planning and operation level. Based on diverse practical cases in different countries, the critical reasons of wind power curtailment have been concluded and discussed in [3]. And many regulation control methods were proposed to reduce the curtailment and increase wind power integration [8-11].

So far, there are few publications considering OCC to assess wind power production in an operation situation; moreover, none of those proposed regulation control methods against the uncertain wind power curtailment considers OCC and reliability of generation system. However, it is obvious that OCC could be used to evaluate the impact of wind power on operational reliability of power system, which should also be considered in the operation and control process of those power systems with wind power integrated. In this paper, a multi-agent system (MAS) based optimal wind power curtailment control strategy with the consideration of OCC is proposed to prevent the uncertain wind power curtailment and help to increase the wind power integration.

The rest of paper is organized as follows: a brief introduction of OCC, related optimal wind power curtailment strategy and the MAS based strategy implementation are presented in Section II; then in Section III, this strategy is demonstrated by the study cases based on IEEE reliability test system and practical Danish market data; and finally, the conclusion is made in Section IV.

II. ALGORITHMS OF CONTROL STRATEGY

A. *Operational Capacity Credit*

1) Basic definitions of PCC

In this paper, the reliability index-LOLP is adopted for the case study. Assume there is a power system with a set of generators indexed as 1, …, *n*. The total generation capacity is $C_{tot} = \sum_i^n C_i$, where C_i is the installed capacity of generator unit *i*. Based on the probabilistic methods [4], the LOLP of a power system is the probability that the load is bigger than the available generation capacity, which can be expressed as:

$$LOLP_n = P(L > C_{tot} - C_{out}) = P(E > C_{tot}) \quad (1)$$

where L is the physical load of the system, C_{out} is the sum of outage generators and $E = L + C_{out}$ is the equivalent load.

According to well-known Baleriaux-Booth formula [4], the probability distribution of equivalent load can be represented by the load duration curve f(x):

$$f_i(x) = p_i f_{i-1}(x) + q_i f_{i-1}(x - C_i) \quad (2)$$

where C_i and q_i are installed capacity and forced outage rate of generator *i*, $p_i = 1 - q_i$. $f_0(x)$ is the original load duration curve without considering the generator outage rate, and $f_i(x)$ is the load duration curve considering the outage impacts of generators from 1 to *i*. Then the equation (1) can be also expressed as:

$$LOLP_n = P(E > C_{tot}) = f_n(C_{tot}) \quad (3)$$

Some definitions of PCC have been introduced in former section. Here the definition of equivalent firm capacity (C_{EFC}) is adopted: "The equivalent firm capacity of the studied generating unit is defined as the capacity of a fictitious 100% reliable unit which results in the same reliability level decrease as the studied unit" [4]. When the new generator indexed as $n + 1$ is integrated into the former system, then the LOLP of this new system is:

$$LOLP_{n+1} = f_{n+1}(C_{tot} + C_{n+1}) \quad (4)$$

According to the definitions, if the new generator is a fictitious 100% reliable unit, then:

$$LOLP'_{n+1} = f_n(C_{tot} + C_{EFC}) \quad (5)$$

Let $LOLP'_{n+1}$ equal to $LOLP_{n+1}$ to keep the reliability level, then the C_{EFC} can be obtained by (6), and the capacity credit degree CC_{n+1} of generator $n + 1$ can be given by (7). The illustration of equivalent firm capacity can be seen in Figure 1.

$$C_{EFC} = f_n^{-1}(LOLP_{n+1}) - C_{tot} \quad (6)$$

$$CC_{n+1} = C_{EFC}/C_{n+1} = [f_n^{-1}(LOLP_{n+1}) - C_{tot}]/C_{n+1} \quad (7)$$

2) OCC

In the operation situation, the probabilistic method of PCC for a specific time period is not enough for real time system operation assessment and regulation. In order to accept more wind power, here the capacity credit definitions can be changed into (8-10):

$$LOLP_{n.t} = P(E_t > C_{tot.t}) = f_{n.t}(C_{tot.t}) \quad (8)$$

$$C_{EFC.t} = f_{n.t}^{-1}(LOLP_{n+1.t}) - C_{tot.t} \quad (9)$$

$$CC_{n+1.t} = C_{EFC.t}/C_{n+1.t} \quad (10)$$

where $t = 1, \ldots, T$, T is the time horizon of interest (One month in this paper), the variable with subscript "*t*" represents the related variable at t^{th} hour in this paper.

It should be noted that in different hours, the output of each generator will be different as well as the related forced outage [12], so the load duration curve should be calculated in every hour based on the changing variables and multi-state models [13].

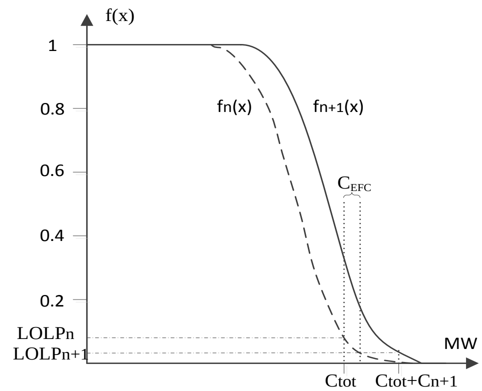


Figure 1. Illustration of equivalent firm capacity based capacity credit

It can be found that the related definitions of OCC are calculated in every time step of total studied time period, which represent the time correlated characteristics of power system. These operational definitions are also able to help generation regulation control when generation and load prediction is considered. There are already a lot of literature on short term wind power prediction applied in system operation and control [10] [11], and prediction error in next one hour is very small [14], the wind power forecast is regarded to be good enough in this paper, which will be not discussed further here. The workflow of OCC prediction can be seen in Figure 2.

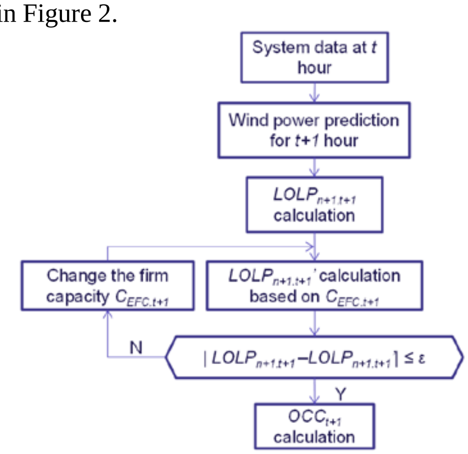


Figure 2. The workflow of OCC prediction

3) Wind power plant model in capacity credit calculation

The wind power output is more variable than conventional generation output, so the multi-state model can be used here. If the i^{th} generator is a wind power unit, then the load duration equation (2) can be rewritten as:

$$f_i(x) = \sum_{m=1}^{N_s} p_m f_{i-1}(x - \overline{C_m}) \quad (11)$$

where N_s represents the number of the operation states of this unit, p_m is the probability of state m, $\overline{C_m} = C_i - C_m$; obviously, $\sum_{m=1}^{N_s} p_m = 1$.

B. Wind Power Curtailment Strategy

In order to reduce uncertain wind power curtailment and keep system reliability, the predicted operational C_{EFC} can be regarded as minimum wind power output which should not be curtailed. Based on this idea, the C_{EFC} for each wind plant can be set as a constraint limit in the calculation model. Then, with the aim to minimum the operation cost of the whole power system, the proposed optimal wind power curtailment model for every hour operation can be expressed as:

$$minF_{t+1} = f_{g.t+1} + f_{l.t+1} \quad (12)$$

The main constraints are:

$$\sum P_{gi,t+1} = L_{t+1} \quad (13)$$

$$V_{bus}^{min} \leq V_{bus.t+1} \leq V_{bus}^{max} \quad (14)$$

$$P_{gi,t+1}^{min} \leq P_{gi,t+1} \leq P_{gi,t+1}^{max} \quad (15)$$

$$C_{gwi} * OCC_{i,t+1} = P_{gwi,t+1}^{min} \leq P_{gwi,t+1} \leq C_{gwi} \quad (16)$$

$$P_{T,t+1} \leq P_{T,t+1}^{max} \quad (17)$$

where F_{t+1} is the operation cost of power system at t+1 hour; $f_{g.t+1}$ ($= f_{gC.t+1} + f_{gchp.t+1} + f_{gw.t+1}$) is the operation cost of generation system; $f_{gC.t+1}$, $f_{gchp.t+1}$, and $f_{gw.t+1}$ represent the related operation costs of conventional generation, local combined heat and power (CHP) and wind generation systems which will be mainly studied based Denmark data in this paper ; $f_{l.t+1}$ is the operation cost of load shedding at t+1 hour; $P_{gi,t+1}$ is the active power output of i^{th} generator; L_{t+1} is the predicted load consumption at t+1 hour; C_{gwi} is the installed capacity of i^{th} wind plant; V_{bus}^{min} and V_{bus}^{max} are minimum and maximum values of bus voltages; $P_{gi,t+1}^{min}$ and $P_{gi,t+1}^{max}$ are minimum and maximum values of active power output of i^{th} generator at t+1 hour; $P_{T,t+1}^{max}$ represent the maximum values of transmission lines. When the specific power system is considered, the network power flow equations should be added in the constraints.

The equation (16) is actually contained by (15), which emphasize that the capacity credit is used to determine the lower limit of related wind plant. Also in this algorithm, the operation cost of load is set to be negative, which means loads will be kept as many as possible. Then load shedding will be the last option after all other control methods for regulating the power system load flow. On the other hand, the operation cost of wind generation system is set to be the lowest positive one, which means the wind power has the highest priority in all the power sources to be dispatched. Hereby, the wind power curtailment can be hopefully limited effectively.

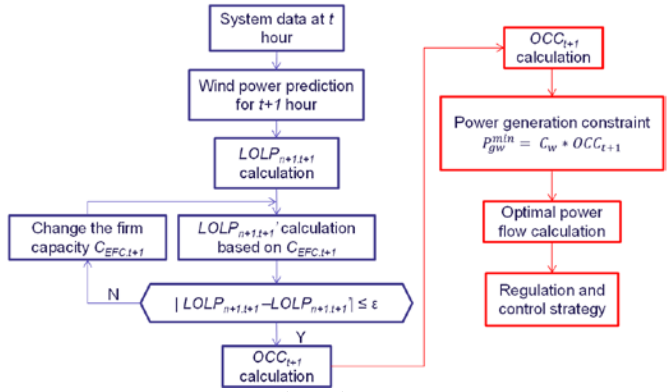


Figure 3. The workflow of proposed control strategy

C. Strategy Implementation

In order to implement the proposed control algorithms, a multi-agent system based control strategy is adopted, as shown in Figure 4.

This MAS based control system adopts a three-level hierarchical structure, which is comprised by distributed agent level, cooperation society level and central processing level. Moreover, every agent in this system has three basic functions: information collection, decision making according to the prevailing state and decision execution [15].

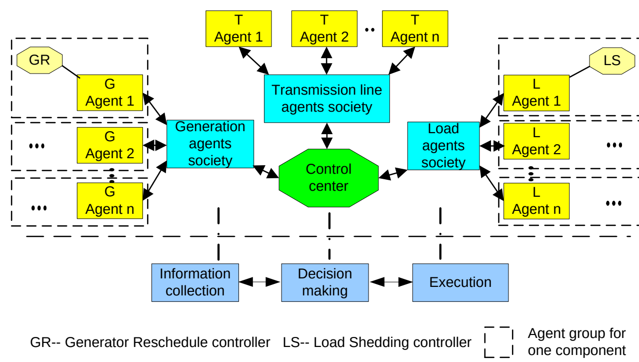
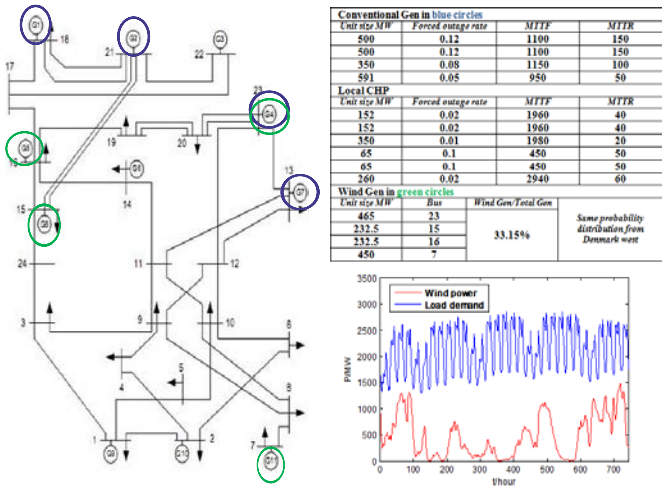


Figure 4. The structure of MAS based detection strategy

In the distributed agent level, unit agents on transmission lines and generators will monitor and send the state information of related power components to control center (CC). At the same time, the controller agents, including generator reschedule controllers and load shedding controllers, will similarly monitor and send the related information to CC. The distributed agents in the lowest level can be grouped into agent societies according to the similarity of their functions, such as generation agent society, transmission agent society, load agent society and etc. This is the middle level which builds an effective cooperation environment between agents, i.e. priority setting for different controller group or sensitivity mapping between different agents, which will be discussed in another paper. The control center agent is in the highest level of the MAS, which is responsible to collect system wide information from all the lower level agents, do the online state analysis and make system wide decision for the proposed wind power curtailment strategy.

III. CASE STUDY

The IEEE reliability test system (RTS-24) [16] is adopted in this paper to testify the proposed wind power curtailment strategy, as shown in Figure 5. The generation data and related outage rates can be also found in this figure. The one-month (2013, Jan) Danish wind power data and load data comes from Energinet.DK [17]. There are 4 conventional generators, 6 local CHPs and 4 wind farms in this test system. The generation data (including conventional generation, wind generation and local CHP generation) and load data have been proportionally distributed to the test system network, which can be also seen from Figure 5.



Conventional Gen in blue circles

Unit size MW	Forced outage rate	MTTF	MTTR
500	0.12	1100	150
500	0.12	1100	150
350	0.08	1150	100
591	0.05	950	50

Local CHP

Unit size MW	Forced outage rate	MTTF	MTTR
152	0.02	1960	40
152	0.02	1960	40
350	0.01	1980	20
65	0.1	450	50
65	0.1	450	50
260	0.02	2940	60

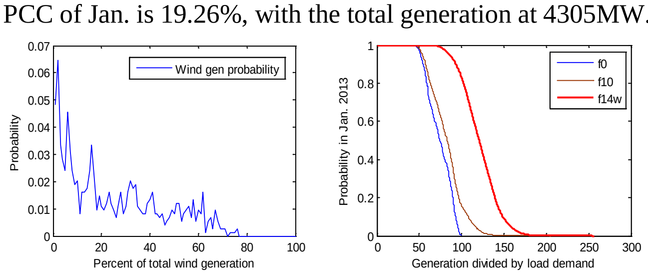
Wind Gen in green circles

Unit size MW	Bus	Wind Gen/Total Gen	
465	23	33.15%	Same probability distribution from Denmark west
232.5	15		
232.5	16		
450	7		

Figure 5. The IEEE RTS 24 bus test system

A. Capacity credit analysis

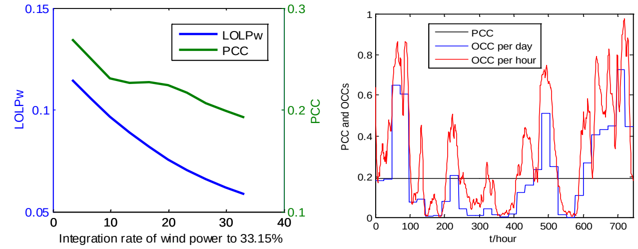
The probability distribution curve of wind power in one year can be seen in Figure 6 (a). The 100-state generation model can be used to simulate the wind plant generation, and the total installed capacity of wind power is 1480MW. Then consider the different generation probabilities, the load duration curves can be seen in Figure 6 (b), where f0 represents original system load duration curve, f10 is the load duration curve with consideration of the forced outage rates of 4 conventional generators and 6 local CHPs, f14w represents the curve considering the generation probabilities of all the generators including 4 wind farms. Based on f14w curve, the PCC of Jan. is 19.26%, with the total generation at 4305MW.



(a) Probability curve of wind generation (b) Load duration curves

Figure 6. Wind generation probability and load duration curves

Meanwhile, if the integration rate of wind power is changed, the LOLP and related PCC will be changed subsequently, as shown in Figure 7 (a). Obviously, with the increasing integration rate, the final LOLP (LOLPw) and PCC of test system decrease slowly. In order to apply the capacity credit definitions in the operation situation, the OCC per hour can be calculated according to the workflow described in Figure 3, which can be seen in Figure 7 (b). The OCC per day can similarly be obtained and shown in the same figure.

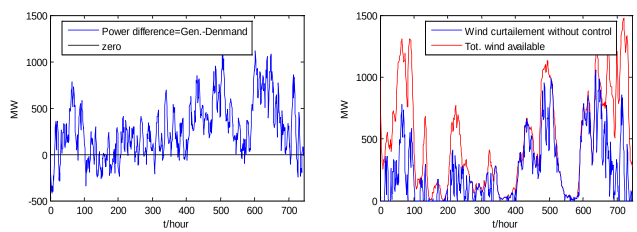


(a) LOLP and PCC vs Wind integration (b) PCC and OCC in days (hours)

Figure 7. LOLP, PCC and OCCs when wind power integration

B. Effects of Wind Power Curtailment Strategy

According to original data collected from Energinet.DK, the difference between total generation and total consumption can be seen in Figure 8 (a). If wind power is chosen to curtail firstly, then a big amount of wind power will be lost accordingly, as shown in Figure 8 (b). Here we assume there is no power transferring between external networks; the local generation and consumption regulation will be the only relied control methods.



(a) The total difference (b) Wind power curtailment without control

Figure 8. The power difference and original wind power curtailment

When the proposed minimizing wind curtailment strategy is implemented; the OCC will be used as the lower limit of related wind plants, the wind power will be set with the highest priority to be dispatched in the test system, and the MAS base control system built in RTDS and LabVIEW [17] will be used to implement the proposed control strategy. Based on MAS based control system, every hour the distributed unit agents and controller agents will send their present information to the agents in upper layer. In the control center, the wind power and load demand will be predicted firstly for the next hour operation, then the best operation condition for next hour will be obtained based on the proposed optimization algorithms in Section II.B. Comparing this obtained operation condition with former hour operation condition, the next hour control strategy (including the control locations and control amounts) can be easily defined. Finally, the distributed controller agents will execute the related control strategy when the orders from control center have been received. The simulation results can be seen in Figure 9.

It can be seen from Figure 9, total consumption curve and total generation curve are almost the same to keep the system power balance, meanwhile the difference between total available wind power curve and total dispatched wind power curve are very small which means the wind power loss has been minimized effectively. At the same time, it can also be found that the dispatched power generated by local CHPs and conventional generators have been limited significantly.

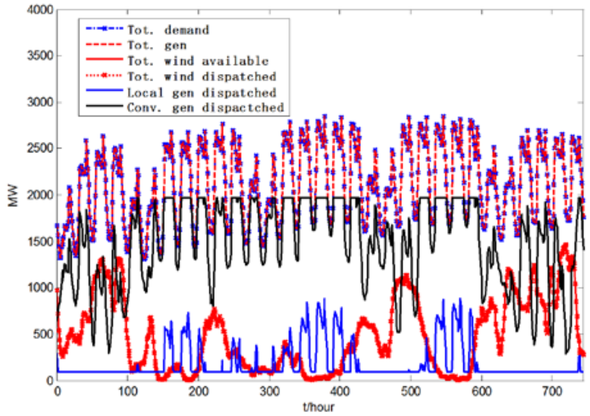
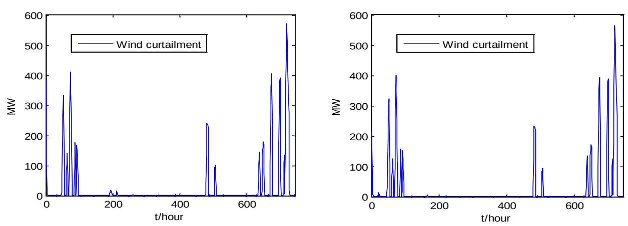


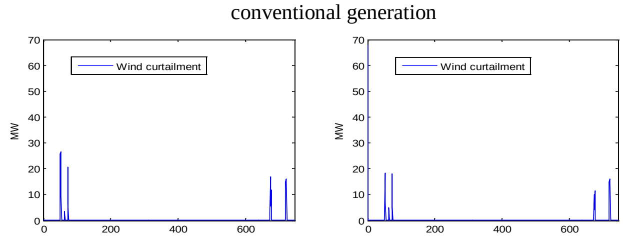
Figure 9. The results with the proposed control strategy

The diverse scenarios of wind curtailment under the proposed control strategy with different wind power dispatch priority and OCC prediction method can be seen in Figure 10 and Figure 11. The priorities are regulated by the methods in Section II.B. When the wind power is set as same priority as conventional generation, then the wind curtailed amount per hour using daily OCC prediction can be seen in Figure 10 (a) while the one using hourly OCC prediction is in Figure 10 (b). When the wind power is set with the highest priority in all kinds of generation sources, the wind curtailed amount curve with the daily OCC prediction and hourly OCC prediction can be seen in Figure 11 (a) and (b) respectively.



(a) With OCC per day (b) With OCC per hour

Figure 10. The wind curtailment with setting wind power same priority with conventional generation



(a) With OCC per day (b) With OCC per hour

Figure 11. The wind curtailment with setting wind power highest priority in all kinds of generation

IV. CONCLUSION

In this paper, an optimal wind power curtailment strategy considering operation capacity credit is proposed to reduce the uncertain wind power curtailment and maximum the integrated wind power. The related definitions of operational capacity credit have been explained and applied in the power system operation situation. Based on hourly OCC prediction, the optimal wind power curtailment strategy has been described, and the credit capacity of wind power is used to help define wind farms' generation constraints. Multi-agent system based control structure has been adopted to coordinate the diverse system components to work together and realize this system wide target. The simulation results demonstrated the effectiveness of the proposed strategy. The effects of prediction accuracy and operation stability constraints on the proposed control strategy will be investigated in the future.

ACKNOWLEDGMENT

This work is carried out within the project of Development of a Secure, Economic and Environmentally-friendly Modern Power System (SEEFMPS) supported by the Danish Council for Strategic Research (DSF 09-067225).

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