Paper

A Basic Study of Wind Generator Stabilization with Doubly-Fed Asynchronous Machine

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This paper investigates the function of DASM (Doubly-fed ASynchronous Machine) with emphasis placed on its ability to the stabilization of the power system including wind generators. P (active power) and Q (reactive power) compensation from DASM can be regulated independently through secondary-excitation controlling. Simulation results by PSCAD show that DASM can restore the wind-generator system to a normal operating condition rapidly even following severe transmission-line failures. Comparison studies have also been performed between wind turbine pitch control and proposed method.

Keywords: DASM (doubly-fed asynchronous machine), wind generator, wind turbine pitch control, PSCAD/EMTDC

1. Introduction

Generation of electricity using wind power has received considerable attention worldwide in recent years. It has been predicted that the annual growth of wind power between 1998 and 2040 would be between 20–30% (1). However, the continuous trend of the increasing of the number of wind generators would influence the operation of existing utilities networks. Up to now many concerns (2)~(5) have been focused on three principal problems of the wind generator system; (problem 1): Reactive power compensation is required for the operation of the general wind generator (induction machine) in steady state, otherwise the power quality of the system will be decreased; (problem 2): When a large electrical disturbance occurs in the network, the terminal voltage of the wind farm will decrease while the rotor speed of the machine will increase tremendously, which will lead to the collapse down of the system; (problem 3): When wind power fluctuates tremendously due to wind speed variations such as wind gust, the power delivered to the network system will suffer power surge if there is no adequate amount of active power compensation.

Although various ways, such as capacitor banks have been supposed to compensate the reactive power for the wind generator in steady state, because of its fixed capacity, the reactive power supplied to the wind generator will be superfluous sometimes while insufficient sometimes, depending on the output of the generator. Controlled static VAR compensation (6)(7) can offer the variable reactive power compensation both for steady state and transient state. When large electrical disturbances, such as 3LG (three-line-to-ground) fault, occurs in the network, terminal voltage will decrease, thus rotor speed of the wind generator will be accelerated, and consequently much more reactive power will be consumed from the network system, which leads to the drop of the wind farm voltage. As SVC can respond to this with adequate amount of reactive power compensation, wind farm voltage, and also wind generator rotor speed can recover to the initial state. In addition, since wind farm suffer severe wind gust frequently, when wind speed fluctuates, active power supplying to the network will also fluctuate accordingly. However, at this time active power compensation from SVC is impossible. The combination of SVC and battery storage system (8)(9) seem to be a solution to all the three problems, in which active and reactive power compensation can be supplied at a time. However, in this case, full capacity inverter is required, which makes the system costly, and harmonic is inevitable. Moreover, in the battery storage system, the output of the active power can not change rapidly due to its chemical limitation. So after all, no ways have been found to solve the above three problems at a time.

DASM (Doubly-fed Asynchronous Machine) seems to be a solution to these problems. It has been emerged as a system stabilizer by injecting/absorbing adequate amount of active/reactive power quickly and instantaneously to the network system. The rotor of the DASM is fed by a three-phase, sinusoidal current of slip frequency, which enables to regulate the active and reactive power compensation for the system independently through secondary excitation controlling (10). Moreover, as compared to the combination of SVC and battery storage system, the capacity of the inverter required for the system is about 0.3 times the DASM power rating, which makes it cheaper. In addition, less harmonic is found, and it is much quicker in its electrical action. So DASM might be a good solution to the 3 problems facing the

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wind generator system.

It is well known that hydro generator by using DASM has been put into practical use successfully [11]. On the other hand, there are also some reports concerning the application of flywheel generator by using DASM for the stabilization of the power system [12]. However, up to now, few discussions have been done on the stabilization of wind generator by flywheel generator using DASM.

Therefore, it is supposed that DASM, when properly controlled, can be used to provide locally the leading reactive power compensation for the wind generator in steady state; be used to stabilize the wind power system under large electrical disturbances in the network, with adequate amount of reactive power compensation; and be used to stabilize the wind power system under a severe wind gust, with adequate amount of active power compensation. In this paper, DASM, with proper control scheme, is proposed to enhance the stability of wind generator system, and various simulations are done to verify the propositions above.

Simulation studies by PSCAD/EMTDC were performed to verify the effectiveness of the DASM on the stabilization of wind generator system when a 3LG fault occurs and when wind generators suffer severe wind gusts. Simulation studies on the effectiveness of the DASM on transient stability problems have been done on both single wind generator system and multiple wind generator system. Comparison studies between the wind turbine pitch control and proposed method on single wind generator system when 3LG fault occurs have also been done. Two typical types of wind speed patterns are used to verify the effectiveness of DASM on smoothing power surge and terminal voltage of the wind farm during wind gust.

2. Model System Configuration

The system used as a basis for this investigation is shown in Fig. 1, in which SG denotes a synchronous generator and a DASM is connected to the high-voltage side of a wind generator (induction generator, IG) through a Δ/Y transformer. Table 1 shows various parameters of each generator. There is a local transmission line with one circuit between the main transmission line and a transformer at the wind power station.

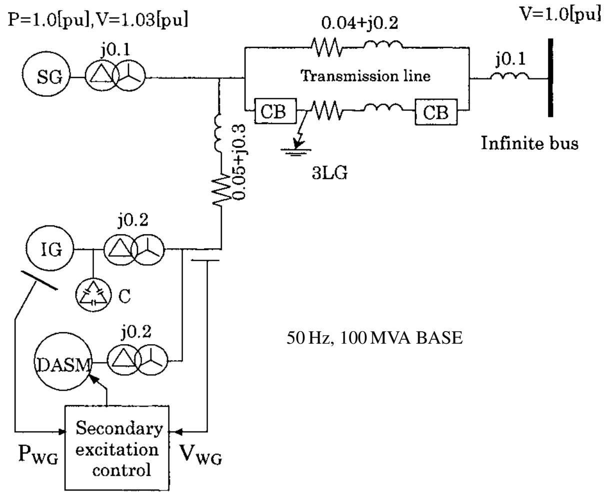


Fig. 1. Power system model

Though a wind power station is composed of many generators practically, it is considered to be composed of a single generator with total power capacity in the first few parts of the paper. A condenser C, is connected to the terminal of the wind generator to compensate the reactive power demand for the induction generator in steady state. The value of C has been chosen so that the power factor of the wind power station becomes unity when the terminal voltage and output power are 1.0 [pu].

AVR and governor control systems are considered in the synchronous generator model, and they are shown in detail in Fig. 2.

The DASM used is based on a wound rotor structure, whose rotor is supplied with an alternating current of slip frequency. Therefore the resulting magnetic flux due to the impressed rotor currents, rotates with slip frequency referred to the rotor and with the network frequency referred to the stator; whereby it generates the corresponding counter

Table 1. Nominal values and parameters of each generator

SG		Wind generator(IG)		DASM
Rated output (MVA)	100	Rated output (MVA)	50	50
Rated voltage(KV)	11	Rated voltage(KV)	0.69	11
r_a(pu)	0.003	r_1(pu)	0.01	0.0045
x_a(pu)	0.13	x_1(pu)	0.1	0.142
X_d(pu)	1.2	X_{mu}(pu)	3.5	2.75
X_q(pu)	0.7	r_2(pu)	0.01	0.0045
X_d' (pu)	0.3	x_2(pu)	0.08	0.142
X_d'' (pu)	0.22	H(sec)	1.5	19.5
X_q'' (pu)	0.25			
T_{do}' (sec)	5.0			
T_d'' (sec)	0.04			
T_q'' (sec)	0.05			
H(sec)	2.5			

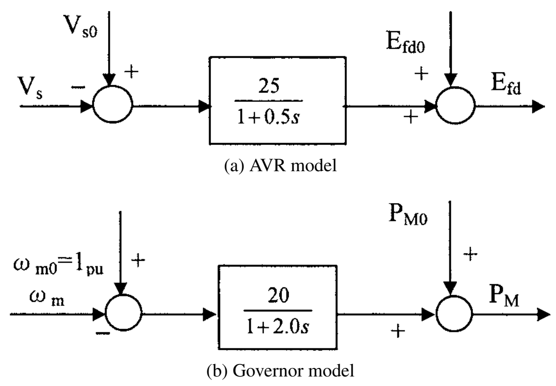


Fig. 2. Control system models of synchronous generator

magnetic flux within the stator. So the amplitude and phase position of the stator current and thereby the active and reactive power consumption of the machine is determined by control of the rotor current. Although various ways[(13)~(15)] has been proposed to control the rotor current, the simplest way of PI controlling is used in the paper, to verify the effectiveness of the DASM to the stabilization of the wind power system. Moreover, in the paper the rotating reference frame (dq frame) to analyze the DASM is fixed on the space axis of stator voltage.

In the control scheme illustrated in Fig. 3[(10)], when P_{WG} (active power from wind farm into the network system) and V_{WG} (wind farm terminal voltage) are detected, the P/Q compensation required from DASM is thus determined. To regulate the error between the desired and detected values of P/Q, a two-step PI controller is used, the first step of which is APR/AQR, and the second is ACR. These controllers are shown in Fig. 4. Therefore the required field voltage is specified and applied to the rotor side of the DASM. In Fig. 4, P_{WG} and P_{WG}^{ref} are the active power output and its reference value of wind farm ; P_{DASM} and P_{DASM}^{ref} are the active power detection and its reference value of DASM; Q_{DASM} and Q_{DASM}^{ref} are the reactive power detection and its reference value of DASM respectively. V_{WG} and V_{WG}^{ref} are detection and its reference value of the wind farm terminal voltage respectively, and V_{WG} is the RMS value of the detected three phase instantaneous values V_a, V_b, V_c, and given by

$$V_{WG} = \sqrt{\frac{Va^2 + Vb^2 + Vc^2}{3}} \quad \cdots\cdots (1)$$

In the paper, we simulate the secondary-exciting source with an ideal DC source for the sake of simplicity, and only the fundamental component of inverter output is considered.

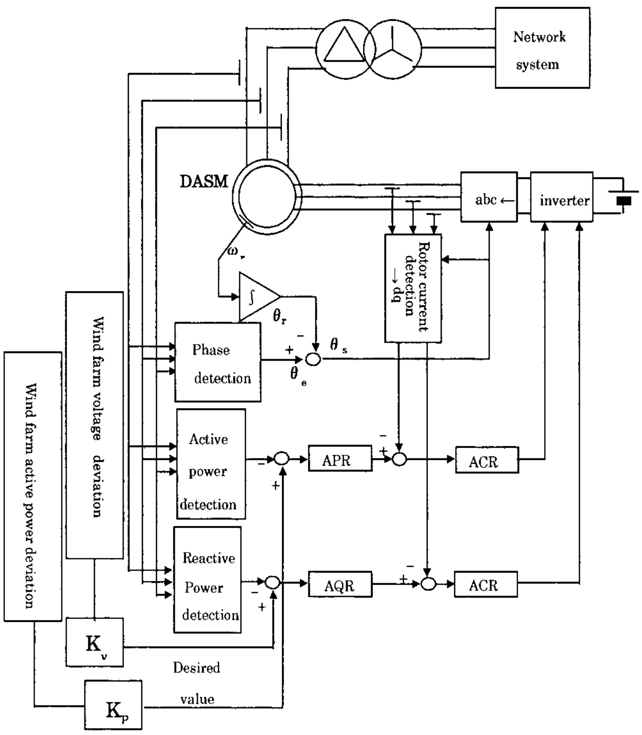


Fig. 3. DASM circuit configuration

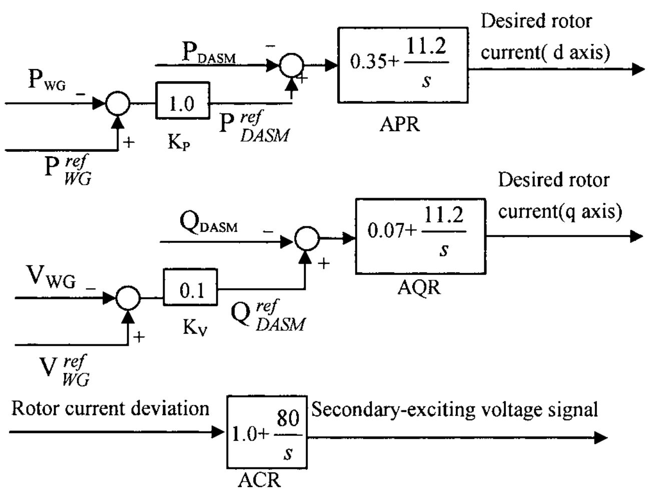


Fig. 4. Control signal blocks for DASM

3. Simulation Studies and Discussions on the System Transient Stability Problems

3.1 Simulation Studies on the Single Wind Generator System The general way to deal with wind generators when a fault such as a 3LG (three-line-to-ground) fault occurs in the network system is to disconnect them from the grid and then apply brake to stop them. Although there are also reports investigating the effect of the pitch control system on the transient stability recently[(16)], this paper proposed a new way of compensating the amount of required reactive power from DASM to recover the voltage when a 3LG fault occurs.

To investigate the validity of the proposed method, a 3LG fault is applied in the following three kinds of circumstances, and simulation results are studied and compared:

(Case 1): Capacitor banks are connected at the terminal of the wind generator to offer the required reactive power in steady state.

(Case 2): Capacitor banks are connected at the terminal of the wind generator and pitch control systems is equipped with the wind turbine. The pitch control system model of the wind turbine and the wind turbine torque characteristic[(16)] are shown in Fig. 5 and Fig. 6. The time constant T_W of the control system is $T_W = 3$ [sec]. The minimum output torque of the turbine has been limited to 0 to ensure it works as a generator. The developed wind turbine torque shown in Fig. 6 can be expressed as

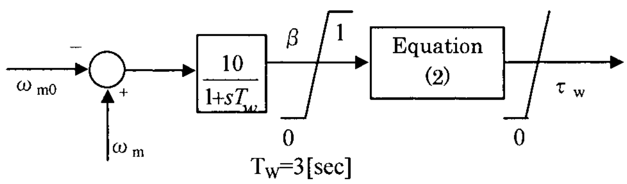


Fig. 5. Pitch control system model

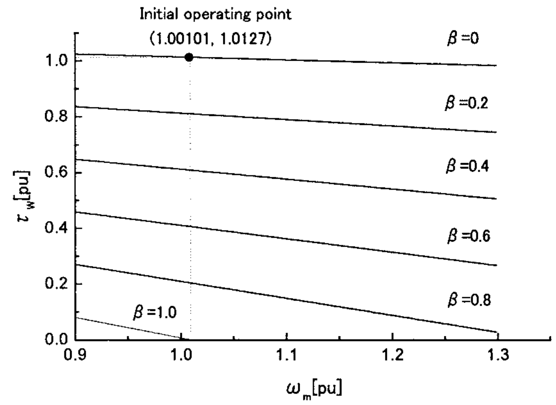


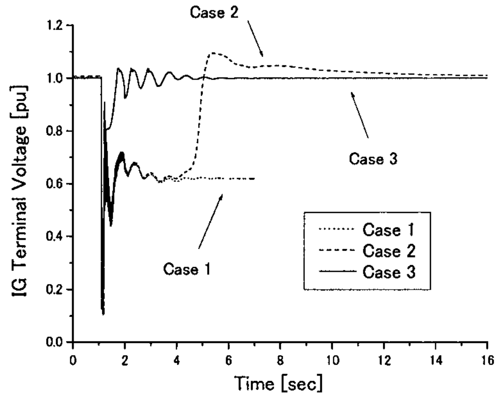
Fig. 6. Wind turbine torque characteristic

$$\tau_{w\,[pu]} = (C'_1\beta + C'_2)\omega_{m\,[pu]} + (C'_3\beta + C'_4) \cdots\cdots\cdots (2)$$

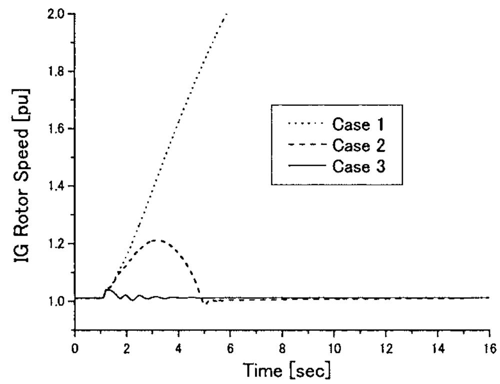
in which, w_m denotes the pu generator speed, β denotes the pu blade pitch angle of wind turbine, and the coefficients have been determined as:

$$\left.\begin{aligned} C'_1 &= -0.632 \\ C'_2 &= -0.101 \\ C'_3 &= -0.373 \\ C'_4 &= 1.115 \end{aligned}\right\} \cdots\cdots\cdots (3)$$

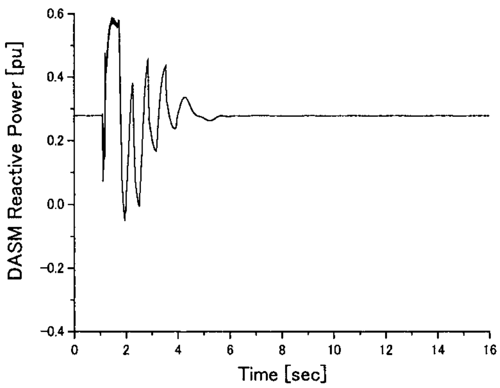
(Case 3): Without the capacitor banks at the terminal of the wind generator, DASM is placed nearby to provide the required reactive power compensation in steady state. The mechanical input to the DASM is 0 [pu] and the output from DASM has been limited to 0.5 [pu] (rated output in 100 MVA base). Besides, pitch control system described in case 2 is not included.



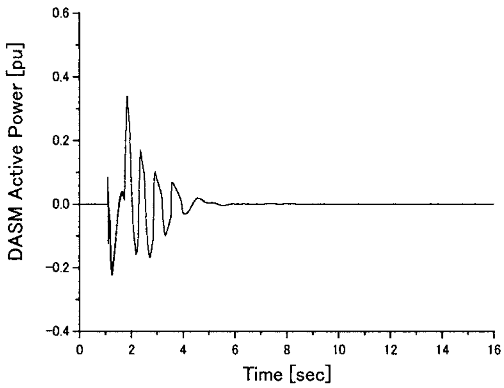
(a) IG terminal voltage



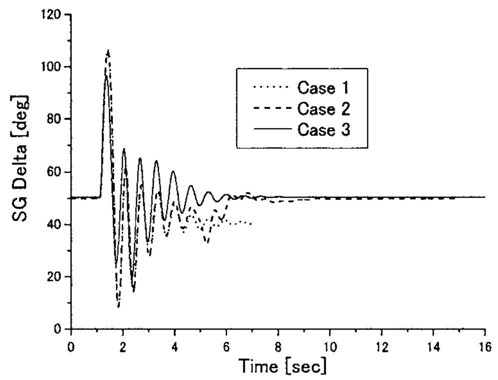
(b) IG rotor speed



(c) DASM reactive power output (case 3)



(d) DASM active power output (case 3)



(e) Synchronous generator load angle

Fig. 7. Simulation results (I)

Table 2. Initial values of wind generator and synchronous generator

IG				SG	
P(pu)	V(pu)	C(pu)	V_W(m/s)	P(pu)	V(pu)
0.500	1.000	0.264	12.49	1.000	1.034

In the above three cases, the grid configuration is totally the same as shown in Fig. 1. Fig. 7(a)~(e) show various simulation results when a 3LG fault occurs at 1.1 s, the CBs (Circuit Breaker) are opened at 1.2 s and re-closed at 2.0 s. The initial values of the wind generator and synchronous generator are shown in Table 2, in which the condenser value, 0.264 [pu] (100 MVA base), is for case1 and 2. V_W denotes the wind speed applied to the turbine in the initial operating point shown in Fig. 6. Because of the step out of the machine, the simulation result of case 1 is cut at 7 seconds.

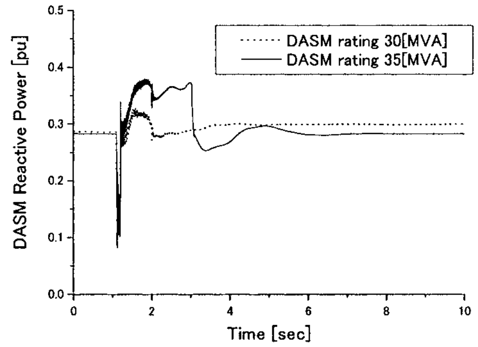
Fig. 7(a) and Fig. 7(b) show the terminal voltage and rotor speed of the wind generator. It is clear that when fault occurs, voltage collapse and rotor speed keeps on increasing tremendously for case 1. Although it regains pre-fault voltage and rotor speed both for case 2 and case 3, apparently the latter is much more effective than the former: case 3 reaches the pre-fault voltage in less than 4 seconds while case 2 deviates somewhat from the initial condition even after 14 seconds. It is also evident from the figures that for case 2, both voltage and speed fluctuate greatly when fault occurs as compared with case 3. Fig. 7(c)~(d) show various reaction of the DASM to the accident in the system. It is clear that after fault, DASM contributes to the stabilization of the system by offering adequate amount of reactive power compensation, and that even in the steady state DASM offer 0.277 [pu](100 MVA Base) reactive power, the amount of which is generally offered by the capacitor banks to maintain the system voltage. This means that DASM works effectively in providing reactive power compensation to the wind generator in steady state. While the active power output of DASM is controlled to 0 [pu] in steady state, it oscillated after fault because of the cross coupling with the reactive power part. Fig. 7(e) shows synchronous generator load angle response, and it remains stable in each of the three cases. It may be concluded that the dynamic behavior of wind generators do not have so significant effect on the stability of synchronous generators.

So as far as the transient stability is concerned, it can be said that although both case 2 and case 3 can be used to stabilize the power system, DASM appears to be much more effective in decreasing the transient of the system than the wind turbine pitch control system. The results also show that instead of conventional capacitor bank, the DASM works effectively in providing locally the leading reactive power compensation to the wind generator in steady state.

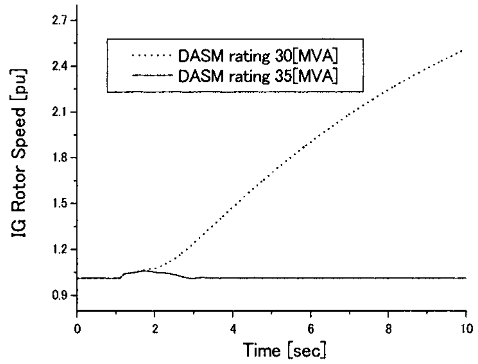
The followings are some discussions on the simulation results and conclusions:

(1) It is concluded above that both pitch control and DASM can be used to the stabilization of the wind generator system. But concerning the ability of stabilization, DASM is much more effective than the pitch control. Although it seems that by decreasing the value of Tw, the ability of pitch control can be improved, it is impossible. As Tw is the time constant of pitch controller for wind turbine, it corresponds to the speed at which pitch angle changes. The pitch angle of the blades can not be changed so fast because the twisting of the pitch will give big stress to the blade.

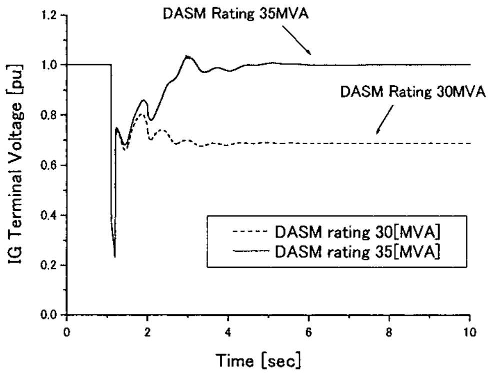
(2) Just as described above, to stabilize the wind generator system in transient state, adequate amount of reactive power compensation is needed. Although it seems that capacitor banks can function as the stabilizer at this time, it is also not effective. Generally, the value of capacitor banks is determined to satisfy the steady state reactive power requirement. But when 3LG fault occurs, capacitor banks can not satisfy the huge reactive power requirement due to terminal voltage drops. In the meantime, if the value of capacitor bank is set in a way to satisfy the huge reactive power requirement when 3LG fault occurs, the reactive power supplied will be superfluous for steady state, and the terminal voltage will go beyond the voltage limitation.



(a) DASM reactive power output



(b) IG rotor speed



(c) IG terminal voltage

Fig. 8. Simulation results (II)

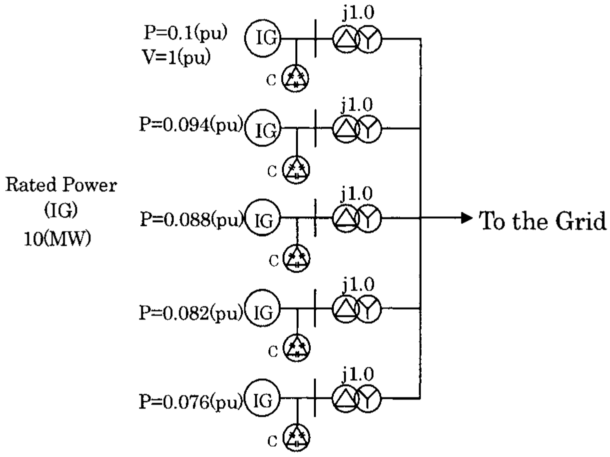
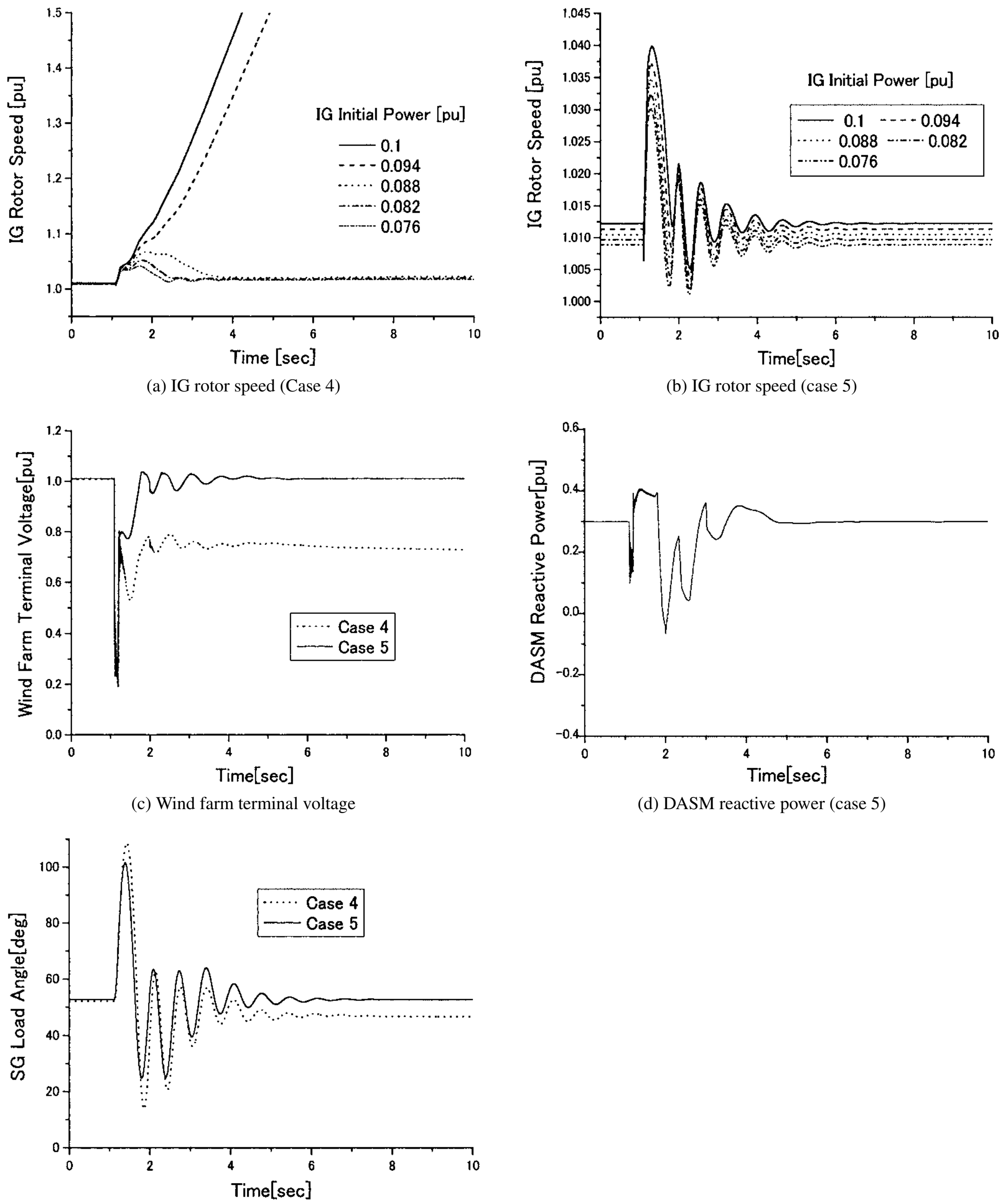


Fig. 9. Wind generator part of the model system

Table 3. Initial values of the wind generators and synchronous generator

IG	P(pu)	0.076	0.082	0.088	0.094	0.100
	V(pu)	1.011	1.009	1.006	1.003	1.000
	V_W(m/s)	10.95	11.35	11.74	12.12	12.49
	C(pu)	0.053 (100 MVA Base, for Case 4)				
SG	P(pu)	1.000				
	Q(pu)	0.222				
	V(pu)	1.013				
	T_G(pu)	1.003				
	E_f(pu)	1.703				
	δ (deg)	52.84				



(a) IG rotor speed (Case 4)

(b) IG rotor speed (case 5)

(c) Wind farm terminal voltage

(d) DASM reactive power (case 5)

(e) SG load angle

Fig. 10. Simulation results (III)

On the other hand, in contrast to the fixed capacity of condenser bank, the reactive power output of DASM can be widely changed to compensate the voltage variation, both for steady state and transient state.

3.2 Discussion on Minimum DASM Ratings The following case study examines the minimum DASM power ratings required to achieve wind generator voltage recovery during and after a 3LG fault.The same simulation study (case 3) is repeated with the same fault condition described above but with different DASM ratings.

Soundness of these are tested and simulation results are shown in Fig. 8(a)~(c). It is evident from the figures that with rating 30 [MVA] DASM, IG rotor speed and terminal voltage fail to regain its initial value when a 3LG fault occurs because the possible maximum reactive power compensation from the DASM is limited, while with rating 35 [MVA] DASM, IG rotor speed and terminal voltage recover to its initial state when a 3LG fault occurs because of the adequate amount of reactive power compensation from the DASM.

So it can be said that the minimum requirement of DASM rating for this system is 35MVA and decrease beyond this would lead to instability when three-line-to-ground fault occurs.

3.3 Simulation Studies on Multiple Wind Generator System As explained previously, simplified lumped wind generator model was considered by now, but in most cases, wind power station is practically composed of many separated generators.

In order to examine the effect of DASM on the practical multiple wind generator system, 5 wind generators (each 10 MVA power rating) with different output are used for the transient stability simulation study, and fault conditions are the same as those described above. Two cases below are considered in the simulation study:

(Case 4): with capacitor banks connected at the terminals of the wind generators.

(Case 5): with DASM (35 MVA) placed nearby while without the capacitor banks at the terminals of the wind generators.

Pitch control system of wind turbine is not considered in both cases. The schematic model of the wind generators is shown in Fig. 9 and the rest of the model are the same as those shown in Fig. 1. The initial values of each wind generator and synchronous generator are shown in Table 3.

Fig. 10(a)~(e) show various simulation results of the wind generator system. From the figures, it is clear that after the fault wind generators with high output go out of step because of the high initial rotor speed. It is also clear that after the fault, for case 5 the system regains its pre-fault voltage and rotor speed due to the reactive power compensation from DASM, while the system experience voltage collapse and tremendous speed increasing for case 4. The reactive output of DASM reaches 0.29 [pu] in steady state to meet reactive power compensation requirement of the system. In addition, synchronous generator load angle shown in Fig. 10(e) remains stable in each of the two cases.

It can be concluded from all the results above that DASM also work effectively on decreasing the transient of the multiple wind generator system.

Although it seems that DASM may be replaced by SVC in offering the variable reactive power when 3LG fault occurs, it is less effective because of the disability of SVC in offering active power compensation when wind power fluctuates, which will be discussed in Section 4.

4. Simulation Studies and Discussions on the Wind Generator Power Fluctuation Problems

It is well known that the wind speed is fluctuating because of its turbulent nature and it vary on a random basis. Thereby the output of the wind generator can't be connected to the network directly since it is continuously varying. Although the output may sometimes be maintained constant by adjusting its blade pitch angle, the generator can sometimes be unstable during highly variable wind conditions. Although various ways have been tried [17][18], a new way using DASM is proposed in this paper to stabilize the power fluctuations from the wind farm to the network system.

To investigate the effectiveness of the proposed method, simulation is done on the multiple wind generator system shown in Fig. 9. The two cases (case 4 and case 5), system model and the initial values of each wind generator and synchronous generator are totally the same as those described in Section 3.3.

As the wind speed is randomly changing all the time, it is important to investigate its influence to the system when the multiple generators are under different wind gusts. Among various wind patterns, it is considered firstly in the paper that 2 of the 5 wind generators are under one type of wind gust, while the other 2 are under an opposite type of wind gust. As some of the generators will be accelerated while others will be decelerated, the overall active power from the wind farm will be counteracted somewhat, the system may be stable to some extent even only with capacitor bank.

It is also studied that 4 of the 5 wind generators are under the same type of wind gust. As all the generators will be accelerated at the same time in this case, there may be a high possibility of leading to the total collapse of the system if without the adequate compensation from DASM.

Based on the expectations above, two representative wind speed patterns are chosen for the simulation, and superiority of DASM over capacitor banks when wind speed changes are tested.

(1) First, the wind speed variations shown in Fig. 11 have been applied to 4 of the 5 wind generators for both cases, case 4 and case 5.

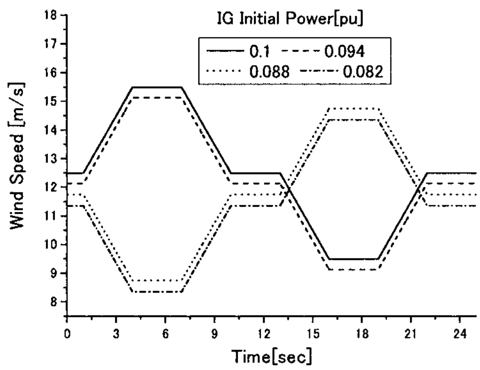
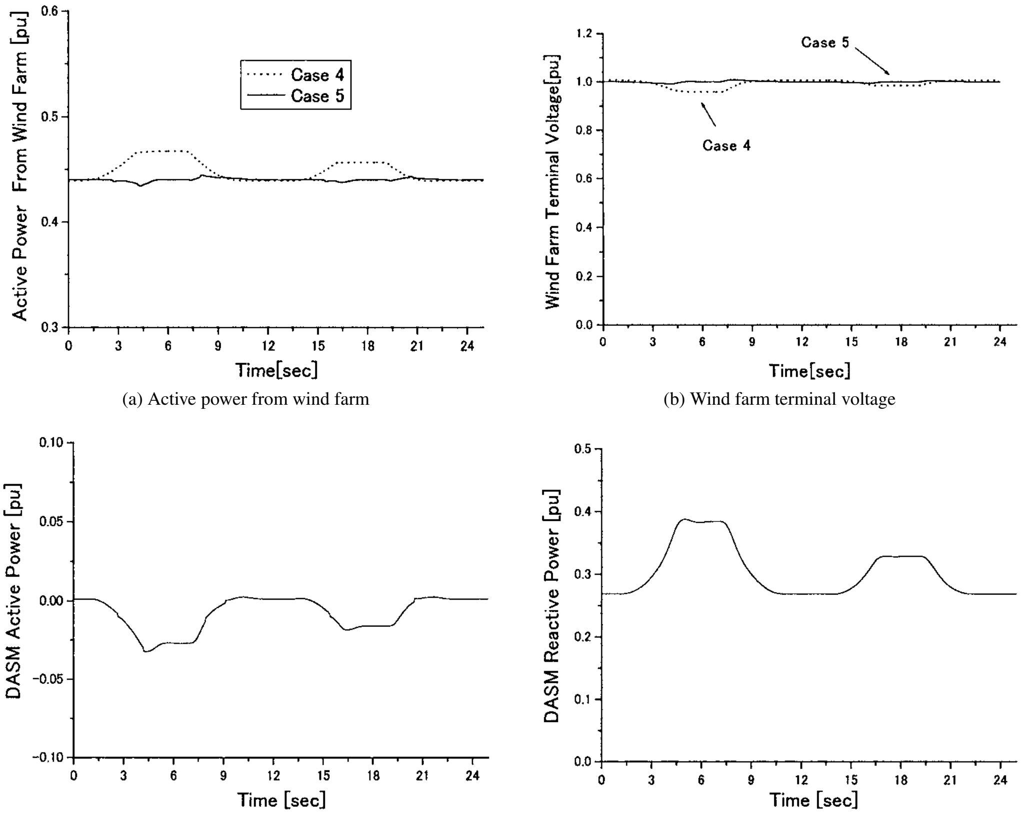


Fig. 11. Wind speed (pattern 1)



(a) Active power from wind farm

(b) Wind farm terminal voltage

(c) DASM active power (case 5)

(d) DASM reactive power (case 5)

Fig. 12. Simulation results (IV)

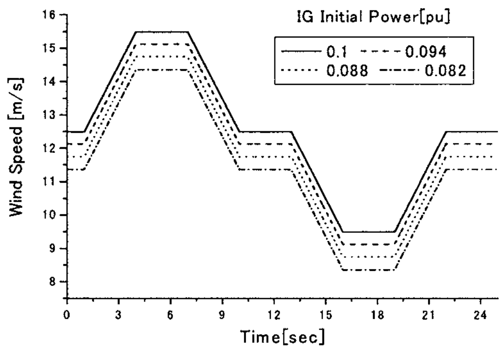


Fig. 13. Wind speed (pattern 2)

Simulation results are shown in Fig. 12(a) to (d). It is clear that, for case 4, active power from wind farm (shown in Fig. 12(a)) fluctuate greatly with the fluctuation of wind power supplied to the wind turbine. It is also clear that wind farm terminal voltage also fluctuates greatly because the reactive power demanding of the wind farm changes when wind speed changes. On the other hand, for case 5, both the active power and terminal voltage of the wind farm maintains almost constant. The reason is that when wind power fluctuates, DASM offers adequate amount of active power (shown in Fig. 12(c)) to the system to counteract the effect of wind power applied to the wind turbine. The reactive output of DASM (shown in Fig. 12(d)) is also fluctuating when wind power fluctuates in order to maintain the wind farm voltage constant.

Therefore it can be said that for wind speed pattern 1, DASM can smooth the fluctuations of output power and terminal voltage of the wind farm.

(2) To investigate the universality of the proposed method, a much more severe pattern is studied, in which the 4 of the 5 wind generators are subjected to the same type of wind gust as shown in Fig. 13.

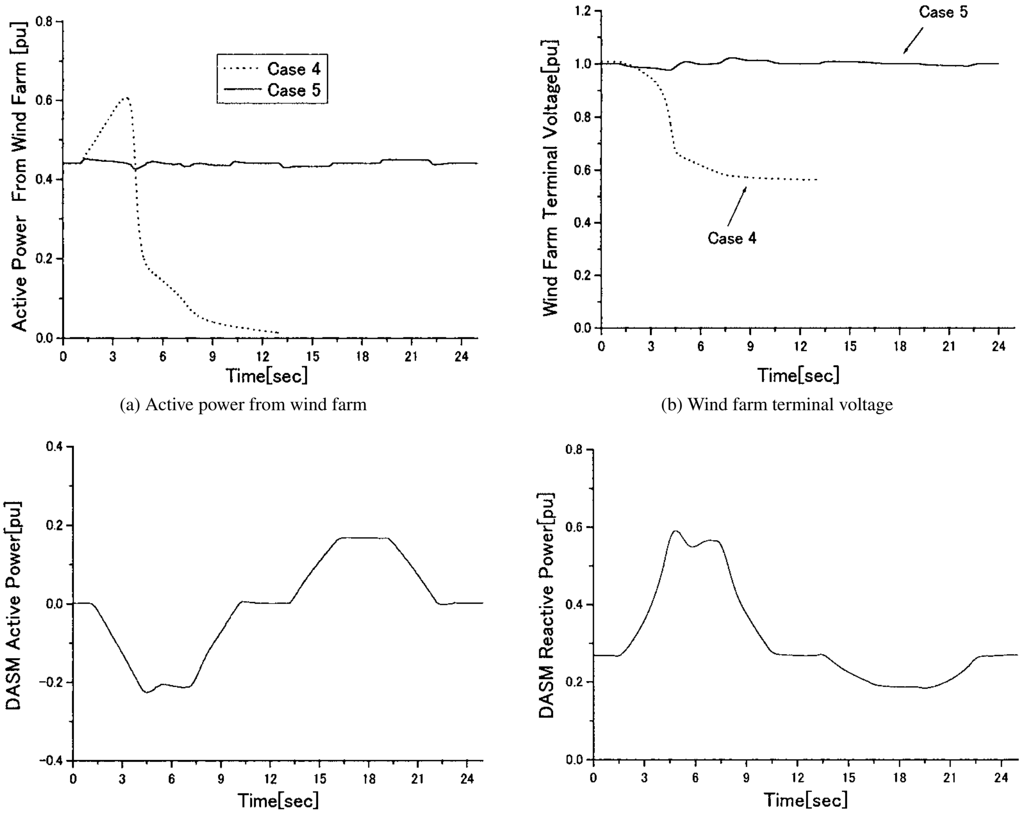
Simulation results are shown in Fig. 14(a) to (d). It is clear that, for case 4, wind generators go out of step, and active power from wind farm (shown in Fig. 14(a)) and wind farm terminal voltage(shown in Fig 14(b)) collapse totally

On the other hand, for case 5, since DASM supply adequate amount of active and reactive power compensations (shown in Fig. 14(c) and (d)) to the system, both the power output and terminal voltage of the wind farm (shown in Fig. 14(a) and (b)) can be maintained almost constant.

Therefore it can be said that, even in the severe wind pattern shown in Fig. 13, DASM works much effectively in stabilizing the system though the wind generators go out of step if there is not DASM.

5. Conclusions

The paper proposed a new way of stabilization of the wind generator system with DASM. Various simulation results by PSCAD show the effectiveness of preventing the voltage collapse of the wind generators after a 3LG fault with the reactive power compensation from DASM. Comparison studies have also been performed between the wind turbine pitch control and the proposed method. The apparent superiority



(a) Active power from wind farm

(b) Wind farm terminal voltage

(c) DASM active power (case 5)

(d) DASM reactive power (case 5)

Fig. 14. Simulation results (V)

of the latter to the former is validated. It can be said that DASM can be used as a much more effective way to stabilize the power system as compared with conventional pitch control system. It has also been found that DASM can be used to provide locally the leading reactive power compensation to the wind generators in the steady state.

Simulation has also been done on multiple wind generator system when wind power fluctuates randomly. Two typical types of wind speed patterns are used in the paper. Both results show the effectiveness of DASM on smoothing variations of output power and terminal voltage of the wind farm when wind power fluctuates.

All in all, simulation results show that DASM can be used to minimize the influence to the system under large electrical disturbances in the network and under a severe wind gust effectively. Simulation results also show the effectiveness of DASM in providing locally the leading reactive power compensation to the wind generator in steady state.

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