영구자석형 동기발전기를 이용한 풍력단지의 플리커 저감

Flicker Mitigation in a Wind Farm by Controlling a Permanent Magnet Synchronous Generator

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Abstract: The power quality of wind energy becomes more and more important in connecting wind-farms to the grid, especially weak grid. This paper presents the simulation of a wind farm of a permanent magnet synchronous generator (PMSG) and a doubly fed induction generator (DFIG). Flicker mitigation is performed by using PMSG as a static synchronous compensator (STATCOM) to regulate the voltage at the point of common coupling (PCC). A benefit of the measure is that integrating two function of to control the active power flow and to reduce the voltage flicker in a wind farm. Simulation results show that controlling PMSG is an effective and economic measure in reducing the flicker during continuous operation of grid connected wind turbines regardless of short circuit capacity ratio, turbulence intensity and grid impedance angle.

Keywords: flicker mitigation, power quality, wind turbine, reactive power compensation, distributed generation

I. INTRODUCTION

The main impetus for renewable energy growth has been increasing concern over global warming, and a range of policy instruments have been used to promote carbon-free technologies; these are briefly reviewed. Therefore, in recent years wind power generation has experienced a very fast development in the whole world. With these quick increases in wind power penetration into the grid, the influence of wind-turbines on quality of power has become an important issue. One of the important power quality aspects is flicker.

Besides some other ways, using STATCOM connected in shunt to the PCC is one of the most effective methods to reduce the flicker level. The reactive power flow of the STATCOM is controlled in proportion to the output active power of the wind turbine [1,3-5].

During the continuous operation of wind turbines, flicker emissions are produced. The flicker is caused by power fluctuations which mainly emanate from variations in the wind-speed, the tower shadow effect and the mechanical properties of the wind turbine [2].

In this paper, simulation models of a doubly fed induction generator and a permanent magnet synchronous generator developed in PSCAD/EMTDC [6] is presented, and the control schemes of the wind turbine are described. Flicker mitigation when using PMSG to regulate the voltage at the PCC of the wind farm is investigated. As the proposal scheme is capable on flicker mitigation and voltage regulation, so it replaces STATCOM reducing its extra cost and losses. It is clear that multi-function interface of the PMSG will improve the utility from the technical and economic point of view. The simulation results are discussed to indicate the potential benefits of the proposed scheme.

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II. SIMULATION MODELS OF WIND TURBINES

1. Permanent Magnet Synchronous Generator (PMSG)

Permanent magnet synchronous generator is connected to the grid with using a back-to-back full-scale PWM voltage source as shown in Fig. 1.

The objective of the generator-side converter controller is to maintain the DC link voltage at the reference value.

The reference value of the active power P_{pcc_ref} is compared with the measured value P_{ppc}. The error between these two signals is processed by a PI controller, whose output provides the reference angle to grid-side vector control of PWM.

To implement the load angle controller the reference value of the reactive power, Q_{pcc_ref}, may be set to zero for unity power factor operation.

2. Doubly Fed Induction Generator (DFIG)

The doubly fed induction generator allows power output or input into the stator winding as well as the rotor winding of an induction machine with a wound rotor winding. Using such a generator it is possible to get a good power factor even when the machine speed is quite different from synchronous speed. Such machines can therefore operate without the need for excessive

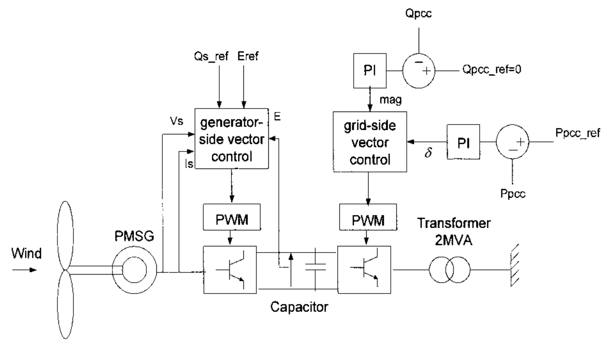


그림 1. 영구자석형동기발전기의 부하각 제어방식에 대한 블럭선도.

Fig. 1. Block diagram for load angle control schemes of permanent magnet synchronous generator.

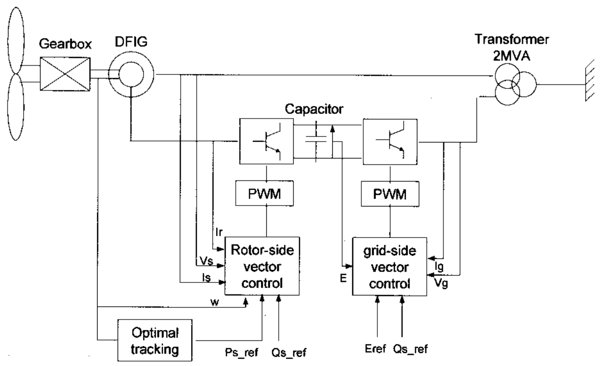


그림 2. 이중여자유도발전기 벡터제어 블럭선도.

Fig. 2. Block diagram for the vector-control schemes of doubly fed induction generator.

shunt compensation. As shown Fig. 2., it is possible to control the active and reactive power independently in stator side using PWM power converter connected in rotor side.

In vector-control scheme for the rotor side, the rotor current I_r of the machine can be resolved into the well known direct and quadrature components i_d and i_q. The torque in the machine is the vector cross product of these two vectors, and only the component i_d is contributes to the machine torque and hence to the power. The component i_q then controls the reactive power entering the machine. If i_d and i_q can be controlled precisely, then so can the stator side real and reactive powers.

The aim of the grid-side vector control is to keep the DC voltage on the capacitor at a constant value. In effect, this means that the grid side converter is supplying the real power demands of the rotor side converter. It may also be responsible for controlling reactive power flow into the grid.

III. FLICKER EMISSION OF WIND TURBINES CONNECTED TO GRID

In proposed system a wind farm with a doubly fed induction generator and a permanent magnet synchronous generator is connected to grid at bus 2 through a line 1-2, where the impedance magnitude Z corresponding to rate of X/R as shown in Fig. 3. The magnitude of the Thevenin's equivalent impedance can be found out by the rated voltage and the short circuit capacity.

The wind turbines drives a 2 MW doubly fed induction generator and a 2 MW permanent magnet synchronous generator. Parameters of these generators in detail are provided in Table 1 and 2.

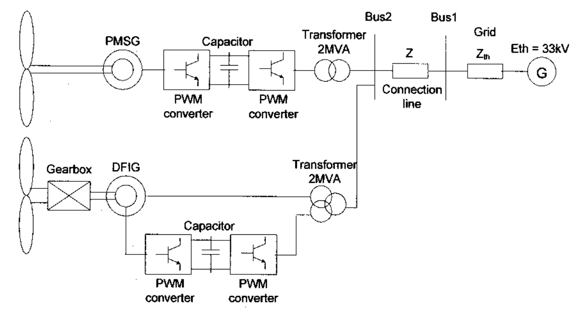


그림 3. 계통에 연결된 DFIG와 PMSG의 블럭선도.

Fig. 3. Block diagram of a grid connected wind turbines with a DFIG and a PMSG.

표 1. DFIG 파라미터.

Table 1. DFIG Parameters.

Parameter	Value
Rated power	2MW
Rated voltage	0.69 kV
Base angular frequency	376.99 rad/s
Stator/rotor turns ratio	2.637687
Angular moment of inertia	0.7267 p.u.
Mechanical damping	0.001 p.u.
Stator resistance	0.0054 p.u.
Rotor resistance	0.00607 p.u.
Stator leakage inductance	0.102 p.u.
Rotor leakage inductance	0.11 p.u.
Mutual inductance	4.362 p.u.

표 2. PMSG 파라미터.

Table 2. PMSG Parameters.

Parameter	Value
Rated power	2MW
Rated voltage	0.69 kV
Xd	0.920 p.u.
Xq	0.510 p.u.
Magnetic strength	1 p.u.

This study is concentrated on flicker emission and mitigation of grid connected wind turbines during continuous operation. The level of flicker is quantified by the short-term flicker severity P_{st}, which is normally measured over a ten-minute period. According to IEC standard IEC 61 000-4-15 [6], a flickermeter model is built to calculate value of P_{st}. The short-term flicker severity of bus 2, the PCC, is calculated on the basis of the voltage variation.

Flicker emission of grid connected wind turbines depends on the factors, such as listed below.

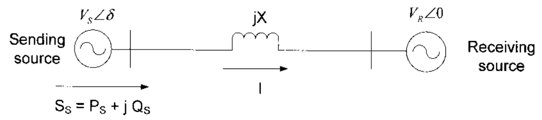
- Mean wind speed, ν
- Turbulence intensity, $In = \frac{\Delta \nu}{\nu}$
- Short circuit capacity ratio, $SCR = \frac{S_k}{S_n}$
- Grid impedance angle, $\psi_k = \arctan\left(\frac{X}{R}\right)$

Where $\Delta\nu$ is the wind speed standard deviation, ν is the mean wind speed, S_k is the short circuit apparent power of the grid where the wind turbines are connected, S_n is the rated apparent power of the wind turbines, R and X are the resistance and reactance of the grid line.

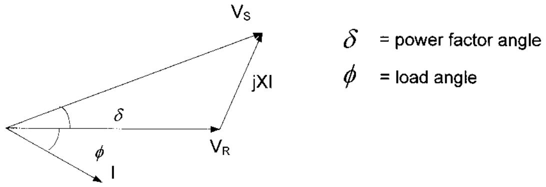
It is recommended that in the distribution networks a flicker emission of P_{st} = 0.35 is considered acceptable for wind turbine installations [7]. For the wind turbines connected to the transmission networks, the flicker contribution from the wind turbines in the connection point shall be limited to be below P_{st} = 0.3 [8].

IV. CONTROL OF PERMANENT MAGNET SYNCHRONOUS GENERATOR TO MITIGATE FLICKER IN THE WIND FARM

Control over the power converter system can be exercised with different schemes. The generator-side converter can be controlled



(a) Equivalent circuit diagram



(b) Phasor diagram

그림 4. 두 소스간의 전력전송.

Fig. 4. Power transfer between two sources.

using load angle control techniques or it can be controlled by means of more accurate but also sophisticated techniques such as vector control. The grid-side converter is normally controlled using load angle control techniques [9]. In this paper, the implementation of the load angle control scheme is used to control PMSG.

The load angle control technique can be explained by analyzing the transfer of active and reactive power between two sources connected by an inductive reactance as shown in Fig. 4. The active power, P_s, and reactive power, Q_s, transferred from the sending-end to the receiving-end may be obtained by equation (1) and (2) respectively.

We have the apparent power of sending source:

$$S_S = V_S I_S^* = V_S\left(\frac{V_S - V_R}{jX}\right)^* = V_S\frac{(V_S^* - V_R^*)}{-jX} = j\frac{V_S^2}{X} - j\frac{V_S V_R^*}{X} \quad (1)$$

Noting from Fig. 4 that $V_S = V_S e^{j\delta}$ and $V_R^* = V_R$

We have

$$S_S = P_S + jQ_S = j\frac{V_S^2}{X} - j\left(\frac{V_S V_R \cos\delta + jV_S V_R \sin\delta}{X}\right) \quad (2)$$

Hence

$$P_S = \frac{V_S V_R}{X}\sin\delta \quad (3)$$

$$Q_S = \frac{V_S^2}{X} - \frac{V_S V_R}{X}\cos\delta \quad (4)$$

Applying these equations (3) and (4) in the case the sending source is PMSG and the receiving source is the grid, the results are:

$$\text{From equation (3)} \Longrightarrow \sin\delta \approx \delta = \frac{P_{PMSG\_ref} X}{V_{bus1} V_{bus2}} \quad (5)$$

$$\text{From equation (4)} \Longrightarrow V_{bus2} = V_{bus1} + \frac{Q_{PMSG} X}{V_{bus2}} \quad (6)$$

Where P_{PMSG_ref} and Q_{PMSG} is reference active power value and reactive power value of PMSG respectively. V_{bus2}, V_{bus1} are the voltages at bus 2 and bus 1. X is inductive reactance of connection line between bus 2 and bus 1 in Fig. 3.

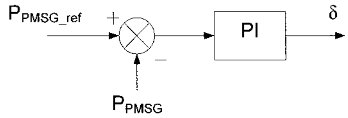


그림 5. 유효전력 제어를 위한 블록선도.

Fig. 5. Block diagram for controlling the active power flow.

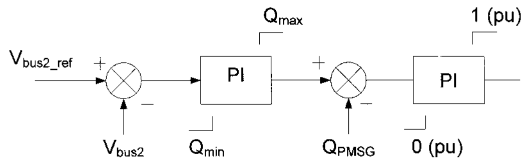


그림 6. PCC 전압조정 블럭선도.

Fig. 6. Block diagram for regulating the voltage at PCC.

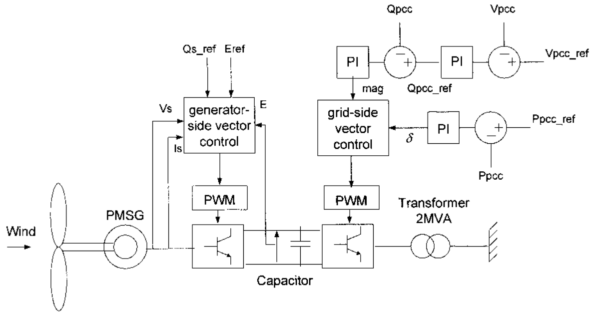


그림 7. 영구자석형 동기발전기의 제어 블록선도.

Fig. 7. Block diagram of controlling the permanent magnet synchronous generator.

From equation 3 it is seen that the active power transfer depends mainly on the phase angle δ by which the sending source voltage leads the receiving source voltage. Therefore, controlling the phase angle δ using PI controller help having a desired active power as shown in Fig. 5

From equation 4 the reactive power transfer depends mainly on voltage magnitudes, and it is transmitted from the side with higher voltage magnitude to the side with lower magnitude. The reference value of the voltage at bus 2, V_{bus2_ref} is compared with the measured value V_{bus2}. The error between these two signals is processed by a PI controller, whose output provides the reference reactive power. Then the reactive power value continues being compared with the measured value Q_{PMSG}. And result of the comparison is input to other PI controller. Finally, the output of the PI controller is supplied to grid-side vector control of PWM as a magnitude of control signal as shown in Fig. 6.

From Fig. 1, Fig. 5, Fig. 6, a control system for PMSG was established in Fig. 7. The values of phase angle δ and the magnitude, mag, is input into grid-side vector control for PWM

V. SIMULATION RESULTS

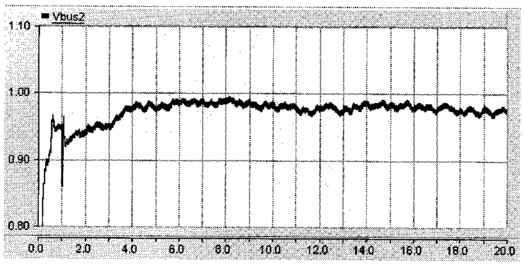
In this paper we just focus on 4 factors impacting on flicker such as mean wind speed, turbulence intensity, short-circuit capacity ratio and grid impedance angle. Therefore if we want to investigate flicker emission of any wind turbines during continuous operation, we must keep three of them at a constant value and give the rest of them variable. Figs. 10, 13 and 16 showed this regulation.

In this paper, mitigating flicker in wind farm is evaluated under the conditions of short circuit capacity ratio, turbulence intensity and grid impedance angle. DFIG is connected to the grid at t=1s and the voltage is shown on the per unit. Simulation of voltage fluctuation is performed during only first 20 seconds.

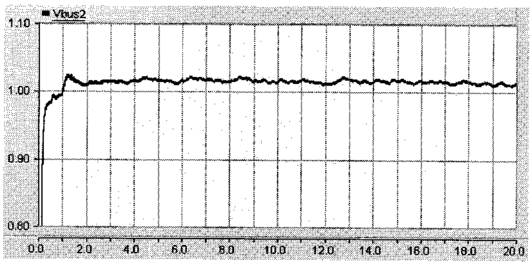
1. Short-circuit Capacity Ratio (SCR)

We know that SCR specifies strength of the grid, so the smaller SCR, the weaker the grid. This results in that the voltage at the connected point is very sensitive with any fluctuation of power as shown in Fig. 8.

As can be seen from the Fig. 9 that after regulating the voltage of PMSG is operated, the voltage at bus 2 becomes smoother.



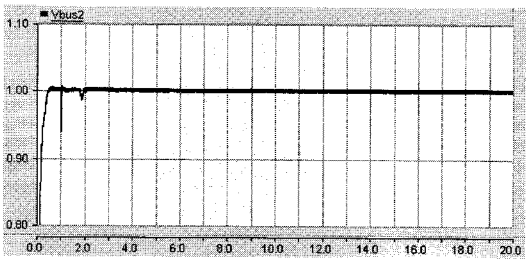
(a) SCR = 2



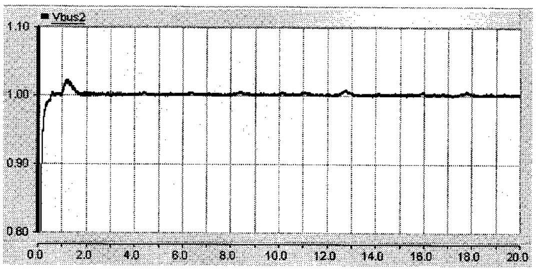
(b) SCR = 10

그림 8. PMSG의 전압제어가 없는 경우 모선의 전압변동.

Fig. 8. Fluctuation of the voltage at bus 2 without the voltage control of PMSG (v = 9m/s, In = 0.1, ψ_k = 63,435°).



(a) SCR = 2



(b) SCR = 10

그림 9. PMSG의 전압제어시 모선의 전압 변동.

Fig. 9. Fluctuation of the voltage at bus 2 with the voltage control of PMSG (v = 9m/s, In = 0.1, ψ_k = 63,435°).

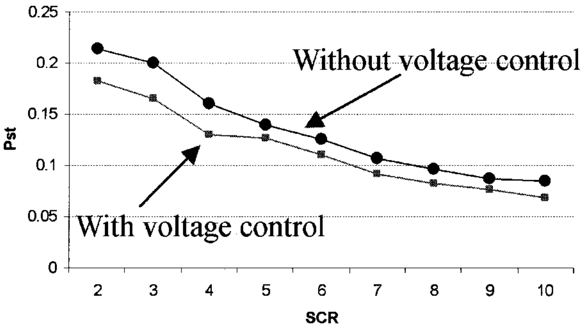


그림 10. 단락용량 변화에 따른 P_{st} 추이.

Fig. 10. P_{st} variation with short circuit capacity (v = 9m/s, In = 0.1, ψ_k = 63,435°).

From the Figs. 8 and 9 we conclude that the result of the low SCR is the increase in short-term flicker severity P_{st} . And the Fig. 10 showed P_{st} with variable short-circuit capacity SCR.

2. Grid Impedance Angle

The voltage change across a power line may be approximately calculated with the following formula 7:

$$\Delta V = \frac{PR + QX}{V} \tag{7}$$

Where P and Q are the active and reactive power flow on the line respectively, R and X are the resistance and reactance of the grid line, and V is the voltage at the line terminal.

The grid impedance angle is very important that the voltage changes from the active power flow may be cancelled by that from the reactive power flow.

Now we compare the voltage fluctuation at bus 2 in two cases: Fig. 11, without the voltage control of PMSG and Fig. 12, with the voltage control of PMSG. It is easy to recognize that the

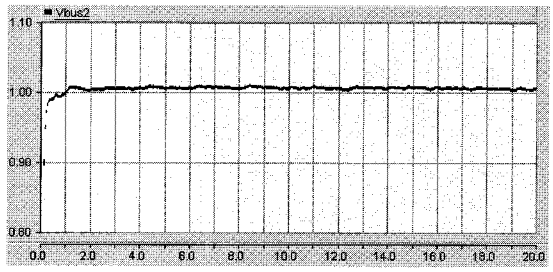


그림 11. PMSG의 전압제어가 없는 경우 모선의 전압변동.

Fig. 11. Fluctuation of the voltage at bus 2 without the voltage control of PMSG (v =9m/s, In = 0.1, SCR = 20, ψ_k =70°).

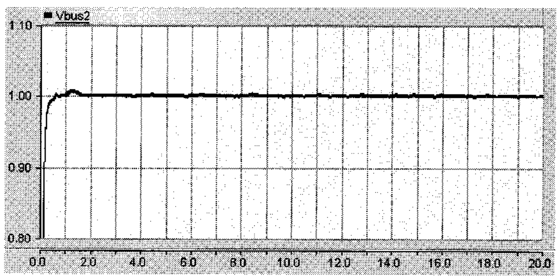


그림 12. PMSG의 전압제어시 모선의 전압 변동.

Fig. 12. Fluctuation of the voltage at bus 2 with the voltage control of PMSG (v = 9m/s, In = 0.1, SCR = 20, ψ_k =70°).

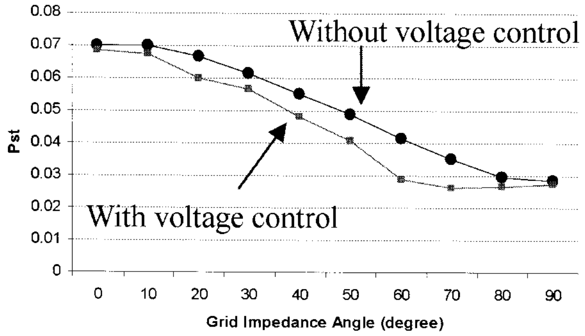


그림 13. 계통 부하 위상각에 따른 P_{st} 추이.

Fig. 13. P_{st} variation with grid impedance angle (deg) (v = 9m/s, *In* = 0.1, SCR = 20).

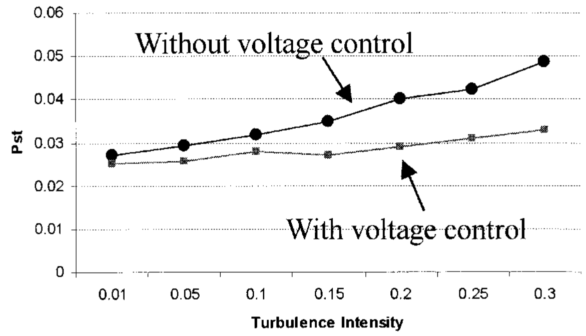


그림 16. 난류강도 변화 따른 P_{st} 추이.

Fig. 16. P_{st} variation with turbulence intensity (v = 9m/s, SCR=20, ψ_k = 63,435°).

voltage at bus 2 is more flat when PMSG run with the voltage control mode.

Fig. 13 shows the variation of flicker with grid impedance angle. When the grid impedance angle approaches 70 degrees, it has minimum flicker level. Since the absorption or generation of reactive power series the power factor for voltage. The grid impedance angle is varied at the time of minimum flicker severity.

3. Turbulence Intensity of the Wind

When the turbulence intensity of the wind is low, the wind profile varies in a small range that corresponds to a rated output power. The voltage fluctuation is low due to a small power fluctuation as a result of the aerodynamic regulation. As the turbulence intensity increases, the wind profile changes significantly which results in a large variation of output power. As a consequence, the voltage fluctuation becomes serious.

Before showing the result of reducing flicker in this aspect, we take a look the voltage changes at bus 2 before and after regulating the voltage of PMSG performed as shown in Figs. 14 and 15 respectively.

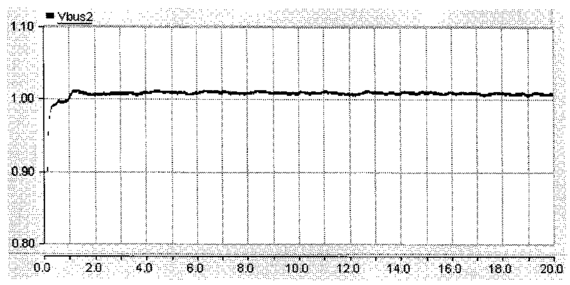


그림 14. PMSG의 전압제어가 없는 경우 모선의 전압변동.

Fig. 14. Fluctuation of the voltage at bus 2 without the voltage control of PMSG (*In* =0.2, v =9m/s, SCR=20, ψ_k = 63,435°).

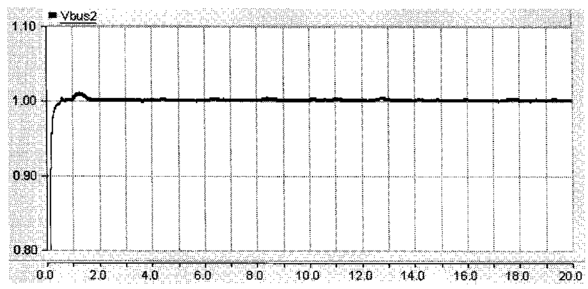


그림 15. PMSG의 전압제어시 모선의 전압 변동.

Fig. 15. Fluctuation of the voltage at bus 2 with the voltage control of PMSG (*In* = 0.2, v = 9m/s, SCR = 20, ψ_k = 63,435°).

Because the voltage at bus 2 becomes smoother under controlling the voltage of PMSG, of course, the short-term flicker severity P_{st} is also reduced.

As be shown in Fig. 16, in low wind speed (for example, v =9 m/s), the P_{st} has an almost linear relation with turbulence intensity. The more turbulence in the wind results in larger flicker emission.

VI. CONCLUSION

The paper describes reducing the flicker level during continuous operation of the grid connected wind turbine by regulating the voltage at the point of common coupling. The proposed multi-functional PMSG-interface replaces the need for other power electronics compensators such as STATCOM. The operational cost of the utility is an important advantage of this measure. In turn, this PMSG-interface is competitive in the new restructured market. Moreover, the simulation results show that the proposed scheme is an effective means to mitigate flicker level during continuous operation of grid connected wind turbines.

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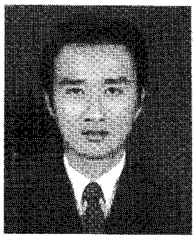
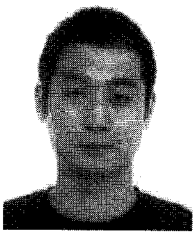


판 반 호 안

2007년 베트남 칸토대 전기공학과 졸업. 현재 제주대학교 전기공학과 석사과정 재학중. 관심분야는 전력전자응용 및 풍력발전제어.



안 진 홍

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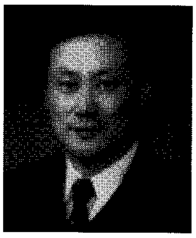

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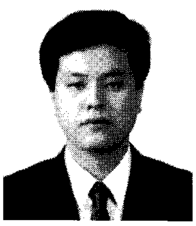

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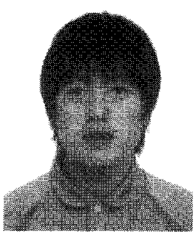

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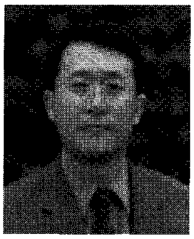

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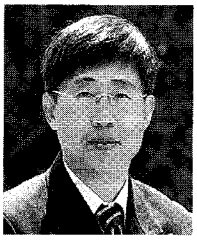

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