

Modeling and Control Strategies of Fuzzy Logic Controlled Inverter System for Grid Interconnected Variable Speed Wind Generator

S. M. Muyeen, *Senior Member, IEEE*, and Ahmed Al-Durra, *Member, IEEE*

Abstract—Variable speed operation of permanent magnet synchronous generator (PMSG) is becoming popular nowadays in wind power industry. Variable speed wind turbine (VSWT) driven PMSG, in general, is connected to the grid using fully controlled frequency converter. Along with the generator side converter the frequency converter necessitates the grid side inverter system which has great impact on stability issue of the VSWT-PMSG, especially in the case of network disturbance. The well-know cascaded controlled inverter system has been widely reported in many literatures, where multiple PI controllers are used in inner and outer loops. However, fuzzy logic controller (FLC) deals well the non-linearity of the power system compared to PI controller. This paper presents a simple fuzzy logic controlled inverter system for the control of grid side inverter system, which suits well for VSWT-PMSG operation in a wide operating range. This is one of the salient features of this study. Detailed modeling and control strategies of the overall system are demonstrated. Both dynamic and transient performances of VSWT driven PMSG are analyzed to show the effectiveness of the control strategy, where simulation has been done using PSCAD/EMTDC.

Index Terms— Frequency converter, permanent magnet synchronous generator (PMSG), transient stability, variable speed wind turbine (VSWT), fuzzy logic controller (FLC).

I. INTRODUCTION

OVER the last decade many renewable energy technology such as solar, wind, bio-mass, wave, etc. have advanced significantly, from the viewpoint of conversation efficiency and unit cost production. Among those renewable energy sources wind energy stands as true alternatives to conventional technologies for electricity generation. Wind energy also has the clean energy feature which is important considering the fact of global warming. In 2008, 27 GW wind power has been installed all over the world, bringing world-wide installed capacity to 120.8 GW. This is an increase of 36% compared with the 2007 market, and represents an overall increase in the global installed capacity of about 28.8% [1].

Fixed speed as well as variable speed wind turbine

generator systems (WTGSs) are emerging in wind power industry, though the former is barely considered for new installations. One of the reasons is that it fixed speed WTGS cannot capture maximum power from the wind. Another shortcoming is the inability to control terminal voltage using only its fixed capacitor bank. The use variable speed WTGS is pretty alluring considering those viewpoints. Therefore, the present market share is dominated by the technology using variable speed WTGS [2].

Few types of variable speed wind turbine (VSWT) generator systems are commercially available, nowadays. Doubly fed induction generator (DFIG) is most commonly used wind generator and abundantly reported in literatures analyzing its both dynamic and transient characteristics [3-7]. DFIG needs a frequency converter with partial rating of it's capacity for variable speed operation. Besides this, multi-pole conventional synchronous generator and permanent magnet synchronous generator are also becoming popular in wind power industry using a full capacity frequency converter for grid interconnection. PMSG is recognized as a promising technology for using as wind generator, both in direct-drive system and the system using a simple single-stage gearbox. One of the major advantages is the high power density of this type of machine [8-9]. The transverse flux design of it makes it possible to fish out some other benefits. The use of PMSG seems to be more prospective in wind power application from now on because the price for the rare-earth magnets decreases remarkably, in the last few years. Some authors have already been reported on VSWT-PMSG technology including dynamic and transient characteristics [10-16]. This study also focuses on variable speed wind turbine (VSWT) driven PMSG, emphasizing the stability issue for secure grid connection.

The VSWT-PMSG, in general, is connected to the power grid using a full-capacity, properly controlled frequency converter technology. Two types of frequency converter topologies are available these days. One, in which, the frequency converter (FC) is composed of generator side AC/DC converter, DC-link, and DC/AC inverter. In the other topology, the frequency converter composed of Rectifier, DC-Chopper, DC-link, and DC/AC inverter. Various control strategies can be adopted for the operation of generator and grid side converter/inverter as reported in [10-16]. It is needed

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S.M. Muyeen and Ahmed Al-Durra works in the Renewable Energy Lab, Electrical Engineering Department, The Petroleum Institute, Abu Dhabi, UAE. Email: s.m.muyeen@pi.ac.ae.

to mention that the control of grid side inverter of the VSWT-PMSG is crucial as it is directly connected to the grid through a step-up transformer and has to fulfill the grid code requirements during both normal and network fault conditions.

The well-know cascaded controlled inverter system is widely reported in many literatures, where several PI controllers are used in both inner and outer loops. The use of lead-lag compensator along with the PI controllers might be incorporated for cascaded control to augment stability. Setting of the parameters of the PI controllers used in cascaded control is cumbersome, especially in power system application which is difficult to express by a mathematical model or transfer function. The aforementioned issues may be resolved incorporating fuzzy logic controller (FLC) as it has the ability to solve problems having uncertainties or imprecise situations.

Therefore, this paper presents a simple fuzzy logic controlled inverter system for the control of grid side inverter system, which suits well for VSWT-PMSG operation in a wide operating range. This is one of the salient features of this study. Interpolated firing pulses are used as the switching signals for the insulated gate bipolar transistors (IGBT) of both converter and inverter. Detailed modeling and control strategies of the overall system are presented. To evaluate the effectiveness of FLC controlled inverter system, both dynamic and transient analyses are performed. Real wind speed data measured in Hokkaido Island, Japan is considered for dynamic analysis for the sake of preciseness. Wind farm grid code is taken into consideration during transient analysis. Transient performance of FLC controlled inverter system is compared with that of cascaded controlled inverter. Finally, it is reported that the proposed control strategy is very effective for driving the VSWT-PMSG at wide operating regions.

II. WIND TURBINE MODELING

The mathematical relation for the mechanical power extraction from the wind can be expressed as follows [17]:

$$P_w = 0.5 \rho \pi R^2 V_w^3 C_p(\lambda, \beta) \quad (1)$$

where, P_w is extracted power from the wind, ρ is the air density [kg/m^3], R is blade radius [m], V_w is the wind speed [m/s] and C_p is the power coefficient which is a function of both tip speed ratio, λ , and blade pitch angle, β [deg]. To Calculate C_p for the given values of β and λ the following numerical approximations have been used [17-18].

$$\lambda = \frac{\omega_r R}{V_w} \quad (2A)$$

$$\lambda_i = \frac{1}{\lambda + 0.02\beta} - \frac{0.003}{\beta^3 + 1} \quad (2B)$$

$$C_p(\lambda, \beta) = 0.73 \left[\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2 \right] e^{-\frac{18.4}{\lambda_i}} \quad (2C)$$

where ω_r denotes the rotor speed of wind turbine.

In VSWT, generated power from the turbine depends on the power coefficient, C_p . For the wind speed of VSWT, there is a specific turbine rotational speed which generates the maximum power. In this way, the maximum power point tracking (MPPT) for each wind speed increases the energy generation in VSWT. The power coefficient curve with the MPPT curve is shown in Fig.1, from which it can be seen that, for any particular wind speed, there is a rotational speed, ω_r , which generates the maximum power, P_{max} , called also as the optimum power, P_{opt} .

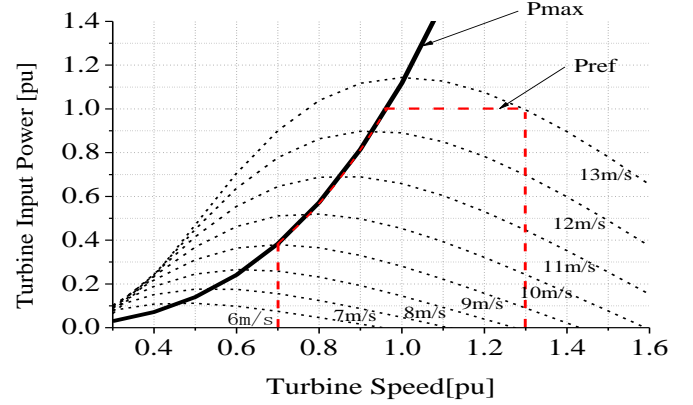


Fig. 1. Turbine characteristic with maximum power point tracking

When the wind speed changes, the rotational speed is controlled to follow the maximum power point trajectory. It should be noted here that the measurement of the precise wind speed is not so easy. Therefore, it is better to calculate the optimum power, P_{opt} , without measuring wind speed as shown below.

$$P_{opt} = P_{max} = 0.5 \rho \pi R^2 \left(\frac{\omega_r R}{\lambda_{opt}} \right)^3 C_{p_{opt}} \quad (3)$$

From eq.(3), it is clear that the optimum generated power is proportional to the cube of rotational speed, ω_r . If the reference optimum power, P_{opt} , is greater than the rated power of PMSG, then the pitch controller is used to control the rotational speed. Therefore, the reference optimum power will not exceed the rated power of the PMSG. In this study, the pitch controller used in [15] is considered.

III. MODELING AND CONTROL STRATEGIES OF INDIVIDUAL COMPONENTS

In this study, the direct drive VSWT-PMSG concept is adopted with the utilization of fully controlled frequency converter. The frequency converter consists of generator side AC/DC converter, DC link capacitor, and grid side DC/AC inverter. Each of converter/inverter is a standard 3-phase two-level unit, composed of six IGBTs and antiparallel diodes. The PMSG model available in the package software PSCAD/EMTDC is used [19]. The control strategy of the frequency converter is demonstrated below.

A. Generator Side Converter

The well-known vector control scheme is used as the control methodology of generator side converter. As this converter is directly connected to the PMSG, its q-axis current can control the active power. The active power reference, P_{opt} , is determined in such a way to provide maximum power to the grid. On the other hand, the d-axis stator current can control the reactive power. The reactive power reference is set to zero for unit power factor operation. The angle, θ_r , for the transformation between abc and d/q variables is calculated from the rotor speed of PMSG. The detailed of the generator side converter is available in [15].

B. Grid-Side Inverter

Fuzzy logic, in general, is an innovative technology that enhances conventional system design with engineering expertise. The use of fuzzy logic can help to circumvent the need for rigorous mathematical modeling. Unlike the reasoning based on classical logic, fuzzy reasoning aims at the modeling of reasoning schemes based on uncertain, tolerant, or imprecise information. In addition, it has inherent abilities to deal with imprecise or noisy data; thus, it is able to extend its control capability even to those operating conditions where linear control techniques fail (i.e., large parameter variations). Therefore, in this study, fuzzy logic controlled inverter system is proposed for grid interfacing of VSWT-PMSG, which can deal well the nonlinearity of power system as well as can work in wide operating range.

The schematic diagram of the FLC controlled grid side voltage source inverter is shown in Fig. 2. The voltage source inverter is connected to the grid through a step-up transformer, which can be expressed by a resistance, R and reactance, X .

The phasor quantities \bar{V} , \bar{V}_c , and \bar{I} represent the ac grid voltage at the high voltage side of the transformer, output ac voltage of the voltage source inverter, and current following from the ac grid to the voltage source inverter, respectively. The real power, P , and reactive power, Q , flowing through the voltage source inverter can be derived easily as expressed below.

$$\left. \begin{aligned} P &\propto I_d \propto -V_{cq} \\ Q &\propto -I_q \propto -V_{cd} \end{aligned} \right\} \quad (4)$$

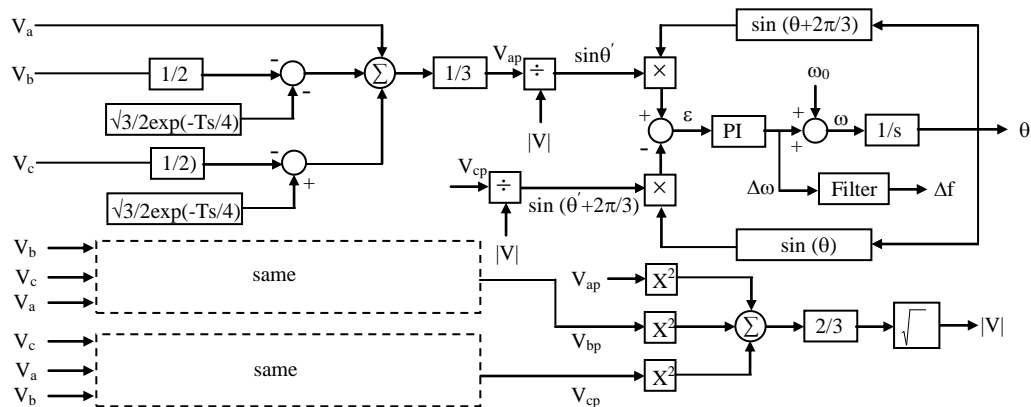


Fig. 3. Block diagram for PLL [20]

where, I_d and I_q are d and q components of the current phasor. V_{cd} and V_{cq} are d and q components of the voltage source inverter output ac voltage. The dq quantities and three-phase electrical quantities are related to each other by reference frame transformation. The angle of the transformation is detected from the three phase voltages (v_a, v_b, v_c) at the high voltage side of the transformer by using phase locked loop (PLL) as shown in Fig. 3. The derivation of eq. (4) is shown in the appendix.

Again, if we neglect the switching losses and harmonics, then the following expression can be obtained.

$$P \propto V_{dc} I_{dc} \quad (5)$$

Where, V_{dc} and I_{dc} are the dc voltage and current of the voltage source inverter, respectively.

Based on this concept, the simple control strategy shown in Fig. 4 is developed in this study for the operation of grid side voltage source inverter. The fuzzy controllers produce the reference signals which consequently generate the interpolated gate pulses after being compared with triangular carrier wave.

In the control blocks, the proposed FLC systems find out the reference signals from the error signals of AC grid and DC-link voltages ($e1, e2$), and the change of error signals ($\Delta e1, \Delta e2$).

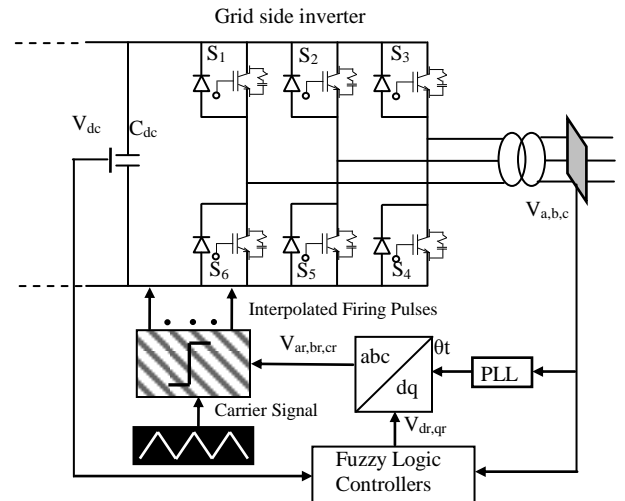


Fig. 2. Schematic diagram of grid side inverter

The FLC is explained in the following:

1) Fuzzification

To design the proposed FLCs, the error signals, $e1(k)$ and $e2(k)$, and change of error signals, $\Delta e1(k)$ and $\Delta e2(k)$ are considered as the controllers inputs. The d and q axis reference voltages (V_{dr} and V_{qr}) are chosen as the controllers outputs, which is actually the reference signals to generate the

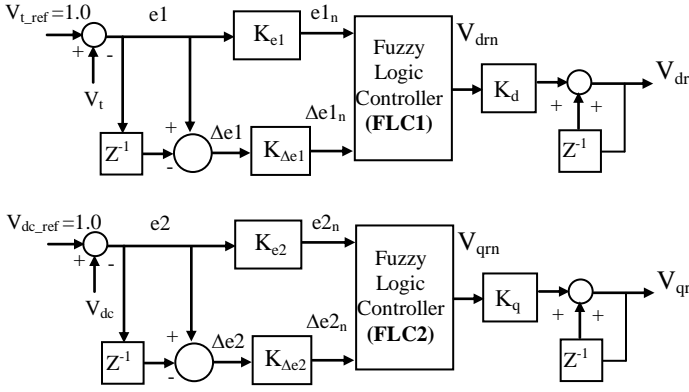


Fig. 4. Control block diagrams for FLC controlled inverter

switching pulses for IGBT devices. For convenience, the inputs and outputs of the FLCs are scaled with coefficients K_{e1} , K_{e2} , $K_{\Delta e1}$, $K_{\Delta e2}$, K_d and K_q as shown in Fig. 4. These scaling factors can be constants or variables and play an important role for FLC design in order to achieve a good response in both dynamic and transient states. In this work, these scaling factors are considered as constant for the simplicity of controller design, and are selected by trial-and-error in order to obtain the best system performance. In Fig. 4, the Z^{-1} represents one sampling time delay. The triangular membership functions with overlap used for the input and output fuzzy sets are shown in Fig. 5 in which the linguistic variables are represented by NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). To keep the design simple similar membership functions are considered for both FLCs as shown in Fig. 5. The grade of input membership functions can be obtained from the following equation [21].

$$\mu(x) = [w - 2|x - m|] / w \quad (6)$$

where, $\mu(x)$ is the value of grade of membership, w is the width, m is the coordinate of the point at which the grade of membership is 1, and x is the value of the input variable.

2) Rule Base

The fuzzy mapping of the input variables to the output is represented by IF-THEN rules of the following forms:

IF $\langle e_{n1}$ is NB \rangle and $\langle \Delta e_{n1}$ is NB \rangle THEN $\langle V_{drn}$ is PB \rangle

IF $\langle e_{n1}$ is PB \rangle and $\langle \Delta e_{n1}$ is PB \rangle THEN $\langle V_{drn}$ is NB \rangle

The entire rule base is given in Table 1. There are total 49 rules to achieve the desired reference signals.

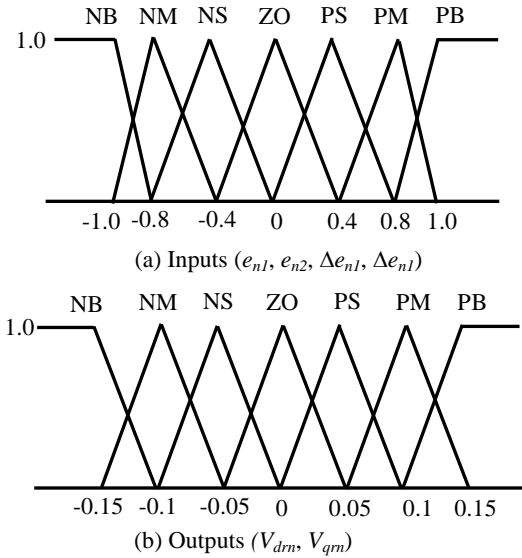


Fig. 5. Fuzzy sets and their corresponding membership functions for FLC1 and FLC2

3) Inference & Defuzzification

In this work, for the inference mechanism, Mamdani's max-min (or sum-product) [21] method is used. The center of gravity method [21] is used for defuzzification to obtain V_{drn}/V_{qrn} , which is given by the following equation:

$$V_{drn} / V_{qrn} = \frac{\sum_{i=1}^N \mu_i C_i}{\sum_{i=1}^N \mu_i} \quad (7)$$

TABLE 1
FUZZY RULE TABLE FOR FLCs 1 AND 2

$V_{dr,n}/V_{qr,n}$		$\Delta e_{n1}/\Delta e_{n2}$						
		NB	NM	NS	ZO	PS	PM	PB
e_{n1}/e_{n2}	NB	PB	PB	PM	PM	PS	PS	ZO
	NM	PB	PM	PM	PS	PS	ZO	NS
	NS	PM	PM	PS	PS	ZO	NS	NS
	ZO	PM	PS	PS	ZO	NS	NS	NM
	PS	PS	PS	ZO	NS	NS	NM	NM
	PM	PS	ZO	NS	NS	NM	NM	NB
	PB	ZO	NS	NS	NM	NM	NB	NB

Where, N is the total number of rules, μ_i is the membership grade for i -th rule and C_i is the coordinate corresponding to the respective output or consequent membership function [$C_i \in \{-0.15, -0.1, -0.05, 0, 0.05, 0.1, 0.15\}$] for both FLC1 and FLC2. The actual reference signals (V_{dr} and V_{qr}), can be found out by multiplying V_{drn} and V_{qrn} by the scaling factor K_d and K_q , respectively.

Sinusoidal pulse width modulation (PWM) controller, composed of three main circuits (i.e., high-frequency carrier circuit, sinusoidal modulating reference signal circuit, and the interpolated firing pulse circuit), is modeled on the PSCAD/EMTDC software, which generates the switching signals for the IGBT gates in FLC controlled inverter. The interpolated firing pulse circuit is a simulation technique concerned with generating firing pulses through interpolation procedure. This allows for exact switching between time steps based on a comparison between the sinusoidal reference and the high-

frequency carrier signal [22]. The carrier frequency is chosen 1050 hz. The rated dc-link voltage is 2.3 kV.

IV. MODEL SYSTEM

The model system used for dynamic and transient stability analyses of VSWG-PMSG is shown in Fig. 6. Here one PMSG is connected to the infinite bus through a generator-side converter, dc-link capacitor, grid-side inverter, transformer, and double circuit transmission line. The parameters of the PMSG are shown in Table. 2. The system base is 5MVA.

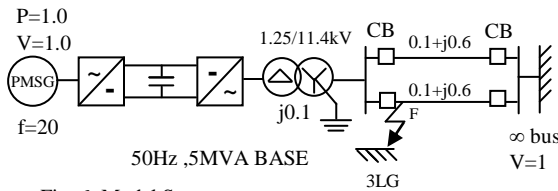


Fig. 6. Model System

TABLE 2
GENERATOR PARAMETERS

Rated Power	5 [MW]	Stator Resistance	0.01[pu]
Rated Voltage	1.0 [kV]	d-axis Reactance	1.0[pu]
Frequency	20 [Hz]	q-axis Reactance	0.7[pu]
Number of Poles	150	Field Flux	1.4[pu]
H	3.0 [sec]		

V. SIMULATION RESULTS

The system shown in Fig. 6 is simulated using laboratory standard power system simulator PSCAD/EMTDC [19]. FORTRAN program is incorporated with PSCAD to implement FLC and the subroutine is called at every time step from PSCAD. The time step is chosen 0.00002 sec. The simulation time is chosen 300 sec and 5 sec for dynamic and transient stability analyses, respectively.

A. Dynamic Characteristic Analysis

Dynamic characteristic of VSWG-PMSG is analyzed under wide range of wind speed variation shown in Fig. 7, which is a real data measured in Hokkaido Island, Japan. One of the advantages of variable speed operation of wind generator is that

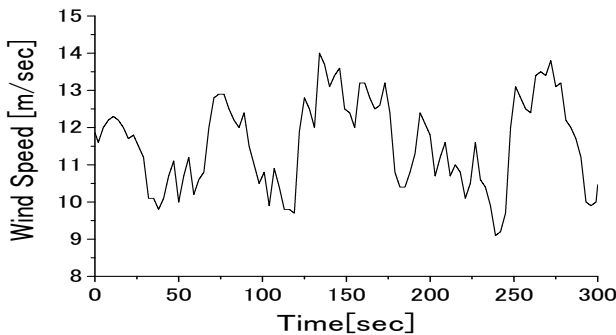


Fig. 7. Wind speed data

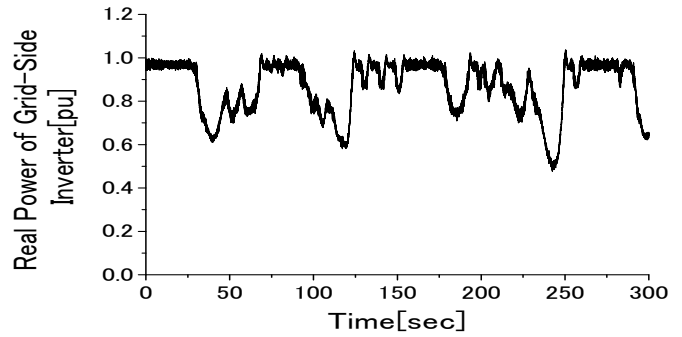


Fig. 8. Real power supplied to the grid

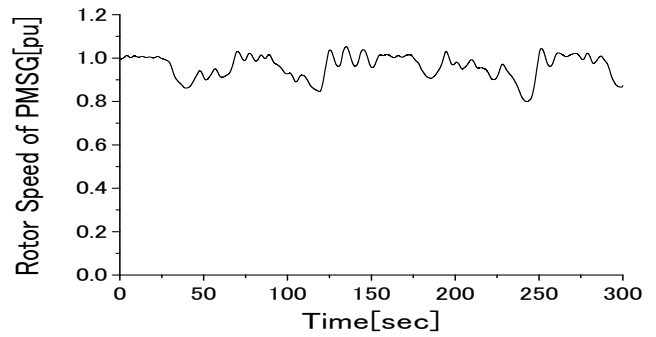


Fig. 9. Rotor speed of PMSG

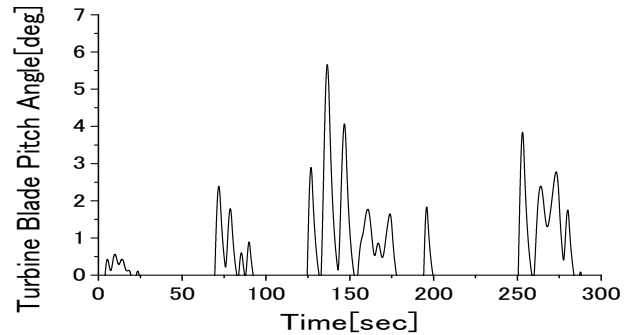


Fig. 10. Wind turbine blade pitch angle

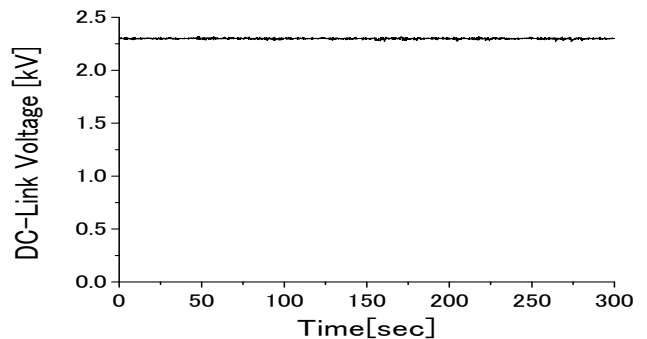


Fig. 11. DC-Link voltage of the frequency converter

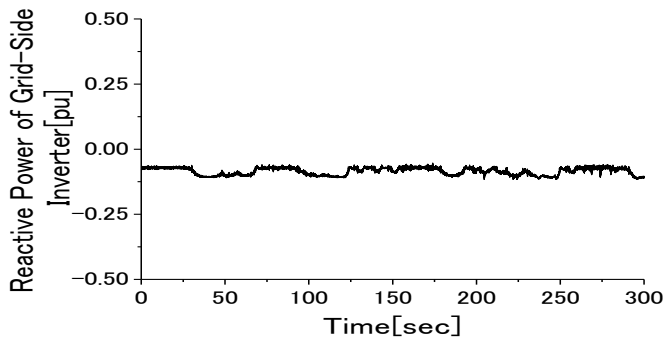


Fig. 12. Reactive power of the grid side inverter

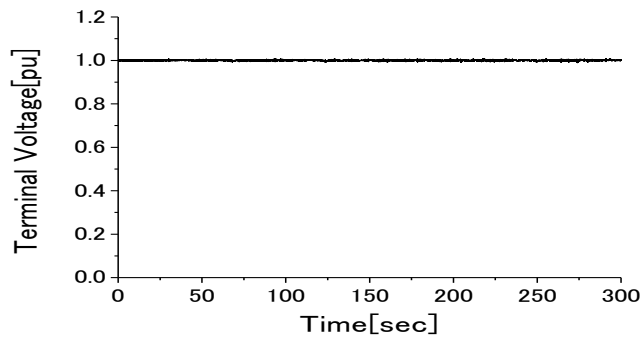


Fig. 13. Terminal voltage at the high voltage side of transformer

it can extract the maximum power from wind by adjusting rotor speed of the wind turbine according to the wind speed variation, provided that the captured power should not exceed the rated power of PMSG. Figure 8 shows the maximum power supplied to the grid. It is seen that output power is close to the rated value when wind speed is above the rated value because there are some power losses in the frequency converter and it will not reach to the rated output power. The response of the PMSG rotor speed is shown in Fig. 9 which ensures the variable speed operation of PMSG under different operating conditions. When rotor speed exceeds the nominal speed of PMSG, the blade pitch angle is controlled so that PMSG speed will not exceed the rated value as shown in Fig. 10. The increase of blade pitch angle will help to reduce the mechanical power extraction from wind turbine itself. The response of DC-link voltage is shown in Fig. 11. It is seen from that figure that the DC-link voltage variation is very small even though there is a wide wind speed fluctuation. The reactive power of the grid can be controlled by grid side inverter shown in Fig. 12, which consequently maintains the constant grid voltage, which was one of the objectives of the proposed fuzzy logic controlled inverter. The response of rms voltage at the high-tension side of the transformer is shown in Fig. 13. In the case of unity power factor operation by the grid side inverter the grid side voltage variation cannot be handled properly. From the dynamic analysis, it is seen that the FLC controlled inverter system can transfer maximum power to the grid maintaining constant voltage set by transmission system

operator (TSO) under randomly varying wind speed condition.

B. Transient Characteristic Analysis

To validate the effectiveness FLC controlled inverter the severe symmetrical three-line-to-ground fault (3LG) is considered as the network disturbance. The fault occurs at 0.1 sec, the circuit

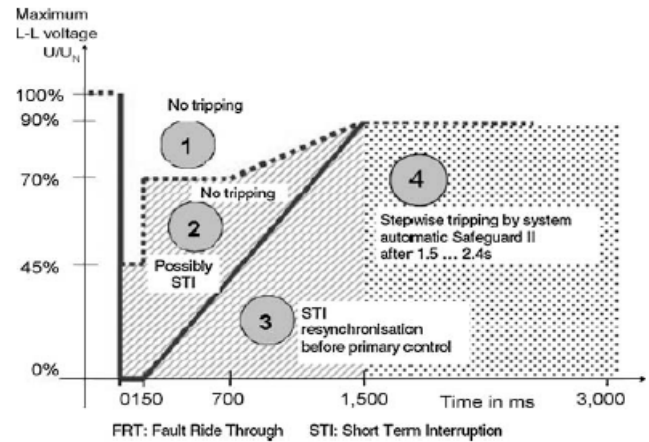


Fig. 14. Low voltage ride-through standard set by E.On Netz

breakers (CB) on the faulted lines are opened at 0.2 sec, and at 1.0 sec the circuit breakers are reclosed. In the simulation study, it is assumed that wind speed is constant and equivalent to the rated speed. This is because it may be considered that wind speed does not change dramatically during the short time interval of the simulation for the transient characteristic analysis. The transient performances of FLC controlled inverter is compared with that of cascaded controlled inverter system as reported in the previous study [15].

Wind farm grid code is fairly important to analyze the transient characteristics of WTGS. The wind farm grid codes are more or less similar. In this study, the simulation results are described in light of the recent grid code, set by E.On Netz. The fault ride-through (FRT) requirement is imposed on a wind power generator so that it remains stable and connected to the network during network faults. Disconnection from the grid may worsen a critical grid situation and can threaten the security standards when wind penetration is high. In Germany, wind generating plants are expected to acquit themselves during a low-voltage disturbance as summarized in a voltage versus time curve shown in Fig. 14. Wind turbines are required to stay on the grid within areas 1 and 2. [23-24].

Both the FLC and cascaded controlled grid side inverters can provide necessary reactive power during the network disturbance. Therefore, the terminal voltage can return to its pre-fault level as shown in Fig. 15 using both inverter systems. However, FLC offers low overvoltage, reduced oscillations, small steady state error compared to the cascaded controlled inverter. The PMSG rotor becomes stable in both cases as shown in Fig. 16, FLC controlled inverter helps quickly to reach the speed to the pre-fault level. The real power response of grid side inverter is shown in Fig. 17. FLC controlled

inverter gives low oscillations and better performance especially during the time of reclosing the circuit breaker. The DC-link voltage response of the frequency converter is shown in Fig. 18.

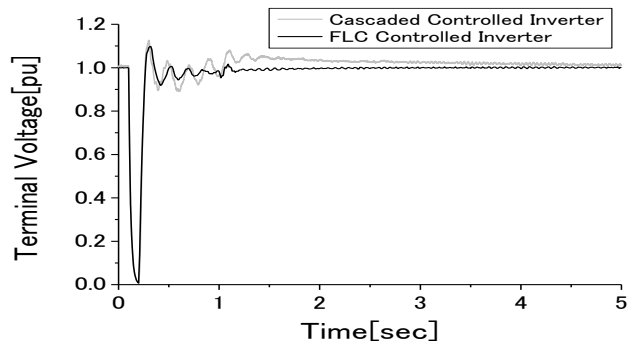


Fig. 15. Terminal voltage at the high voltage side of transformer

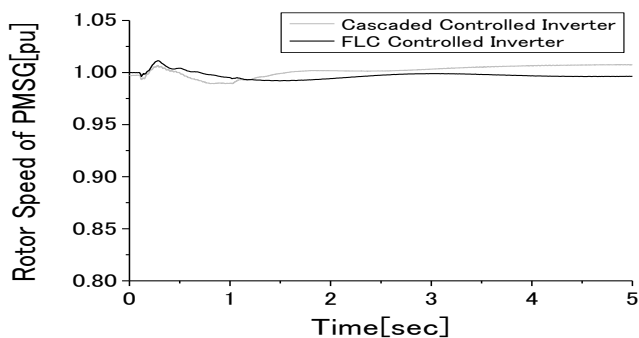


Fig. 16. Rotor speed of PMSG

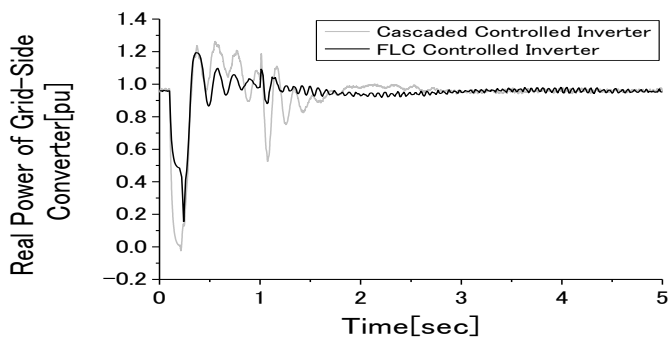


Fig. 17. Real power of the grid side inverter

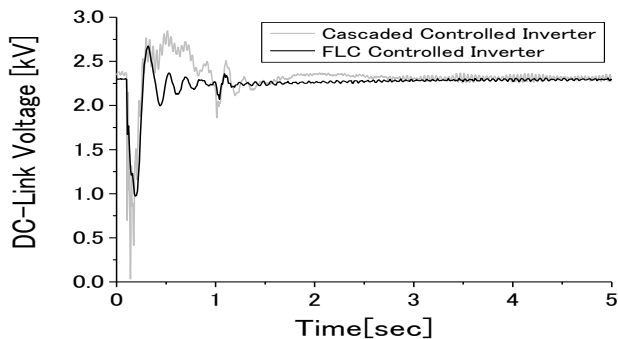


Fig. 18. Dc-link circuit voltage

It is noticeable that FLC controlled inverter gives much better response in the case of DC-link voltage and keep the voltage variation in acceptable range.

There exist different types of non-linearity and uncertainty in power system. The controllers used in power system applications should require to adopt with these non-linearities. It is found that FLC controlled inverter can deal the system non-linearity very well and gives better performance compared to conventional cascaded controlled inverter system where we have 4 PI controllers. The design of FLC controlled inverter is straightforward and cost might even be comparable.

The terminal voltage response indicates that the proposed system augments the LVRT capability of VSWT-PMSG during the severe 3LG fault and achieve the requirements of wind farm grid code. From Figs. 15-18, it is also found that FLC controlled inverter gives low oscillation, faster response, and can minimize the overshoot and steady state error compared to cascaded controlled inverter system.

VI. CONCLUSIONS

This paper presents a novel architecture for fuzzy logic controlled inverter system suitable for variable speed wind turbine driven PMSG. The inverter of the VSWT-PMSG has to withstand against network disturbance as well as normal operation. The FLC controlled inverter system can successfully handle those issues working in a wide operating range. The intricacy of the controller design can also be avoided. The performance of the overall system has been evaluated using both dynamic and transient analyses. The transient performance of the proposed control is compared with the well-known cascaded control. This control strategy is even suitable for other direct drive or one stage gearbox enabled wind turbine generator system for grid connectivity. Finally, it is concluded that the proposed FLC controlled inverter system might be a good choice for the application of grid connected wind turbine generator system.

VII. ACKNOWLEDGEMENT

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APPENDIX

Derivation of eq.(4) is as follows.

The grid side voltage phasor, \bar{V} , is synchronized with the controller reference frame by using the phase locked loop (PLL). Therefore, if we see from the controller side, then the angle of grid side voltage phasor seems to be zero. In that case, the following expressions can be made.

$$\bar{I} = \frac{V - (V_{cd} + jV_{cq})}{R + jX} \quad (A)$$

$$I_d = \frac{1}{R^2 + X^2} [R(V - V_{cd}) - XV_{cq}] \quad (B)$$

$$I_q = \frac{-1}{R^2 + X^2} [X(V - V_{cd}) + RV_{cq}] \quad (C)$$

$$P = \text{Re}(\overline{VI}^*) = VI_d \quad (D)$$

$$Q = \text{Im}(\overline{VI}^*) = -VI_q \quad (E)$$

From (D) and (E), the following relationship can be obtained.

$$\begin{cases} P \propto I_d \\ Q \propto -I_q \end{cases}$$

If $R \ll X$ (as a winding resistance of transformer is much smaller than the leakage reactance), then from (B) and (C), we can get the following relationship.

$$\begin{cases} I_d \propto -V_{cq} \\ I_q \propto V_{cd} \end{cases}$$

Finally,

$$\begin{cases} P \propto I_d \propto -V_{cq} \\ Q \propto -I_q \propto -V_{cd} \end{cases}$$

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