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Semiconductor Devices of Wind Power Converter and Its Control

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Abstract

For large power wind turbines, large-signal disturbance in wind power converter require a sufficiently large stability region around the quiescent values. The nonlinear and uncertain variations in power converter lead the control difficulty. In this paper, we will discuss the control strategy and 3 hierarchies in Power Electronic Building Blocks (PEBBs) after analyzing non-linear and uncertain variation of power semiconductor devices. A potential function based Lyapunov function will be introduced.

Keywords: Doubly fed induction generator, uncertainty, nonlinear, locally stable, global stability.

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1. Introduction

With the continuous increase in power rating of wind turbines, the turbines currently reach 6 MW in practice; with some prototype even already 10 MW. For a large-signal disturbance in wind power converter, it is desirable to have a sufficiently large stability region around the quiescent values. The traditional PI vector control could be only for a very small stability region. If the device sizes and the control strategy are not selected appropriately, a much shorter lifetime of power converter may be expected.

The nonlinear problems of power converter have been discussed for many years, Hamill and Jefferies (1988), Deame and Hamil (1990), Hamill *et al.* (1992), Deame(1992), Tse(1994), but their discuss focused on nonlinear phenomena and circuits of the converters. The switch loss and switch inductor model in semiconductor device nonlinearity is discussed in [1], [2]. Actually, the main power loss in semiconductor power devices is due to the conduction loss.

In comparison, power MOSFET has stable device parameter but the conduction loss is high at high voltage rating. IGBT that is closer to that of a BJT than a MOSFET possesses low conduction loss and a high breakdown voltage but the on-resistance parameter is an uncertain nonlinear variable that make the controls difficult. So using adaptive control of global stability instead of PID control of locally stable is becoming increasingly important.

2. Semiconductor Devices

A power converter, consisting of matrix of power semiconductor switched and one or several passive components, helps to convert and control electrical power from ac to dc, dc to dc, dc to ac, or ac to ac. Converter evolution essentially followed the device evolution. Of course, the debates among the application of semiconductor devices for wind power converter have never been stopped.

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2.1. Power MOSFET devices

US National Renewable Energy Laboratory (NREL) has designed a 1.5 MW wind turbine with the PM generator connected to the grid through a full-scale SiC MOSFET based converter as shown in Fig. 1.

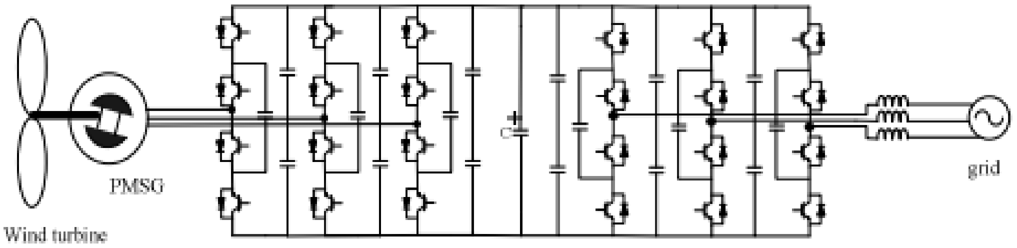


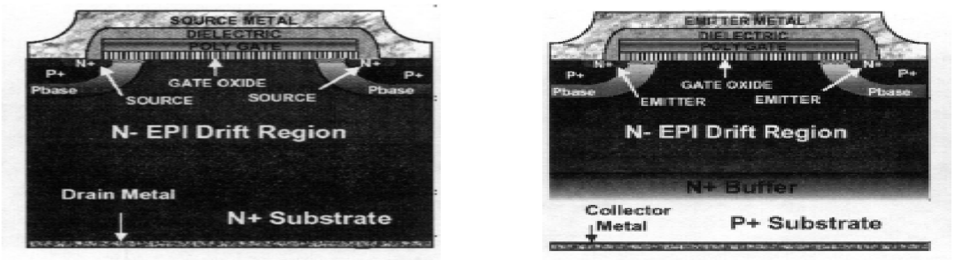
Fig. 1. 1.5 MW wind turbine with a full-scale SiC MOSFET based converter.

Because no SiC devices are available at this rating, the converter is assumed to be composed of 10 SiC-based converters rated at 150 kW. The power MOSFET based converter in wind turbine is a voltage-controlled device that requires only small input current. An averaging technique is employed to study the converter power loss [3]. The on-resistance of SiC MOSFET is calculated by

$$R_{on} = R_d\left(\frac{1}{8}+\frac{1}{3\pi}M\cos(\varphi)\right) \tag{1}$$

where M is modulation index, φ is phase angle and R_d is slope resistance. Because of the stable modulation index M, the on-resistance is almost constant for a wide range of input voltage in MOSFET. That leads low switching loss, more stability and controllability, but the conduction loss is high at high voltage rating. We future discuss a power law relationship between on-resistance and breakdown voltage that may help us to understand why so far the power MOSFET is only application in low-power high-frequency converters.

A traditional power MOSFET is shown in Fig. 2.



Power MOSFET IGBT

Fig. 2. Silicon high-voltage switching devices.

For the power MOSFET, the drift currents was driven by electrostatic field that has clear physics significance. The electrostatic field is irrotational field that is $\oint_l \vec{E}\cdot\overrightarrow{dl}$ and the divergence meets $\nabla\cdot\vec{E}=\rho/E$. The electrostatic field in the drift and body regions of these device structures satisfies electrostatic field Gauss's law

$$\nabla\cdot\vec{E}=\frac{q(Nd-Na+n-p)}{\varepsilon s} \tag{2}$$

Because the electric field in the drift region of the power MOSFET assumes to vary only along the drain-to-source direction (direction z of the coordinate system to be the vertical source-to-drain direction), the equation (2) becomes a one-dimensional first-order differential equation $dE_z/dz=qN_d/\varepsilon_s$ and its solution easily shown to be

$$\vec{E}(z) = \frac{qN_d}{\varepsilon_s}(z - z_p)\vec{Z} \tag{3}$$

and the potential can be calculated by integrating equation (2) as

$$V(z) = \frac{qN_d}{\varepsilon_s}(Z_p - \frac{Z^2}{2}) \tag{4}$$

The avalanche breakdown and on-resistance of the drift region can be calculated from (3) and (4). Eliminating the doping density of the drift layer, we obtain the equation that relates specific on-resistance of the drift layer to its avalanche breakdown voltage:

$$R_{on} = \frac{2A^{1/2}}{\mu_n \varepsilon_s} BV^{2.5} \tag{5}$$

Equation (5) shows that the specific on-resistance of the drift layer is proportional to the avalanche breakdown. It is considered as the silicon limit that leads very high conduction losses as the breakdown voltage becomes large. Theoretically, there is a limit to high voltage power MOSFET devices.

2.2. IGBT devices

Fig. 2 shows a typical insulated gate bipolar transistor (IGBT). It is similar to the power MOSFET in appearance but the operating is completely different from the power MOSFET. The N^+ buffer layer controls the amount of holes injected by P^+ collector, resulting in a conductive modulation effect instead of field modulation effect in MOSFET. IGBT combines the operating principles of the high impedance, like MOSFET and low conduction loss, like BJT and is typically used in high voltage. However, the performance of an IGBT is closer to that of a BJT than a MOSFET.

It is very important to understand that in the description of BJT current flow only diffusion-current components are considered. The drift currents due to thermally generated minority carriers are usually very small and can be neglected. The diffusion-current in BJT is a sharp contrast in physics meaning to the MOSFET where the drift-current is driven by electrostatic field. The diffusion equation can be expressed as

$$\nabla \cdot J_p = q\frac{\partial p}{\partial t} \tag{6}$$

where the hole current densities J_p is caused by hole diffusion motion $q\frac{\partial p}{\partial t}$. Non-equilibrium carriers due to semiconductor doping produce a concentration gradient and leads the diffusion motion rather than electrostatic charge moving driven by electrostatic field $\vec{E}$ like equation (2). The detail diffusion theory refers to transport theory and non-equilibrium statistics physics that are not the topic of discussion in this paper.

Using the same averaging technique, the conductive loss equation is shown as (7) for the IGBT [4].

$$P_{con} = I^2 R_{on} = I^2 R_d (\frac{1}{8} - \frac{1}{3\pi} M \cos\varphi) + IV(\frac{1}{2\pi} + \frac{M\cos\varphi}{8}) \tag{7}$$

where M is modulation index. For IGBT, the value of M is random variable. It is the diffusion motion in IGBT that leads the value of on-resistance changes with the current and temperature.

3. Control in Converter

The power electronic building blocks (PEBBs) standard that was made by US Navy is now widely accepted and adopted. The control software based on PEBB concept is divided into 3 hierarchies – system level control, application manager (AM), and Hardware manager(HM).

3.1. AM-HM Levels Control

According to the PEBB standard, the AM level implements the converter control algorithm and the HM level generates switch pulses. The interface of AM-HM levels translates PWM commands into switch PWM pulse related information.

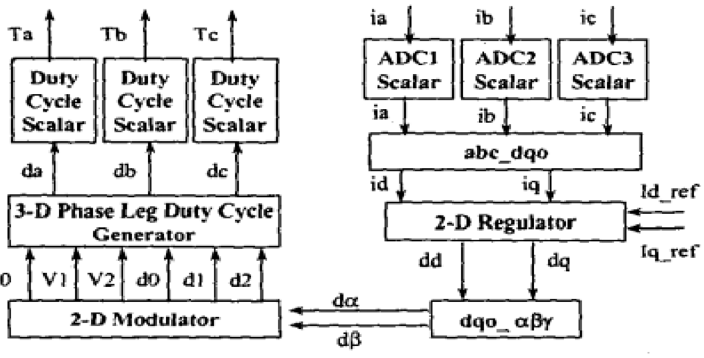


Fig.3. Control algorithm diagram of AM level

Fig.3. shows the control algorithm of AM level implemented by software objects for this three-phase DC-AC converter[5]. The object "Duty Cycle Scalar" transform duty cycle into clock ticks, which can be used directly by a specific HM to generate switching pulses. In this section, we will discuss the global stability and trading problems in AM level control.

3.1.1. Global stability control of converter

In general, traditional PI vector control of wind power converter is based on a linear small-signal mode of the controlled plant to design their performance in the frequency domain, as shown in Fig. 4.

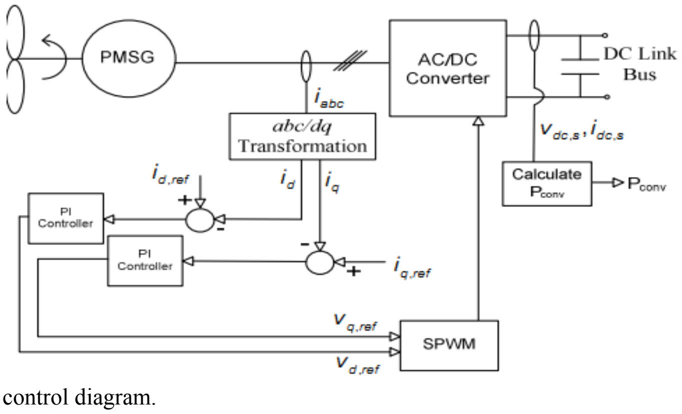
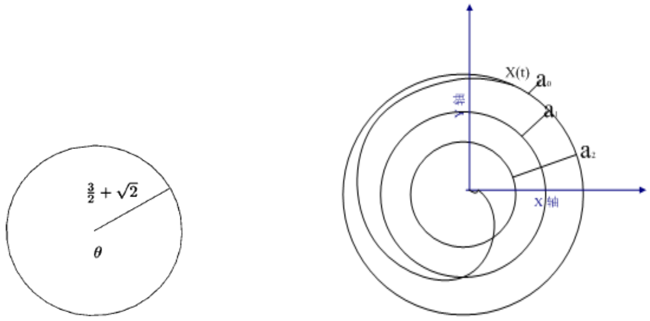


Fig.4. Generator-side converter control diagram.

When the linearized model is used for control design, the system will be locally stable and a particular feedback law will lead a very small stability region. The size of uncertainty is described by the Lipschitz constant. It is shown that if p and L satisfy the following relationship: $L+1/2 \ge \sqrt[(1+F)]{pl}\left(1+1/p\right),\ \ PL>1$ There will be a no globally stabilizing feedback for the corresponding class of uncertain systems. Lei Guo [6] have given an exactly limit of the feedback mechanism that is deal with that feedback is a ball with radius L=3/2 + $\sqrt{2}$, as shown in Fig. 5.

It has been shown that if the sampling period is larger than a certain value, then globally stabilizing sampled-data does not exist even if the nonlinearity has a linear growth rate. For a large-signal disturbance in wind power converter, it is desirable to have a sufficiently large stability region around the quiescent values, as shown in Fig. 5. If not, the wind turbine converter may get into trouble. It can be found that the converter lifetime of the DFIG wind turbine is less than one year when a wind speed is higher than 9 m/s [7].



(a) (b)

Fig. 5. Local stability and global stability: (a) limit of the feedback region and (b) stability region around the quiescent values.

Control of uncertain variation of power converter is an adaptive stochastic control problem. Adaptive control has the ability to deal with larger class of uncertainties via a Lyapunov function based on-line estimation. For the engineering purposes, an adaptive controller is embedded to the control loop to reach the object of the global stability control.

3.1.2. Tracking control of converter

It is appears that sensorless vector control of wind turbine generator is the clear trend of the future, but the converter nonlinear errors (conduction loss and dead time) introduce a distortion in estimated voltage that reduces the accuracy of the flux estimation. The error due to the converter nonlinear drops needs an adaptive compensation and the converter should track a reference signal varying within a reasonably large range.

Several types of power-electronic converter can be described as a switched system [8] and

$$\dot{x} = (DA_1 + (1–D)A_2)x + (DB_1 + (1–D)B_2)v, \quad y = Cx \tag{8}$$

where D is duty cycle and y is the output voltage or current. We consider a buck-boost converter and the matrices in (8) are given as follows:

$$A_1 = \begin{pmatrix} \frac{R_{on}+R_L}{L} & 0 \\ 0 & -\frac{1}{RC} \end{pmatrix}, \quad A_2 = \begin{pmatrix} -\frac{R_L}{L} & \frac{1}{L} \\ -\frac{1}{C} & -\frac{1}{RC} \end{pmatrix}, \quad B_1 = \begin{pmatrix} \frac{1}{L} & 0 \\ 0 & 0 \end{pmatrix}, \quad B_2 = \begin{pmatrix} 0 & -\frac{1}{L} \\ 0 & 0 \end{pmatrix}, \quad C = [0 \quad 1].$$

where R_{on} is on-resistance of IGBT. Suppose that a desired output for y is given as r and the tracking error $e := y - r$. Because of the uncertain variation of converter parameter, not all reference can be tracked. What we do is to find a stability region for an equilibrium point $X_a = \int y(t)dt$ is a constant. The stability region for the new equilibrium state can be easily converted to tracking region of the given reference output r, and future converted to the tracking domain for the reference $r + y_0$ of the original system output (8). In actual practice, we need to construct an adaptive controller connected in series to the feedback loop that compensates the nonlinear errors of the output automatically.

3.1.3. Lyapunov function

All of the problems about the global stability and the tracking performance boil down to find a Lyapunov function for the adaptive controller. Lyapunov stability methods in the control of reliability theory are actually an identification and lack of operability. In order to find a Lyapunov function, it will be considered a set of equilibrium points together with a switching strategy that makes the system globally asymptotically stable. We would like to introduce a potential function based Lyapunov function as follow.

The question is that are there any existence of time-dependent potential function for stochastic differential equations that used to describe the diffusion and drift behaviors in semiconductors? If the answer is yes, we are able to construct a global optimization potential function as global Lyapunov Function [9]. A global Lyapunov function can be defined as： Let $\psi: R^n \rightarrow R$ is a C^1 function. Then the ψ satisfying the following conditions is called a global Lyapunov functions :

(a) $\nabla \Psi(q^*) = 0$ for all q^*, where $\dot{q} = f(q^*) = 0$

(b) $\dot{\Psi}(q) = \frac{d\Psi}{dt}|q \le 0$ for all $q \in R^n$.

Corresponding to the energy function in physical science and Lyapunov function in control theory, the two fields strong associated with each other. The potential function $\Psi(q)$ is uniquely determined by a diffusion matrix and deterministic force.

3.2. System level control

The implementation of a real distributed intelligence in wind turbine is the development trend [10].The purpose of system level control for wind turbine power converter is suitable to the distributed control system architecture of wind turbines and to enable a kind of “Plug & work” in power converter. PEBB for high power converter used in electronic power transmission and distributed system have been started under the initiative of IEEE Working Group PAR 1767 [11].

The advance in ideas of distributed control for wind turbine should be the cheep computing, communication resources, minimum downtime and recovery of faulty devices of wind turbine. Autonomous recovery of application within the distributed control system has been implemented using the IEC 61499 reference model [12]. A universal controller has been designed that allows system designers to quickly create an implementation of control algorithms [13].

4. Conclusion

A comparison between MOSFET device and IGBT device has been presented. The diffusion-current in IGBT and drift-current in MOSFET are two absolutely different physical operating that can be given by diffusion equation and electrostatic field Gauss’s law. The nonlinear and uncertain variations in the power converter make it difficult to be controlled in a linear small stability region, so the adaptive control is naturally becoming important. A global optimization potential function for stochastic differential equations is introduced as global Lyapunov Function. The PEBB and distributed control idea was discussed briefly. It is expected that more stable wind power converters are used to the wind turbine market.

References

[1] Athalye P, Maksimovic D, Erickson R. Averaged switch modeling of active-clamped converters. In: *Proc. of IEEE Industrial Electronics Annual Conference*, 2001:1078-1083.

[2] Abid S, Ammous A. Average modeling of DC-DC and DC-AC converters including semiconductor device non-linearities. In: *Proc. of International Conference on Design and Test of Integrated Systems in Nanoscale Technology*, 2006:384-389.

[3] Ozpineci B, Tolbert LM, Islam SK, Hasanuzzaman M. Effects of silicon carbide (SiC) power devices on HEV PWM inverter losses. In: *Proc. of the 27th Annual Conference of the IEEE Industrial Electronics Society*, 2001:1061-1066.

[4] Bierhoff MH, Fuchs FW. Semiconductor losses in voltage source and current source IGBT converters based on analytical derivation. In: *Proc. of IEEE 35th Annual Power Electronics Specialists Conference*, 2004:2836-2842.

[5] Guo J, Celanovic I, Borojevic D. Distributed software architecture of PEBB based plug and play power electronics systems. In: *Proc. of the Sixteenth Annual IEEE Applied Power Electronics Conference and Exposition*, 2001:772-777.

[6] Zhang Y, Guo L. A limit to the capability of feedback. *IEEE Trans. on Automatic Control*, 2002; 47(4):687-692.

[7] Wei L; Kerkman RJ, Lukaszewski RA, Lu H, Yuan Z. Analysis of IGBT power cycling capabilities used in doubly fed induction generator wind power system. In: *Proc. of IEEE Energy Congress and Exposition*, 2010;3076–3083.

[8] Hu T. A nonlinear-system approach to analysis and design of power-electronic converters with saturation and bilinear terms. *IEEE Trans. on Power Electronics*, 2011; 26(2):399-410.

[9] Ao P. Potential in stochastic differential equations: novel construction. *J. Phys. A: Math., Gen.*, 2004; 37(3):L25-L30.

[10] Yang J, Fu X, Xue S. Distributed application control of wind turbines: system, algorithm, and programming. *Journal of Electronic Science and Technology*, 2013; to appear.

[11] Herold S. A practical assessment of the guide for control architecture for high power electronics used in electric power transmission and distribution systems. In: *Proc. of IEEE Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century*, 2008:1-4.

[12] Strasser T, Froschauer R. Autonomous application recovery in distributed intelligent automation and control systems. *IEEE Trans. on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, 2012; PP(99):1-17.

[13] Francis G, Burgos R, Wang F, Boroyevich D. A power electronics communication protocol for distributed digital control architectures. In: *Proc. of IEEE Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century*, 2008:1-8.