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Research on excitation control system of multi-functional flexible power conditioner

***Abstract**. A new kind of FACTS equipment, the multi-functional Flexible Power Conditioner (FPC), is proposed in this paper. The proposed equipment makes use of an advanced synchronous condenser and a flywheel with an AC excitation and vector control technology based power electronics device. It can perform multi-functions including energy storage, active and reactive power generation when used in power systems to enhance the stability of it. A 10kVA excitation control system of FPC was developed. Based on the analysis of control strategy, the start, steady and dynamic performances are studied experimentally. Experimental results show that soft start and various operation states can be implemented. And the excitation control system can be applied to flywheel type FPC system.*

***Streszczenie.** Zaproponowano nowy rodzaj urządzenia FACTS – wielofunkcyjny, elastyczny kondycjoner mocy FPC. Kondycjoner wykorzystuje koło zamachowe jako zasobnik energii. Urządzenie umożliwia magazynowanie energii, generację bierną lub czynną do poprawy stabilności systemu. Opracowano system sterowania o mocy 10 kVA. Start, ciągła praca i właściwości dynamiczne systemu były analizowane eksperymentalnie. (**Badania systemu sterowania wzbudzeniem w wielofunkcyjnym elastycznym kondycjonerze energii**)*

Keywords: Flexible power conditioner, Flywheel energy storage, DFIM, Vector control.
Słowa kluczowe: FACTS, koło zamachowe, magazynowanie energii.

Introduction

Flywheel energy storage system used for power supply improvement has attracted great attention in the recent years. Compared with the other energy storage system, the flywheel energy storage system has many advantages such as very high power density, long service time, insensitivity to environmental conditions and free maintenance. Double-fed induction machines (DFIM) is widely used in wind energy generation system, hydropower energy generation and pump station. A new FACTS device, the multi-functional Flexible Power Conditioner (FPC), which consists of a flywheel energy storage system based on DFIM, is proposed in this paper. [1]

Compared with the conventional "synchronous condenser" which is able to compensate the reactive power only, the proposed FPC is a more powerful device. The advantage of it is its capacity of controlling both active and reactive power. The FPC, showed in Figure 1, is made up of a doubly-fed induction machine (DFIM) connected with flywheel, a back-to-back converter for AC excitation and an excitation vector control system. The speed control of the DFIM makes it possible to achieve stable variable-speed operation. By adjusting the rotor speed, FPC can either release the electric power to the utility grid or absorb it from the utility grid. Similar to that of the superconductive magnetic energy storage (SMES), [2]-[5] FPC can improve the stability of power system and the quality of power supply. [6]

In order to realize the FPC multi-functions and implement the normal operation, the rotor-side converter of the DFIM uses power-control mode or speed-control mode respectively based on the stator flux oriented control. It is used to generate required double-fed excitation of the machine. The FPC DFIM can be considered as a doubly-fed induction generator without prime mover or a doubly-fed induction motor without mechanical load, thus it can be started when a little electromagnetic torque, which overcomes the friction, is addressed. This paper presents a novel control strategy of rotor-side converter, based on the stator flux oriented vector control, to diminish the impulsion to the equipment and power system when DFIM starts. Based on the analysis of control strategy of rotor-side converter, the start, steady and dynamic performances are studied experimentally. Experimental results show that soft start can be implemented and active/reactive power can be regulated independently.

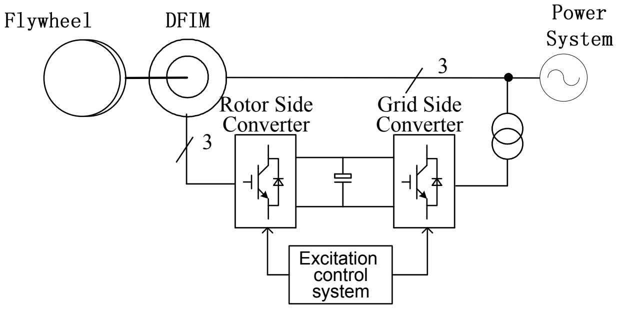

Fig.1 Structure of FPC system

Control strategy of rotor-side converter

A large number of papers describe the modeling of DFIGs [7]-[11]. Only the most important aspects of the modeling will be presented here. A reference frame is chosen to model the DFIG. The model of the induction machine is based on the fifth-order two-axis representation commonly known as the “Park model.” A synchronously rotating reference frame is used with the direct-axis oriented along the stator flux position. In this way, decoupled control between the electrical torque and the rotor excitation current is obtained. The reference frame is rotating with the same speed as the stator voltage. The generator conversion is used in the stator side of FPC DFIM. It means that the currents are outputs and that active power and reactive power have a positive sign when they are fed into the grid. Using the generator convention, the following set of equations results:

Flux linkage equation:

$$\begin{cases} \Psi_{ds} = -L_s i_{ds} + L_0 i_{dr} \\ \Psi_{qs} = -L_s i_{qs} + L_0 i_{qr} \\ \Psi_{dr} = -L_0 i_{ds} + L_r i_{dr} \\ \Psi_{qr} = -L_0 i_{qs} + L_r i_{qr} \end{cases} \tag{1}$$

Voltage equation:

$$\begin{cases} u_{ds} = -R_s i_{ds} + p\Psi_{ds} - \omega_1 \Psi_{qs} \\ u_{qs} = -R_s i_{qs} + p\Psi_{qs} + \omega_1 \Psi_{ds} \\ u_{dr} = R_r i_{dr} + p\Psi_{dr} - \omega_2 \Psi_{qr} \\ u_{qr} = R_r i_{qr} + p\Psi_{qr} + \omega_2 \Psi_{dr} \end{cases} \tag{2}$$

Electromagnetic torque equation:

$$T_{em} = n_p L_0 (i_{qs} i_{dr} - i_{ds} i_{qr}) \tag{3}$$

Rotor motion equation:

$$T_{em} = -\frac{1}{n_p}(D + Jp)\omega_r \tag{4}$$

Stator-side power equation:

$$\begin{cases} P_s = u_{ds} i_{ds} + u_{qs} i_{qs} \\ Q_s = u_{qs} i_{ds} - u_{ds} i_{qs} \end{cases} \tag{5}$$

With *R* being the resistance, *L* is the inductance, *u* is the voltage, *Ψ* is the flux linkage, *D* is the viscous friction coefficient, n_p is the number of pole pairs, *J* is the moment of inertia, ω_r is the rotor electrical angular velocity, *p* is the derivative operator, The subscripts *d* and *q* indicate the direct and quadrature axis components of the reference frame and *s* and *r* indicate stator and rotor quantities, respectively. All quantities above are functions of time. In order to simplify the model above, it is assumed that (a). Neglecting the influence of the stator flux linkage's transient state and orienting the d-axis of the synchronous frame to the direction of the stator flux vector. (b). omitting the stator resistance Rs. Equation (5) and (2) can be written as:

$$\begin{cases} P_s \approx U_{sm} \dfrac{L_0}{L_s} i_{qr} \\ Q_s \approx U_{sm} \dfrac{\omega_1 L_0 i_{dr} - U_{sm}}{\omega_1 L_s} \end{cases} \tag{6}$$

$$\begin{cases} u_{dr} = (R_r + \sigma L_r p) i_{dr} - \omega_2 \sigma L_r i_{qr} \\ \quad = u_{dr1} + \Delta u_{dr} \\ u_{qr} = (R_r + \sigma L_r p) i_{qr} + \omega_2 \sigma L_r i_{dr} + \omega_2 \dfrac{L_0}{L_s} \Psi_{sm} \\ \quad = u_{qr1} + \Delta u_{qr} + \Delta u \end{cases} \tag{7}$$

With $\sigma = 1 - L_o^2 / L_s L_r$ being leakage reactance factor, ω_1 is the stator electrical angular velocity, ω_2 is the slip electrical angular velocity, Δu_{dr} and Δu_{qr} are the decoupled compensations, u_{dr1} and u_{qr1} are the decoupled elements, Δu is the feed-forward element.

Based on equation (3) and (4), it can be deduced to:

$$\omega_r = -\frac{L_0 n_p^2 U_s i_{qr} / L_s \omega_1}{D + Jp} \tag{8}$$

Equation (6), (7) and (8) form the two modes control system of FPC DFIM, which is showed on Figure 2. θ_s is the electrical angle of stator flux, θ_r is the electrical angle of rotor position, θ_{slip} is the slip electrical angle and θ^*_r is the reference angle of rotor voltage.

Fig.2 shows the stator flux-oriented vector control strategy of the FPC DFIM exciter under two mode controls. The controllers used in the current inner loop, the power outer loop and the speed outer loop are designed with typical PI controllers to achieve the excellent static and dynamic performance.

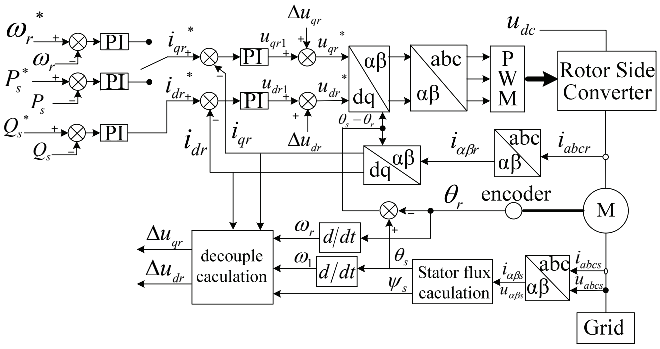

Fig.2 Block diagram of stator flux-oriented excitation control strategy

Key issues of FPC

Two key issues need to be considered during the operation of FPC. The first issue is that it is important to switch the control mode to achieve operation states. The second issue is how to start the FPC DFIM without impulsion to the FPC and power system.

A. Operation state of FPC

Based on the multi-functions of FPC including active and reactive power exchanging from the utility grid the FPC DFIM has three operation states including active power control, reactive power control and speed of flywheel control.

The power system fault will cause unbalanced power, which is the error of the active power the generator sends out and that the power system consumes for the moment. In order to compensate the unbalanced power, FPC exchanges the electric power from the utility grid with the flywheel speed descending or rising.

In order to fully utilize the capacity of the machine and the converter to enhance the system stability and phase regulation ability, FPC doesn't compensate active and reactive power to the system at the same time. So, FPC is namely a conventional "synchronous-speed rotary condenser" capable of only reactive-power control while in phase regulation state. FPC DFIM using speed-control mode to keep the flywheel speed constant and absorbs a little electric energy to compensate various losses reactive-power control.

Except for the two operation state for realizing the FPC multi-functions mentioned hereinbefore, the FPC DFIM has two other states, the speed limitation and floating charge. Considering the limit of the flywheel speed and the converter capacity, there are upper and lower limit of the flywheel speed. Whether at the maximal speed or at minimal speed, FPC DFIM is at speed limitation state without the ability to compensate unbalanced power temporarily. Because the unbalanced power which FPC compensates to the utility grid could be either positive or negative, speed of flywheel keeping a constant between the maximal and minimal speed is ready for release or absorb active power. This state is called floating charge state.

To realize the FPC multi-functions and implement the normal operation, it needs to switch the control mode from one to another. The control system switches the power-mode control to the speed-mode control, when the flywheel speed reaches the maximal or the minimal limit while FPC is compensating the unbalanced power, or when FPC returns to the floating charge state to prepare for the next compensating task after implement one. And the control system exits speed-mode control to the power-mode control, when FPC needs to compensate the unbalanced when power system fault happens. To realize the control mode switch, the control system mutually switches between speed outer loop and power outer loop. The limit of reference value for the current inner loop under speed-mode control is different from that under power-mode control. The output limit of the power outer loop is determined by the converter capacity which decides the maximal power the FPC can compensate to the system. In order not to make an impulse to the system and to regulate the flywheel speed fast, the output limit of speed outer loop is the maximal current that FPC can contain from the utility grid when it operates normally.

B. Start strategy of FPC DFIM

The FPC DFIM can be considered as a doubly-fed induction generator without prime mover or a doubly-fed induction motor without mechanical load, thus it can be started when a little electromagnetic torque, which overcomes the friction, is addressed. This start process, in which the FPC DFIM is started from the static only by AC excitation without any device switching, is called direct-start.

Before the start of the FPC DFIM, the stator is connected to the grid. At this moment when the FPC DFIM is static, the FPC DFIM can be treated as a transformer. Thus, the frequency and phase of the rotor electromotive force is the same as the grid, while the ratio of its amplitude and the grid's is the same as that of stator and rotor. Only when the difference between the voltage of the rotor-side of back-to-back converters and the rotor electromotive force is little, the rotor-side of back-to-back converters could be connected to the rotor windings, or else, a large impulse current, which can damage the machine and the back-to-back converters, may be generated. And the starting process of rotor-side converter is as follows:

(1) The DC-link voltage is offered by the grid-side of back-to-back converters.

(2) The rotor is open and the stator is connected to the grid. Make sure the rotor electromotive force is lower than DC voltage, in order that FPC DFIG starts in sub-synchronous state.

(3) Make some proper value to limit the value of error and output of controller. Phase-locked control works before the rotor-side converter start, make sure the output voltage of rotor-side converter and rotor electromotive force are at the same phase. At the beginning of start, the amplitude of the output voltage of rotor-side converter is due to $\omega_2(L_0/L_s)\Psi_{sm}$ in (7). Therefore, the error between the two voltages of the rotor-side of back-to-back converters and the rotor is so little that nearly no impulse current generates.

(4) When the speed is near the demand, the input error of speed controller is smaller than the limit, so the output of it would be it no longer. Now the speed loop plays a major role to keep the speed stable, and the starting process of FPC DFIM is over.

Experimental results

An experimental system, showed in Figure.1, is constructed for testing this control strategy. And the picture of experimental device of FPC including DFIM, flywheel and the back-to-back converters is shown in Figure.3. TMS320F240 DSP-based digital control platform is designed and employed for implementing the proposed control strategy. Parameters of the FPC DFIM are given in Table 1.

Table 1. Characteristics of DFIM

Machine Characteristic	Value
Rating active power (kw)	10
Mutual inductance (H)	0.2978
Stator inductance (H)	0.3063
Rotor inductance (H)	0.3011
Stator resistance (Ω)	1.4132
Rotor resistance (Ω)	0.3122
Number of pole pair	3
Inertia (kg·m^2)	18.992
Stator voltage (V)	800

Figure.3 Experimental device of FPC

Figure 4 shows the speed of the flywheel, phase current of rotor, line voltage of rotor and active power of stator when FPC starts.

The speed of flywheel rises linearly from 0 to 1100r/min, it means that DFIM is form Sub-synchronous state to Super-synchronous state. The speed of flywheel smoothly becomes stable without any overshoot at the end of the start process. At the point of the cut-in time, the rotor voltages have no sudden change, thus the rotor currents have little impulsion. And then they change smoothly, and the frequency of them changes obviously when the state changes form sub-synchronous to super-synchronous. Meanwhile, the active power of stator is positive value, when the speed of flywheel rises, which means that DFIM absorbs the energy from the utility grid. When the speed of flywheel stops to rise, the active power of stator has small positive value in order to compensating various losses to keep the rotor speed stable.

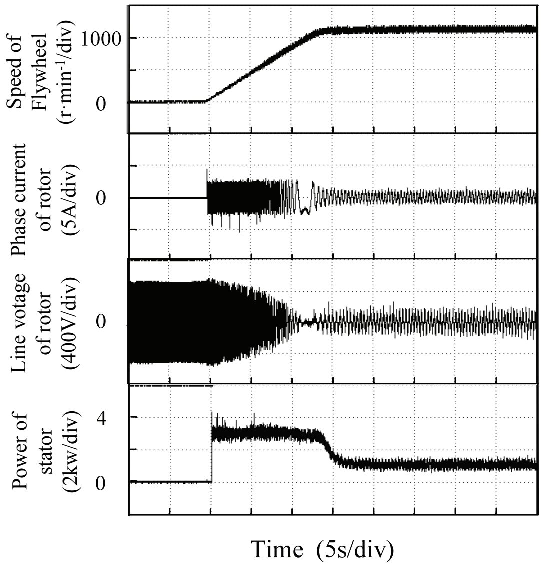

Figure.4 Experimental results of FPC start

Fig.5 shows the speed of the flywheel and stator active power in various operation states. The excitation control system adopts the speed-mode control when the speed of the flywheel is the floating charging speed 1100r/min, minimal speed 300r/min or maximal speed 1300r/min. And when DFIM operates at the active power generation state or the energy storage state, it adopts the power-mode control with the power reference value 6kW or -6kW.

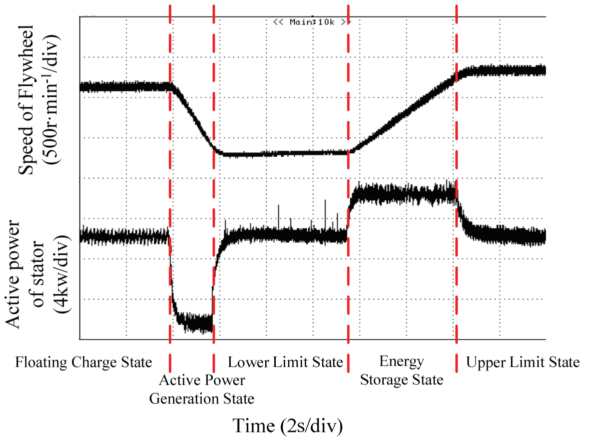

Fig.5 Speed and active power of FPC in various operation states

Conclusion

This paper investigates a new energy storage system based on flywheel, called the multi-functional flexible power conditioner to improve the stability of power system. Base on a third-order model of FPC DFIM, this paper puts forward the excitation control strategy of FPC DFIM. Direct-start strategy for FPC and operation state of FPC are discussed in detail. To verify the proposed control strategy, experimental research is done on a 10kVA experimental device. Experimental result shows that start without impulsion and various operation states can be implemented.

Acknowledgments

The Project Supported by The National Basic Research Program of P.R.China (973 Program) (2009CB219701);
National Natural Science Foundation of P.R.China (50937002);
Power Electronics Science and Education Development Program of Delta Environmental & Educational Foundation.（DREG2009004）

REFERENCES

[1] Gang Li; Shijie Cheng; Jinyu Wen; Yuan Pan; Jia Ma; , "Power system stability enhancement by a double-fed induction machine with a flywheel energy storage system," Power Engineering Society General Meeting, 2006. IEEE

[2] Jing Shi; Yuejin Tang; Yusheng Zhou; Jinglin Chen; Dehong Xu; Huiling Wang; Yafeng Lu; Li Ren; Bin Wei; Jingdong Li; Shijie Cheng; , "Development of a Conduction-Cooled HTS SMES," Applied Superconductivity, IEEE Transactions on , vol.17, no.3, pp.3846-3852, Sept. 2007

[3] Jing Shi; Yuejin Tang; Zhi Li; Li Ren; Jingdong Li; Shijie Cheng; , "Temperature Characteristic of a Conduction-Cooled HTS SMES Magnet," Applied Superconductivity, IEEE Transactions on , vol.19, no.3, pp.2044-2047, June 2009

[4] Jing Shi; Yuejin Tang; Li Ren; Jingdong Li; Shijie Cheng; , "Discretization-Based Decoupled State-Feedback Control for Current Source Power Conditioning System of SMES," Power Delivery, IEEE Transactions on , vol.23, no.4, pp.2097-2104, Oct. 2008

[5] Jing Shi; Yuejin Tang; Kai Yang; Lei Chen; Li Ren; Jingdong Li; Shijie Cheng; , "SMES Based Dynamic Voltage Restorer for Voltage Fluctuations Compensation," Applied Superconductivity, IEEE Transactions on , vol.20, no.3, pp.1360-1364, June 2010

[6] Gang Li; Jing Zhang; Shijie Cheng; Jinyu Wen; Yuan Pan; , "State Space Formulation and Stability Analysis of a Doubly-fed Induction Machine with a Flywheel Energy Storage System," Power System Technology, 2006. PowerCon 2006. International Conference on , pp.1-6, 22-26 Oct. 2006

[7] A. Petersson, Analysis, modeling and control of doubly-fed induction generators for wind turbines, Chalmers Univ., Göteborg, Sweden, 2003.

[8] R. Pena, J. C. Clare, and G. M. Asher, “Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation,” Proc. Inst. Elect. Eng., Electr. Power Appl., vol. 143, no. 3, pp. 231–241, May 1996.

[9] J. Morren, S. W. H. de Haan, and P. Bauer, “Comparison of complete and reduced models of a wind turbine with doubly-fed induction generator,” in Proc. 10th Eur. Conf. Power Electronics Applications, Toulouse, France, Sep. 2003.

[10] V. Akhmatov, “Modeling of variable-speed wind turbines with doubly-fed induction generators in short-term stability investigations,” in Proc. 3rd Int. Workshop Transmission Networks for Offshore Wind Farms, Stockholm, Sweden, Apr. 11–12, 2002, pp. 1–23.

[11] G. Abad, J. Lopez, M. Rodriguez, L. Marroyo, G. Iwanski: Doubly Fed Induction Machine. Modeling and Control for Wind Energy Generation Application, J. Wiley - IEEE Press, 2011, 320 pg.

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