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# Flexible Power Conditioner based on Flywheel Energy Storage

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## Introduction

The power imbalance caused by power system fault may result in the power system instability. The energy storage system is a simple way to compensate the unbalanced power and enhance the system stability. In comparison 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. Flexible power conditioner (FPC) based on flywheel energy storage, which can enhance the stability of power system, is one of the novel FACTS equipment. It performs multi-functions including energy storage, active and reactive power generation when used in power systems [1–3]. With such characters, it can considerably stabilize the power system and forestall those faults of power system when the imbalance of active and reactive power happens. This method is called active stabilization. The equipment with the proposed configuration also can be used in other applications [4–7].

The FPC, showed in Fig. 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. DFIM is widely used in wind energy generation system, hydropower energy generation and pump station. The attractiveness of DFIM stems primarily from its ability to handle large speed variations around the synchronous speed and the excitation converter between the rotor winding and the grid handles only a fraction of the total power to achieve the full control of the system. So the application of DFIM makes big sense to FPC which used in the power system. The FPC DFIM can be regarded as a doubly-fed induction generator without prime mover or a doubly-fed induction motor without mechanical load, so the control method and application technology of DFIM proposed in literature is also suitable for FPC DFIM [8–12].

This paper focuses on the control strategy to realize the multi-functions of FPC and the experimental research on a 10kVA device. It is organized as follows. Based on the multi-functions and operation characteristics of FPC, Section II firstly brings forward five operation state of FPC including energy storage, active power generation, reactive power generation, speed limitation and floating charge. A stator flux-oriented vector control strategy combined power-mode control with speed-mode control is put forward in Section III. In Section IV, the control strategy of grid side converter is shown. To verify the control strategy and the switch control technology at different operation state, experimental research is done on a 10kVA device. Satisfactory characteristics in power regulation and dynamic response are obtained in Section V.

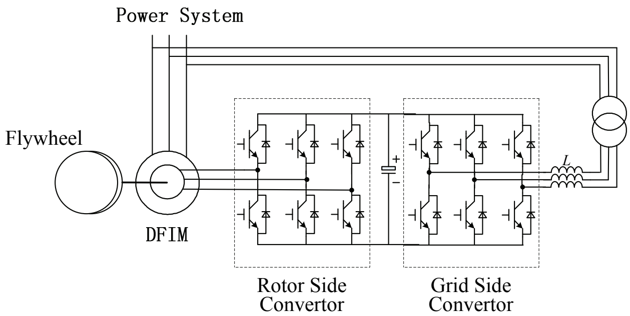



**Fig. 1.** Structure of FPC system

## Operation State of FPC

Based on the multi-functions of FPC including energy storage, active and reactive power generation, the FPC DFIM has three operation states including energy storage, active power generation and reactive power generation.

*A. Energy storage and Active Power Generation State.* The 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 runs at two operation state, the energy storage and active power generation, alternately for the short period of time. At the active power generation state, the FPC DFIM releases the electric power to the utility grid with the flywheel speed descending. At the energy storage state, the FPC DFIM absorbs the electric power from the utility grid with the flywheel speed rising.

*B. Reactive Power Generation State.* In order to fully utilize the capacity of the machine and the converter to enhance the system stability and phase regulation ability, the FPC DFIM 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 keeps the flywheel speed constant and absorbs a little electric energy to compensate various losses.

Except for the three operation state for realizing the FPC multi-functions mentioned hereinbefore, the FPC DFIM has two other states, the speed limitation and floating charge.

*C. Speed Limitation State.* Considering the limit of the flywheel speed and the converter capacity, the flywheel speed will keep rising till the maximal speed when FPC DFIM absorbs the active power from the grid. And the flywheel speed will keep descending till the minimal speed when FPC DFIM releases the active power to the grid. Whether at the maximal speed or at minimal speed, FPC DFIM is at speed limitation state without the ability to compensate unbalanced power temporarily.

*D. Floating Charge State.* To balance the ability to absorb and release active power, FPC is at floating charge state at the mean time because the unbalanced power which FPC compensates to the utility grid could be either positive or negative. That is to say, at the floating charge state, the flywheel speed is keeping a constant between the maximal and minimal speed, usually bigger than the synchronous speed.

Whether in speed limitation state or floating charge state, FPC DFIM is controlled at a certain speed.

**Control strategy of rotor side converter**

From the discussion of section II, FPC DFIM needs to efficiently control the active and reactive power at whichever state it is. The control system of FPC DFIM has to be designed for two modes: power control mode and speed control mode.

The modeling of FPC DFIM can be referred to the DFIM's [3, 8–9]. A synchronously rotating d-q reference frame is used with the d-axis oriented along the stator flux position. The generator conversion is used in the stator side of FPC DFIM, and the motor conversion, which is on the contrary, is used in the rotor side. All these conversions are power invariance coordinate conversions. The mathematical model of the FPC DFIM is given below. Flux linkage equation:

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

Electromagnetic torque equation

$$T_{em} = n_p L_0 (i_{qs} i_{dr} - i_{ds} i_{qr}). \tag{2}$$

Voltage equations:

$$\begin{cases} u_{ds} = -R_s i_{ds} + p\Psi_{ds} - \omega_1 \Psi_{qs}, \\ u_{qs} = -R_s i_{qs} + p\Psi_{qs} + \omega_1 \Psi_{ds}, \\ u_{dr} = R_r i_{dr} + p\Psi_{dr} - \omega_2 \Psi_{qr}, \\ u_{qr} = R_r i_{qr} + p\Psi_{qr} + \omega_2 \Psi_{dr}. \end{cases} \tag{3}$$

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, $\Psi$ is the flux linkage, $D$ is the viscous friction coefficient, $n_p$ is the number of pole pairs, $J$ is the moment of inertia, $\omega_1$ is the grid angular velocity, $\omega_2$ is the slip electrical angular velocity, $\omega_r$ is the rotor electrical angular velocity, $p$ is the derivative operator, $T_{em}$ is the mechanical torque. 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 $R_s$. Equation (5) and (3) 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, $\omega_1$ is the stator electrical angular velocity, $\Delta u_{dr}$ and $\Delta u_{qr}$ are the decoupled compensations, $u_{dr1}$ and $u_{qr1}$ are the decoupled elements, $\Delta u$ is the feed-forward element.

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

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

(6), (7) and (8) form the two modes control system of FPC DFIM, which is showed on Fig. 2. $\theta_s$ is the electrical angle of stator flux, $\theta_r$ is the electrical angle of rotor position, $\theta_{slip}$ is the slip electrical angle and $\theta^*_r$ 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.

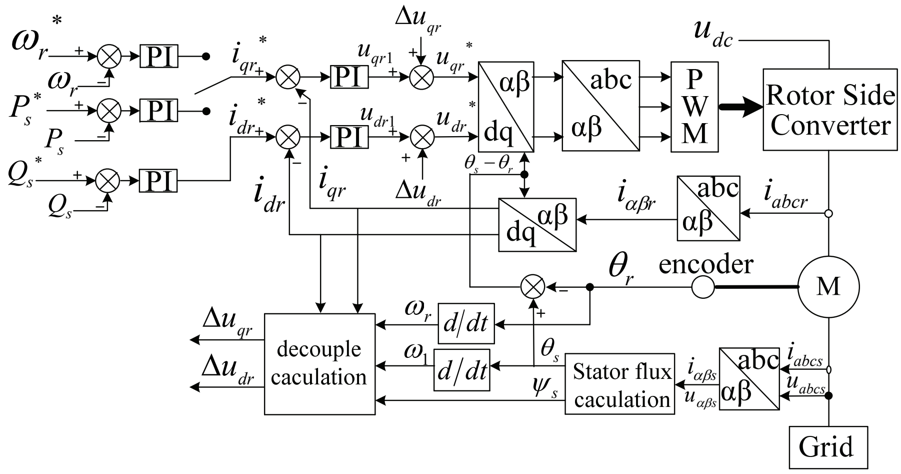


**Fig. 2.** Block diagram of stator flux-oriented excitation control strategy

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.

**Control strategy of grid side converter**

The aim of the grid side converter is to keep the DC-link voltage constant regardless of the magnitude and direction of the rotor power. A vector-control method is used, with a synchronously rotating d-q reference frame oriented along the grid voltage vector position, enabling independent control of the active and reactive power flowing between the grid and the grid side converter. The converter is current regulated, with the d-axis current used to regulate the DC-link voltage and the q-axis current component used to regulate the reactive power [9]. Fig. 3 shows the schematic of the grid side converter. The mathematical model of the grid side converter is showed below:

$$\begin{cases} v_d = -Lpi_d - Ri_d + \omega_1 Li_q + u_d, \\ v_q = -Lpi_q - Ri_q + \omega_1 Li_d + u_q, \\ C \cdot pU_{dc} = i_{dc} - i_L. \end{cases} \tag{9}$$

With R being the resistance, $L$ is the inductance, $u$ is the grid voltage, $v$ is the input voltage of converter, $p$ is the derivative operator, $\omega_1$ is the synchronous electrical angular velocity, $d$ and $q$ indicate the direct and quadrature axis components of the reference frame, and $U_{dc}$ is the DC-link voltage.

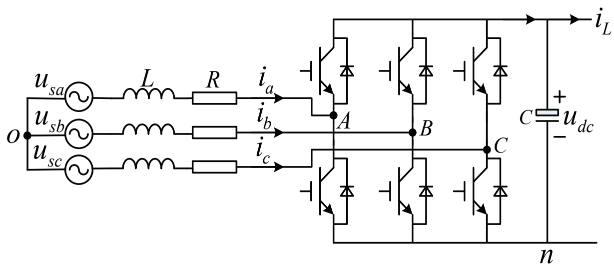


**Fig. 3.** Grid side converter of back-to-back converters

The power equations are:

$$\begin{cases} P = u_d i_d + u_q i_q = u_d i_d = U_{dc} i_L, \\ Q = u_q i_d - u_d i_q = -u_d i_q. \end{cases} \tag{10}$$

(9), (10) construct the voltage control system of the grid side converter, as shown in Fig. 4. In this system, 3s/2s represents the conversion from the abc reference frame to the α-β reference frame, 2r/2s, 2s/2r represent the mutual conversion between the d-q reference frame and the α-β reference frame, K/P represents the calculation process of the magnitude and angle of the input vector.

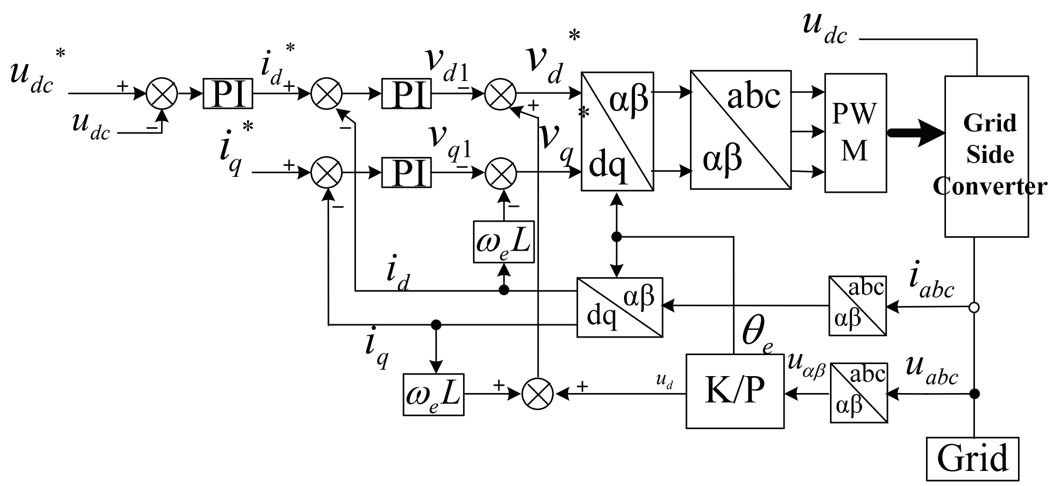



**Fig. 4.** Voltage control system of the grid side converter

**Experimental results**

An experimental system, showed in Fig. 1, is constructed for testing this control strategy. The picture of experimental device including DFIM, flywheel and the back-to-back converters is shown in Fig. 5. TMS320F240 DSP-based digital control platform is designed and employed for implementing the proposed control strategy. The grid-side converter employed the control strategy mentioned at the section IV, and the rotor-side converter uses the one proposed in section III. The demand capacity is 10 kVA, the demand DC-link voltage is 600 V and the demand speed is 970 r/min. Parameters of the FPC DFIM are given in Table I.

**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 |

**Fig. 5.** Experimental device with a DFIM, flywheel and back-to-back converters

In Fig. 6–Fig. 8 are shown the experiment results of implementing the multi-functions including energy storage and active power generation.

Fig. 6 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 1100 r/min, it means that DFIM is from sub-synchronous state to super-synchronous state. Phase current and line voltage of rotor change smoothly, and the frequency of them change 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.

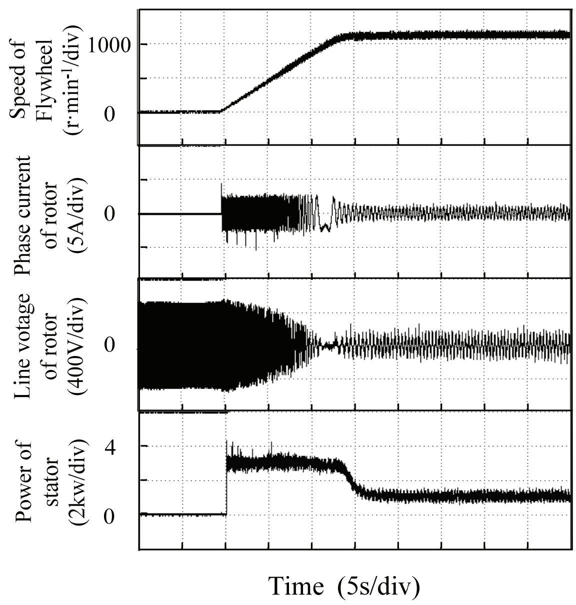



**Fig.. 6**. Experimental results of FPC start

Fig. 7 shows the speed of the flywheel and stator active power Ps. 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.

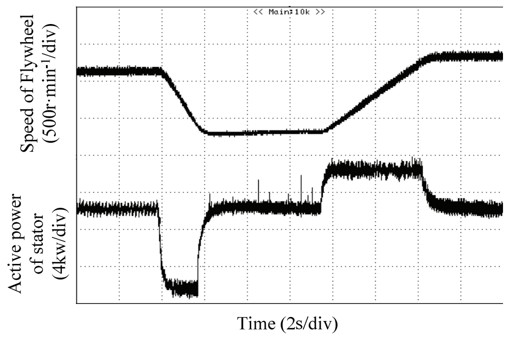
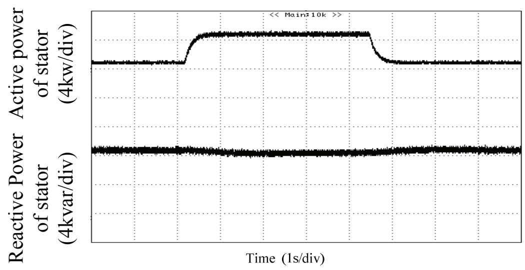
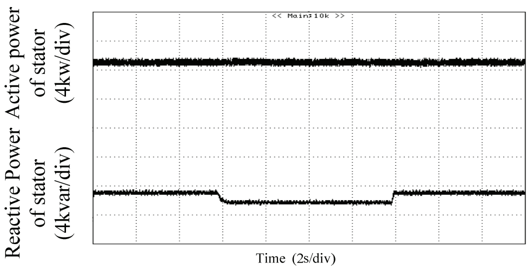



**Fig. 7.** Variety of speed and active power of FPC

Fig. 8 shows active power of stator $P_s$ and reactive power of stator $Q_s$, it adopts the power-mode control. Fig.8 (a) and (b) show the active power of stator and reactive power of stator are controlled respectively and have a quick response. They prove the decouple control of the active power and reactive power.




a)




b)

**Fig. 8.** Experiment results of FPC in power-mode control: a – variance of active power; b – variance of reactive power

Fig. 9 is the experiment results of grid side converter during the whole start process.

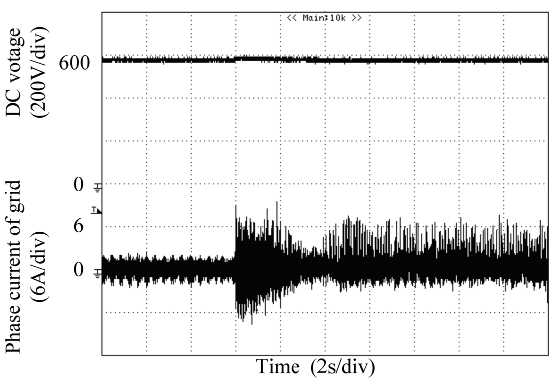



**Fig. 9.** DC-link voltage and phase current of grid of the supply-side converter

The system is started in the following step. Firstly, the grid side converter is started to form and stable the DC-link voltage. And secondly, the rotor side converters start at the moment of 6s. Then, the flywheel is accelerated to 1100r/min. During the whole start process, the DC-link voltage is kept well, and the phase current of grid is also showed in Fig. 9.

## Conclusions

A new Energy Storage System based on flywheel, called the multi-functional Flexible Power Conditioner (FPC), is proposed in this paper. The FPC makes use of an advanced synchronous condenser with a flywheel together with an AC excitation and vector control technology based power electronics device. It can quickly and smoothly regulate exchange of an active and reactive power with the grid. Therefore, it can enhance power system stability by compensating the unbalanced power. Base on a third-order model of FPC DFIM, this paper puts forward the excitation control strategy of FPC DFIM. Voltage control system of the grid side converter is designed. To verify the proposed control strategy, experimental research was carried out on a 10kVA experimental device. The multi-functions of FPC are implemented with satisfactory characteristics.


## Acknowledgements

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## References


1. **Yang H., Wen J. Y., Li G.** Investigation on operation characteristics of multi–functional flexible power conditioner // Proceedings of the CSEE. – Chinese Society of Electrical Engineering, 2006. – No. 2. – P. 19–24.
2. **Li G., Wen J. Y., Cheng S. J.** Investigation on start and cut–in of the multi–function flexible power conditioners // Proceeding of Automation of Electric Power Systems. – Automation of Electric Power Systems Press, 2006. – No. 3. – P. 17–22.
3. **Wu J. B., Wen J. Y., Sun H. S.** A new energy storage system based on flywheel // Power & Energy Society General Meeting, 2009. – Calgary, Canada, 2009. – P. 1–6.
4. **Fujita H., Akagi H., Tan M., Ogasawara S.** Occurrence and suppression of DC–flux deviations in a doubly–fed flywheel generator system // IEEE 38th Industry Application Conference. – Salt Lake City, USA, 2003. – P. 1766–1771.
5. **Akagi H., Sato H.** Control and performance of a doubly–fed induction machine intended for a flywheel energy storage system // IEEE Transactions on Power Electronics, 2002. – No. 1. – P. 109–116.
6. **Akagi H., Sato H.** Control and performance of a flywheel energy storage system based on a doubly–fed induction generator–motor for power conditioning // IEEE 30th Power Electronics Specialists Conference. – Charleston, SC, USA, 1999. – Vol. 1. – P. 32–39.
7. **Zhang J. C., Chen Z. Y., Cai L. J., Zhao Y. H.** Flywheel energy storage system design for distribution network // IEEE

Power Engineering Society Winter Meeting. – Singapore, 2000. – Vol. 4. – P. 2619–2623.
8. **Tapia A., Tapia G., Ostolaza J. X., Sanenz J. R.** Modeling and control of a wind turbine driven doubly fed induction generator // IEEE Transactions On Energy Conversion, 2003. – Vol. 18. – No. 2. – P. 194–204.
9. **Park J. W., Lee K. W., Lee H. J.** Control of active power in a doubly–fed induction generator taking into account the rotor side apparent power // IEEE 35th Power Electronics Specialists Conference. – Aachen, Germany, 2004. – Vol. 3 – P. 2060–2064.
10. **Pena R., Clare J. C., Asher G. M.** Doubly fed induction generator using back–to–back PWM converters and its application to variable–speed wind–energy generation // Electric Power Applications, IEEE Proceedings, 1996. – Vol. 143. – No. 3. – P. 231–241.
11. **Datta R., Ranganathan V. T.** A method of tracking the peak power points for a variable speed wind energy conversion system // IEEE Trans. Energy Conversion, 2003. – Vol. 18. – No. 1. – P. 163–168.
12. **Yifan T., Longya X.** Vector control and fuzzy logic control o f doubly fed variable speed drives with DSP implementation / / IEEE Trans. Energy Conversion, 1995. – Vol. 10. – No. 4. – P. 661–668.

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According to the situation that the power system can only defense the fault passively, a new FACTS device, which is called flexible power conditioner (FPC), based on flywheel energy storage system is proposed.. This device, which employed new technologies such as AC excitation, VSCF and vector control, combines the flywheel energy storage with the traditional phase synchronization technology. FPC can modulate phase, store and generate energy, which can stabilize power system actively. The control strategy and method of FPC is discussed. A 10kVA excitation control system of FPC was developed. Experiment results reflect that this device can quickly and enormously modulate the active power and reactive power in four-quadrant, which makes power system stability possible. Ill. 9, bibl. 12, tabl. 1 (in English; abstracts in English and Lithuanian).

**Zhongwei Chen, Xudong Zou, Shanxu Duan, Huarong Wei. Lankstus galios kondicionierius, kurio veikimas pagrįstas energijos kaupimu smagratyje // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 9(115). – P. 3–8.**

Kadangi energetikos sistemos nuo gedimų gali būti apsaugotos tik pasyviai, pasiūlytas naujas FACTS įtaisas, dar vadinamas lanksčiuoju galios kondicionieriumi (LGK), kurio veikimas pagrįstas energijos kaupimu naudojant smagratį. Šio įtaiso veikimas remiasi naujomis technologijomis, tokiomis kaip kintamosios srovės sužadinimas, VSCF ir vektorinis valdymas, energija kaupiama naudojant smagratį ir tradicinę fazių sinchronizavimo technologiją. Galios kondicionierius gali moduliuoti fazę, kaupti ir generuoti energiją, o tai įgalina aktyviai stabilizuoti energetikos sistemą. Aptarta valdymo strategija ir metodas. Sukurta 10 kVA LGK sužadinimo valdymo sistema. Eksperimento rezultatai rodo, kad šis įtaisas gali keturiuose kvadrantuose greitai moduliuoti aktyviąją ir reaktyviąją galias, leidžiančias stabilizuoti energetinę sistemą. Il. 9, bibl. 12, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).