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POWER SYSTEM STABILIZATION BY A DOUBLE-FED INDUCTION MACHINE WITH A FLYWHEEL ENERGY STORAGE SYSTEM

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ABSTRACT

This paper proposed a new idea of using a large-mass varying-speed flywheel as an energy storage element to form a novel FACTS device called multi-functional Flexible Power Conditioner (FPC). The novel device consists of a double-fed induction machine (DFIM) and a voltage-source pulse width modulation (PWM) rectifier-inverter used as an AC exciter. By changing the speed of the rotating machine, the kinetic energy stored in the rotor with the flywheel will be changed. With an appropriate control strategy, it is able to realize an independent active and reactive power exchanging between the FPC and the grid. Similar to that of the Superconducting Magnetic Energy Storage (SMES), the FPC can be used to improve the stability of power system as well as the quality of power supply. Additional advantage of the FPC over the SMES based device is that it is easy to develop and to operate. Therefore, the cost will be greatly reduced. In order to increase performance of the proposed device, an improved stator flux linkage orientated control strategy for FPC is proposed in the paper. Simulation result of applying the proposed device in a two-machine and an infinite bus system shows that the proposed control provides excellent dynamic characteristics. Very encouraging results are obtained.

Keywords: *AC excitation, flywheel energy storage, vector control, stator flux linkage orientation, stability control*

1. INTRODUCTION

Double-fed induction machines (DFIM) have been employed widely in many large wind farms and pumped storage generating systems with the development of recent power electronics technologies [1]. [•] Flywheel energy storage system used for power supply improvement has also attracted attention in the recent years [2]. 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.

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Compared with the conventional "synchronous speed condenser" which is only capable to control reactive power, the FPC proposed in this paper can also be referred to as an "adjustable speed condenser". The advantage of it is its capacity of controlling both active and reactive power. The rotor windings of a FPC are exited by three-phase low-frequency AC currents with a voltage-fed PWM rectifier-inverter. The rotor position feedback control of the AC excitation current 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 [2]. Similar to that of the superconductive magnetic energy storage (SMES), FPC can improve the stability of power system and the quality of power supply.

In order to decouple the control of the active and the reactive power, the inverter (rotor-side converter) of the DFIM uses the stator flux oriented control (SFOC). It is used to generate required double-fed excitation of the machine. The rectifier (grid-side converter) is used to supply the energy for the excitation. Therefore a grid voltage oriented control (GVOC) is used. The rectifier is usually controlled to maintain a constant DC bus voltage as well as a unity power factor.

As the main objective of the FPC proposed in this paper is to damp out system oscillations and to sustain the voltage of the power system connected after disturbances, the capability of it to maintain system stability and to respond rapidly to the disturbances of the power system are important. This paper proposed an improved SFOC strategy, which can give excellent dynamic performance and considerably enhance the stability of power system. Additional advantage of the proposed SFOC is that it easy to realize in the practice.

2. CONFIGURATION AND MODEL OF THE FPC

System configuration of the proposed FPC is given in Fig. 1. Its model has been discussed in the detail in the literature about DFIMs [3–6]. In the following discussion, a generator convention shown in Fig.1 is used for the variables.

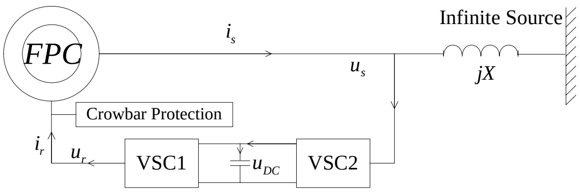


Fig. 1 Basic configuration of a FPC

The DFIM can be modeled by the following equations in the direct (d) and quadrature (q) axis reference frame, which is rotating at synchronous speed ($\omega_1 = 2\pi f_1$):

Stator voltage and rotor voltage:

$$\begin{cases} u_{sd} = -R_s i_{sd} - p\psi_{sd} + \omega_1 \psi_{sq} \\ u_{sq} = -R_s i_{sq} - p\psi_{sq} - \omega_1 \psi_{sd} \\ u_{rd} = R_r i_{rd} + p\psi_{rd} - \omega_s \psi_{rq} \\ u_{rq} = R_r i_{rq} + p\psi_{rq} + \omega_s \psi_{rd} \end{cases} \tag{1}$$

Stator flux and rotor flux:

$$\begin{cases} \psi_{sd} = L_s i_{sd} - L_m i_{rd} \\ \psi_{sq} = L_s i_{sq} - L_m i_{rq} \end{cases} \begin{cases} \psi_{rd} = L_r i_{rd} - L_m i_{sd} \\ \psi_{rq} = L_r i_{rq} - L_m i_{sq} \end{cases} \tag{2}$$

Rotor swing equation:

$$T_m - T_e = -T_e = \frac{J}{n_p}\frac{d\omega_r}{dt} + \frac{D}{n_p}\omega_r \tag{3}$$

Stator power:

$$P_s = u_{sd} i_{sd} + u_{sq} i_{sq} \quad Q_s = u_{sq} i_{sd} - u_{sd} i_{sq} \tag{4}$$

where u is the voltage, i is the current, R is the resistance, L is the reactance, ψ is the flux linkage, ω_1 and ω_r are the stator and rotor electrical angular speed respectively. d and q indicate the direct and quadrature axis components under the rotation synchronizing reference frame. s, r and m indicate the stator, rotor and mutual quantities respectively. D represents the damping torque coefficient which is proportional to the rotor angular speed. n_p and J are the number of pole-pairs and the rotor inertia respectively. The mechanical torque T_m is zero.

3. CONTROL STRATEGY

In order to save the space of this paper, control of the rectifier (the VSC2 shown in Fig. 1) will not be discussed. It is assumed that the voltage

u_{DC} is constant and the rectifier doesn't exchange the reactive power with the power grid. Therefore, the control strategy for the inverter (VSC1 shown in Fig. 1) is discussed only in the paper.

As shown in Fig. 2, the SFOC orients the direct axis of the synchronous reference frame along the stator flux position and the qudrature axis is 90° ahead of the direct axis [7–9]. Since the values of R_s are small, the stator flux is mainly determined by the stator voltage, which is assumed to be constant. This implies that the derivative of the stator flux is close to zero and can be neglected. Then, equations for the flux and the voltage of the stator can be written as follow with ψ_{sm} and U_{sm} representing the magnitude of the stator flux and voltage respectively.

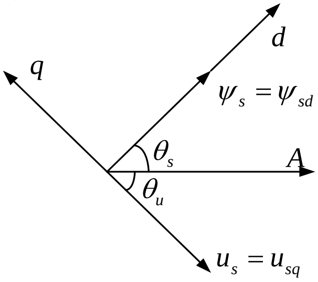


Fig. 2 Stator flux linkage orientation

$$\begin{cases} \psi_{sd} = \psi_{sm} \\ \psi_{sq} = 0 \end{cases} \tag{5}$$

$$\begin{cases} u_{sd} = 0 \\ u_{sq} = -\omega_1 \psi_{sm} = -U_{sm} \end{cases} \tag{6}$$

In this way, a decoupled control for the electrical torque and the rotor excitation current can be obtained. Consequently, control for the active and the reactive power are also decoupled by controlling the q- and d-axis components of the rotor current respectively. The relationship of the stator power, the rotor current and the voltage are given in Eqns.(7) – (9).

$$\begin{cases} P_s = -U_{sm} i_{sq} \\ Q_s = -U_{sm} i_{sd} \end{cases} \tag{7}$$

$$\begin{cases} i_{rd} = \dfrac{-\psi_{sm} + L_s i_{sd}}{L_m} \\ i_{rq} = \dfrac{L_s i_{sq}}{L_m} \end{cases} \tag{8}$$

$$\begin{cases} u_{rd} = \left(R_r + bp\right) i_{rd} - b\omega_s i_{rq} = u_{rd}' + \Delta u_{rd} \\ u_{rq} = \left(R_r + bp\right) i_{rq} - a\omega_s \psi_{sm} + b\omega_s i_{rd} = u_{rq}' + \Delta u_{rq} \end{cases} \tag{9}$$

with $a = \dfrac{L_m}{L_s}$, $b = L_r \left(1 - \dfrac{L_m^{\ 2}}{L_s L_r}\right)$.

Based on the Eqns. (7) – (9), the control system can be designed in a cascade form, which is composed of two composed with two loops, an inner current loop and an outer power loop. Control systems are shown in Fig. 3 and Fig. 4.

Because a small amount of real power flow exists between the rotor windings and the grid, the real power flow is compensated in P_{ref}. Besides, delivering more or less reactive power to the grid will increase or decrease the terminal voltage. So the reactive power control can be replaced by the terminal voltage control.

The traditional SFOC assumes that the terminal voltage is constant. Therefore, equations (5) and (6) are always satisfied. The stator flux vector ψ_s will be 90° ahead of the stator voltage u_s, as shown in Fig. 2. And the stator flux angle θ_s is calculated with the stator voltage angle θ_u. However, the terminal voltage isn't constant in practical cases. For example, the variation of power flow, the disturbances of the grid and the power adjusting of the machine itself will lead to the fluctuation of the terminal voltage. Equations (5) and (6) are no longer satisfied for the reason that the stator flux derivative cannot be completely neglected. This will worsen the performance of SFOC and possibly result in an unstable control system.

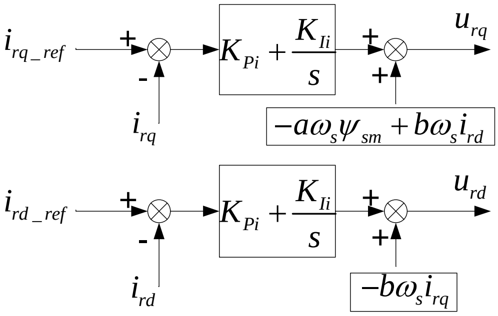


Fig. 3 Rotor current controller

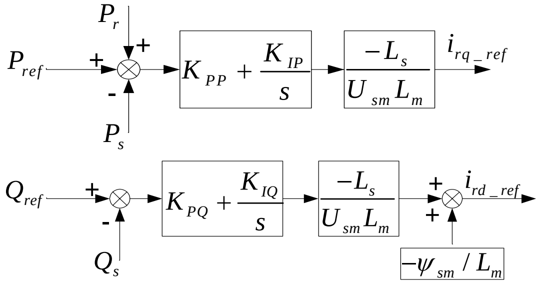


Fig. 4 Power controller

As accurate measurement and computation of the stator flux are difficult, the direct constant stator flux control may be difficult to realize. However, the stator flux can be controlled indirectly by controlling the stator voltage. As has been discussed, the stator flux will be constant and the performance of the SFOC will be excellent as long as the following conditions are satisfied:

$$u_{sd}=0 \quad \text{(a)} \qquad u_{sq}=-U_{sm} \quad \text{(b)} \qquad (10)$$

The condition (10.b) is satisfied by the direct feedback control of u_{sq} as shown in Fig. 5, in which the reactive power control is replaced by the stator voltage of *q* axis control, The exciting current i_{rd} is calculated directly according to Δu_{sq}.

Satisfying $u_{sd}=0$ (10.a) requires a direct control of i_{rq}. However, i_{rq} is the torque component decided by the real power controller. A possible solution is to compensate the i_{rq_ref} by Δu_{sd}, as shown in Fig. 6.

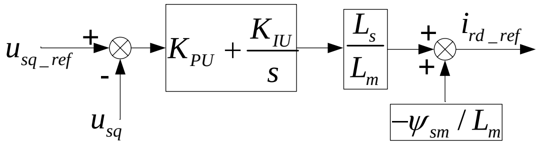


Fig. 5 Stator voltage of q axis controller

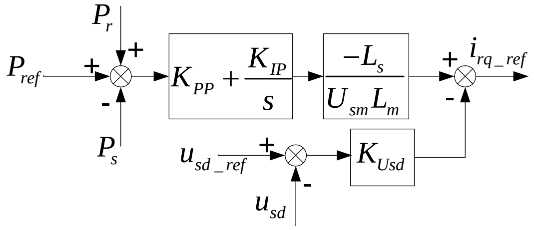


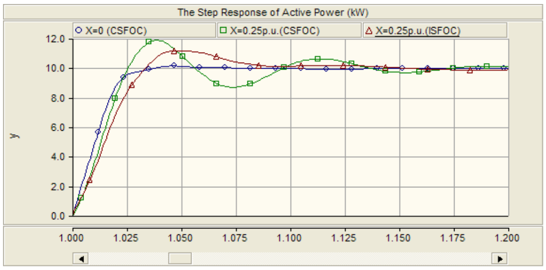
Fig. 6 Active power controller

In the control system, the gain K_{Usd} should be selected properly. A high value of K_{Usd} helps in powerfully compensating the dynamics of u_{sd}, but results in an influenced real power conditioning and a slower power response. For this reason, it is necessary to make a tradeoff between the excellent dynamic performance of the real power conditioning and a constant stator flux keeping.

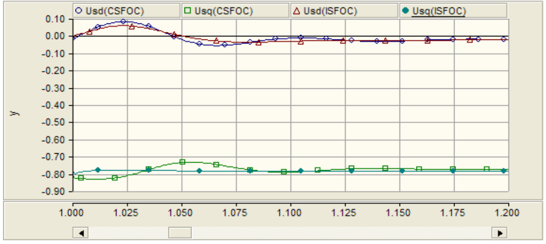
It is necessary to point out that the stator RMS (root mean square) voltage (U_s) control is different from the u_{sd}-u_{sq} control mentioned above. The U_s control keeps the stator RMS voltage at the given value; but u_{sd} and u_{sq} change respectively. Thus the accurate stator flux orientation cannot be obtained.

To investigate the effectiveness of the improved SFOC (ISFOC) over the conventional SFOC (CSFOC), the performance of a FPC with different SFOCs is simulated using EMTDC/PSCAD. A 10kW machine connected with an infinite bus power system with the parameters given in the appendix is used. The system for simulation is the same as shown in Fig.1. Simulation results show that when X 0, the performances with two control strategies are excellent. However, When X 0.25 p.u., it can be seen from Fig. 7(a) that the performance with the CSFOC is worse than that with the ISFOC. The obvious oscillation can be seen if the CSFOC is used and the controlled system is nearly unstable. Moreover, researches indicate that if the CSFOC is used, further increasing of X and changing of the machine parameters or the operation condition may result in an unstable system. However, in all these cases, with the ISFOC, the controlled system is always kept stable.

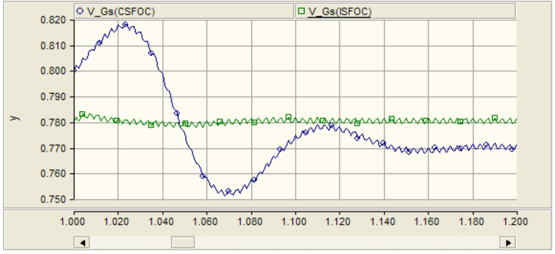
Fig. 7(b) shows fluctuations of u_{sd} and u_{sq} in the ISFOC system are smaller than those in the CSFOC system when a step change occurs in the output active power of the FPC. In addition, Figs.7(c) and 7(d) show that the stator RMS voltage and the stator flux are kept constant basically with the ISFOC being used. However, these variables fluctuate greatly if the CSFOC is used. It can be concluded that the ISFOC has the capability to realize constant stator flux control and the accurate stator flux orientation.



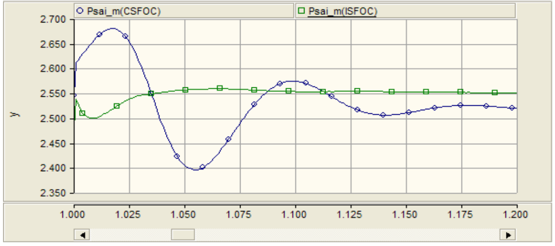
(a) The active power step response



(b) Stator voltages of d axis and q axis



(c) Stator terminal voltages



(d) Stator flux linkage

Fig. 7 Simulation results of the CSFOC and the ISFOC

4. POWER SYSTEM TRANSIENT STABILITY ENHANCEMENT BY FPC

Similar to a synchronous condenser, a FPC can sustain the grid voltage and increase the synchronous torque of generators. Further more, the FPC can compensate the unbalanced energy and increase the damping torque of generators. In [10] the author proposes the power system stabilization by synchronous condenser with fast excitation control. By regulating the kinetic energy of the rotor, the synchronous condenser is able to adjust the real power thus enhancing the system damp. However compared with FPC, the conditioning ability of a synchronous condenser is limited.

The basic model for a stability analysis of a power system with FPC is represented by a two-machine and an infinite bus system composed of a synchronous generator and a FPC [11], as shown in Fig.8. For this system if a large disturbance occurs, the unbalanced power produced by the disturbance may introduce an oscillation of the system or even result in an unstable system. However, if the unbalanced power is compensated by the FPC, the stability of the system will be enhanced.

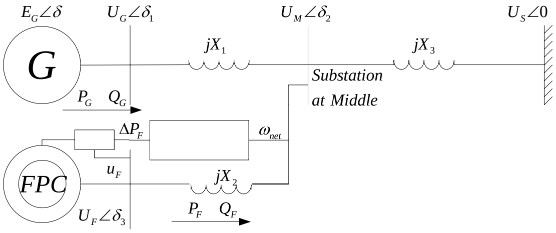


Fig. 8 Two-machine and an infinite bus system

In order to realize a control of the FPC, feedback signals corresponding to the system swing or oscillations are necessary to detect and to measure for FPC. A first order washout circuit (the stabilizing control) shown in Fig. 9 is used to obtain such signal. The input of the washout circuit, ω_{net} (p.u.), can be considered as the signal associated with the unbalanced real power.

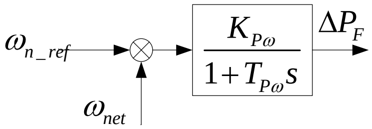


Fig. 9 Stabilizing controller

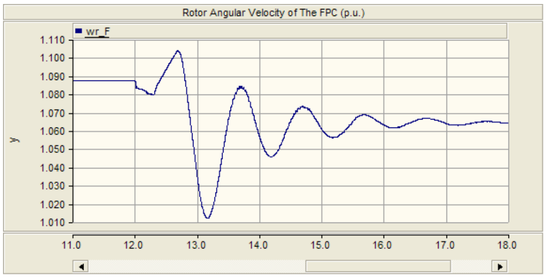
Parameters of the system are given in Table. 1. Parameters of the FPC are obtained from [2]. The generator operates with a standard AC1A exciter with no PSS. The system initial operating point is: U_G 1.1p.u., P_G 0.81p.u., Q_G 0.4p.u.; U_F 1.0p.u., P_F 0p.u.,

Q_F 0p.u.. Other parameters include: $K_{P\omega}$ 210 $T_{P\omega}$ 0.02

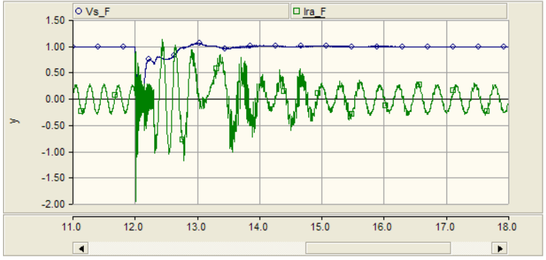
In the system of Fig. 8, a 130ms three-phase to ground fault at the intermediate bus occurs at 12s by a successful fault clearance. System responses with and without the FPC are shown in Fig. 10. It can be seen from Fig. 10 that the generator loses its stability without the FPC, whereas, it keeps stable if the FPC is used. It can be seen from Fig. 10(a) that the rotation speed of machine in FPC changes to cope with the oscillation of the generator unit after the fault, which indicates the energy interchange between the FPC and the connected power system. It is this power exchange that balanced the unbalanced power caused by the fault, which may results in instability of the power system.

TABLE I.parameters of the system

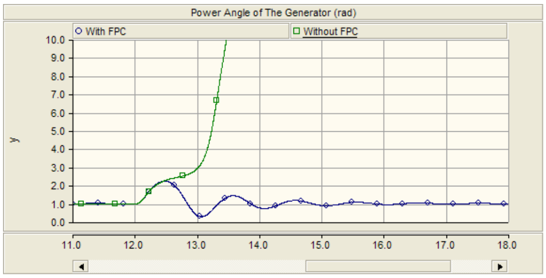
Synchronous Generator (160MVA base)		
Tj=3.3s	Xd=1.014p.u.	Xd'= 0.314p.u.
Xd''=0.28p.u.	Xq 0.77p.u.	Xq''= 0.375p.u.
Td0'= 6.55s	Td''= 0.039s	Tq''= 0.071s
FPC (70MVA base)		
Tj=3.4s	Rs= 0.0013 p.u.	Rr= 0.0013 p.u.
Xs=2.9p.u.	Xr=2.9p.u.	Xm=2.6p.u.
Line and transformer(160MVA base)		
X1=0.33p.u.	X2 0.24p.u.	X3= 0.52p.u.



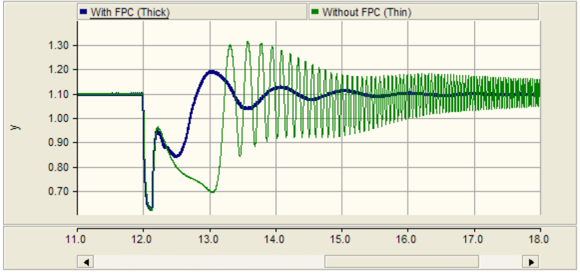
(a) Rotor angular velocity of the FPC



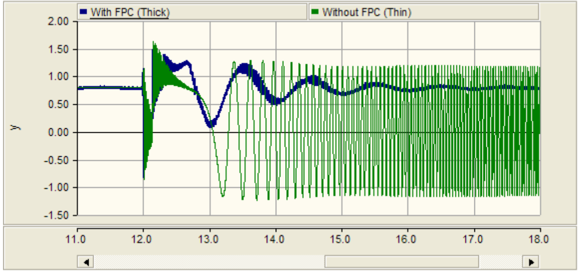
(b) Stator terminal voltage and rotor current of phase A of the FPC



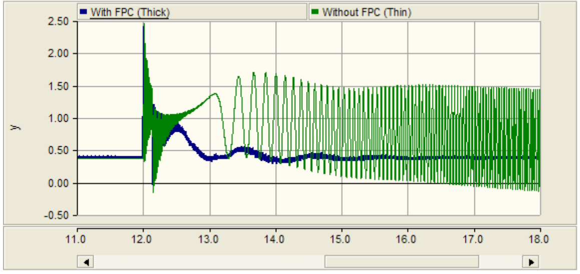
(c) Power angle of the generator



(d) Terminal RMS voltage of the generator



(e) Active power of the generator



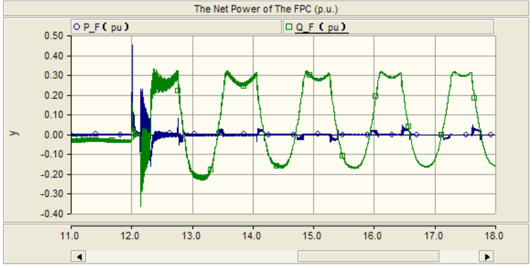
(f) Reactive power of the generator

Fig. 10 Power System Stabilization by FPC

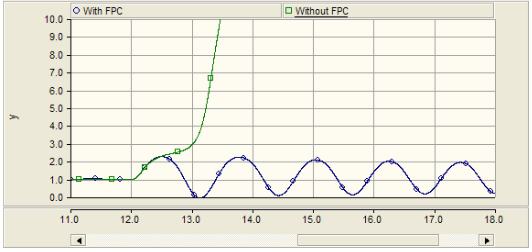
It can be seen in Fig. 10(a) that the FPC rotary speed changes a little during stability control although its rotary inertia is 45% of the generator inertia. However, the simulation shows that the peak power of the FPC approach its rated value during the first swing of the generator. If the rated power capacity of the FPC is reduced, the system oscillation time will prolong and the first swing amplitude of the generator power angle will increase. It can be concluded that there is no especial requirement for the large capacity of the flywheel energy storage system intended for stabilizing power systems. Only the power capacity of the system has dominant and direct effect on the stability control performance. It is expected, of course, to enlarge the flywheel rotary inertia and the energy storage if the economic and technological conditions permit. A flywheel of larger inertia has a smaller rotary-speed variation for the same kinetic energy variation. So the large inertia FPC can keep a small slip, which can reduce the capacity and cost of the converters.

As the FPC proposed in this paper can also work as a synchronous condenser, its performance in providing the reactive power support is investigated. Fig.11 shows that if the FPC operates as a synchronous condenser, there will be not active power control for FPC. As a result, both the FPC and the generator oscillate continually and eventually the generator will lose its stabilities.

The voltage dip due to the short-circuit fault causes serious over-current in stator and rotor windings of the DFIM, which may lead to the protection acting of converters and a tripping of the FPC. In order to make the FPC stay connected to the grid during the grid fault and resume normal operation after clearance of the fault, special control has to be applied. The key is to limit the high rotor currents by the fast and direct current-control in the rotor-side converter. The details are discussed in another paper.



(a) The total power generated by the FPC



(b) Power angle of the generator

Fig. 11 FPC operates as a synchronous condenser

This paper proposed a new kind of FACTS device, FPC. A double-fed induction machine with a flywheel energy storage system together with an improved vector excitation control strategy based on the stator flux linkage orientation are used to form the device. The control strategy and the dynamic performance of the FPC are investigated in the paper. In order to enhance the performance of the FPC, an improved SFOC is proposed. The performance of the improved SFOC is verified by simulation. Compared with the conventional synchronous condenser and other FACTS equipments, FPC has the advantage of realizing both the reactive and active power control. Simulation results on a two-machine infinite bus power system show the effectiveness of the FPC. With the help of the FPC, power system stabilities are greatly improved.

APPENDIX

A. 10kW FPC Parameters (Stator Equivalent Circuit)

P_N=10kW, U_{sN}=800V, J=19kg.m², f_1=50Hz,
R_s=1.5818Ω, R_r=1.4797Ω,
L_s=0.3225H, , L_r=0.3279H, L_m=0.3139H,
Stator / Rotor Turns Ratio: k=3.647

B. Control parameters for the 10kW FPC

K_{Pi}=1.5, K_{Ii}=79.5, $K_{PP} = K_{PQ}$=1.5, $K_{IP} = K_{IQ}$=100, K_{PU}=0.9, K_{IU}=50, K_{Usd}=0.105

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