IECON2015-Yokohama
November 9-12, 2015

Control Strategy of Solid State Power Electronic Transformer under Voltage Disturbance Conditions

Jianhua Wang [1], Binshi Gu[1], Qing Duan[2], Chunyan Ma[2],
1 Jiangsu Provincial Key Laboratory of Smart Grid Technology & Equipment, School of Electrical Engineering
Southeast University, Nanjing, China
Email: wangjianhua@seu.edu.cn

Baojian Ji[3], Jun You[2]
2 China Electric Power Research Institute & Beijing Key Laboratory of Distribution Transformer Energy-saving Technology, Beijing, China
3 College of Automation and Electrical Engineering
Nanjing Tech University, Nanjing, China

***Abstract*—Solid State Power electronic transformer (PET) is an emerging new type of power converter in recent years. It has not only the basic functions of power transformation and isolation, but also the extra functions of power quality control. This paper presents the key control strategies of solid state PET for electrical distribution system application, especially under voltage disturbance conditions. Several critical grid voltage disturbances are generated by a disturbance voltage source based on a three phase PWM inverter. And the solid state PET prototype is tested and passed voltage disturbance ride through function. The experimental results verify the PET power quality control abilities.**

***Keywords*—Solid State Power electronic transformer; Voltage Disturbance Ride Through; Power Quality, Flexible Power Distribution Unit**

I. Introduction

Distribution transformer is the most important and common equipment in power distribution network, which is mainly responsible for voltage transformation and isolation. Traditional distribution transformer is very reliable, but it is bulky, cumbersome and harmonics could not be isolated between primary and secondary sides. And extra equipment is needed to monitor and protect itself for possible breakdown issue. Now days these drawbacks are the real concerns in academics and industries [1].

Therefore, the power electronics based transformer called PET (Power electronic transformer), IUT (Intelligent Universal Transformer) , SST (Solid State Transformer), ST (Smart transformer) and others has gradually become an emerging issue over the last 10 years, especially for railway traction and smart grid [2]-[9]. ABB, Alstom, Bombardier, Siemens have done a lot of work in traction applications. The pilot installation from ABB was completed in mid-2011, and homologation with the Swiss Federal Office for Transport (FOT) was achieved by the end of the year [7]. At the same time, scientists and researchers in the UNIFLEX-PM (Advanced Power Converters for Universal and Flexible Power Management in Future Electricity Networks), FREEDM (the Future Renewable Electric Energy Delivery and Management), MEGA Cube and HEART (The Highly Efficient And Reliable smart Transformer (HEART), a new Heart for the Electric Distribution System) Projects lead by the leading universities are still continuously investigating various issues of PET for smart grid, partly because of that the existing 50/60Hz power system is more complicate than the 16.67Hz traction electric system[8]-[9].

Besides USA EPRI IUT projects, China EPRI also starts the Gen-I PET project for distribution power system, a flexible power distribution unit for future distribution system. The introduction of which is also submitted to IECON 2015 for further presentation [10].

The motivation of this paper is to present the key control strategies of solid state PET for electrical distribution system application, especially under voltage disturbance conditions. Several critical grid voltage disturbances are generated by a disturbance voltage source based on a three phase PWM inverter. And the solid state PET prototype is tested and passed voltage disturbance ride through function. The experimental results verify the PET power quality control abilities.

II. Solid State PET Structure and Topology Based on PEBB

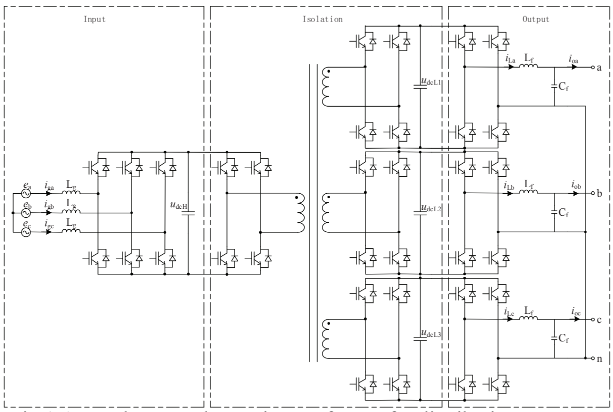


Fig.1 A novel Power electronic transformer for distribution system

A 100KW 600V/220V three-phase four-wire PET prototype is built as Fig.1 shown based on Power Electronics Building Block (PEBB) concept, which is to provide generic building blocks for power conversion, regulation and distribution with control intelligence and autonomy. It comprises a front-end PWM rectifier, a medium frequency open loop isolated dc/dc converter operated under the dc transformer condition, and a downstream three phase combined inverter using the same single phase inverter. The PEBB switching cells result in reduced design effort, increased system reliability and reduced manufacture and maintenance cost [11].

Project Supported in part by the National Natural Science Foundation of China (51207023), by the Cooperative Innovation Fund of Jiangsu Province--the Prospective and Joint Research Project (BY2015070-18), by the Basic and Prospective Science and Technology Project of State Grid Corporation of China (EPRIYDKJ(2014)3317), by the Science and Technology Pillar Program of Zhenjiang City(GY2014029)

The operating principle of the PET is accessible. Firstly, input PWM rectifier converts high voltage alternating current (ac) to direct current (dc). Secondly, the front-end inverter of isolation part converts direct current into high frequency square wave. Then through high frequency isolation transformer, the square wave is coupled to the vice side. The back-end rectifier of isolation part converts ac square wave to low dc voltage. Finally, the output inverter convers the dc voltage to required ac voltage.

Main parameters of the system are shown as follows:

(1) Input stage: rated line voltage is 600Vac, rated line frequency is 50Hz, input inductance is 1.5mH, high voltage dc link capacitors are 2160μF, switching frequency is 4.8 kHz, semiconductor switches are SKM400GB176Ds;

(2) Isolation stage: switching frequency is 2 kHz; transformer primary-secondary ratio is 3:1:1:1, low voltage dc link capacitors are 3000μF, primary semiconductor switches are SKM400GB176Ds and secondary switches are SKM300GB128Ds;

(3) Output stage: output filter inductance is 0.4mH, output filter capacitors are 50uF, switching frequency is 10 kHz, and switches are all SKM300GB128Ds.

It is found in Fig.1 that the proposed PET topology has its inner high voltage and low voltage dc link, so the voltage disturbance and load disturbance isolation would be possible with the help of dc link buffer capacitors. Addition, this topology can isolate the front-end and back-end through the shut of isolation transformer in some emergency situations. Further efforts should be made on the key control strategies, especially in the front-end rectifier.

III. KEY CONTROL STRATEGIES OF SOLID STATE PET

Two key control strategies of the PET have been investigated and presented in this section separately, including control principle of three phases PWM rectifier and phase-locked loop of grid voltage.

1. Control principle of three phase PWM rectifier

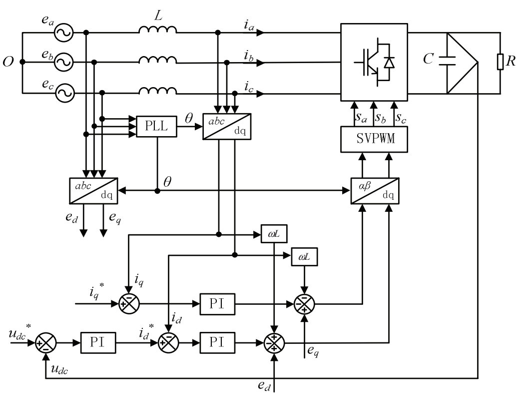


Fig.2 Control diagram of the front end three phase PWM rectifier

As shown in Fig.2, the front end converter of the PET is a three-phase six switch two level PWM rectifier, which could be model with equation (1).

$$\begin{cases} L\dfrac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} - \dfrac{u_{dc}}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \\ C\dfrac{du_{dc}}{dt} = [S_a \quad S_b \quad S_c]\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \dfrac{u_{dc}}{R_L} \end{cases} \tag{1}$$

There are two main control targets: one is to ensure that the dc link voltage constant for disturbance isolation, the other is to keep the grid current sinusoidal and power factor controllable. In order to achieve above two goals, the input PEBB module adopts double loop control methods: the outer dc voltage loop and inner current loop. Considering the speed and accuracy of regulation, the feedforward voltage is added into the control loop.

Considering the regulation of the three phase ac system is not as easy as the dc system, the *abc* stationary frame system could be transferred to the *dq* synchronization reference frame through Clark and Park transformations as equation (2) illustrated. So the ac variables can be transformed to dc variables which are beneficial to calculate and control.

$$\begin{cases} e_d = L\dfrac{di_d}{dt} - \omega L i_q + R i_d + v_d \\ e_q = L\dfrac{di_q}{dt} + \omega L i_d + R i_q + v_q \end{cases} \tag{2}$$

In addition, to reduce the *d*, *q* axis currents' mutual effect in the process of dynamic interaction, feed forward decoupling is introduced in the current loop, and the key control functions are provided in equation (3),

$$\begin{cases} v_d = -(K_{iP} + \dfrac{K_{iI}}{s})(i_d^* - i_d) + \omega L i_q + e_d \\ v_q = -(K_{iP} + \dfrac{K_{iI}}{s})(i_q^* - i_q) - \omega L i_d + e_q \end{cases} \tag{3}$$

where $S_{a,b,c}$ are switch functions, θ is the output power grid voltage vector angle of phase-locked loop, and $\theta=\omega t$, ω is the angular frequency of the grid voltage, and the rated ω=100π rad/s, e_d,e_q are d and *q* axis components of power grid voltage, i_{gd},i_{gq} are d and *q* axis components of power grid current, u_{dc}* is the reference value of dc bus voltage u_{dc},i_d*,i_q* are the reference values of i_d,i_q. In order to achieve the unit power factor of input, the reference value of *q* axis current i_q* is set to 0 here.

2. Phase-locked loop design

An accurate and fast detection of the frequency, phase angle of the grid voltage is essential to assure the correct generation of the reference signals and to cope with the utility codes, especially for those operated under common utility distortions as harmonics, voltage sags, frequency variations and phase jump.

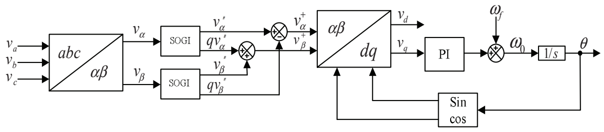


Fig.3 General Structure of a three phase PLL

In this paper, a three phase PLL based on synchronization reference frame is adopted as shown in Fig.3. The orthogonal voltage is generated from second order generalized integrator (SOGI) method as shown in Fig.4.This generated orthogonal system is filtered without delay by the same structure due to its resonance at the fundamental frequency. And the PLL here tracks the line frequency accurately and rapidly.

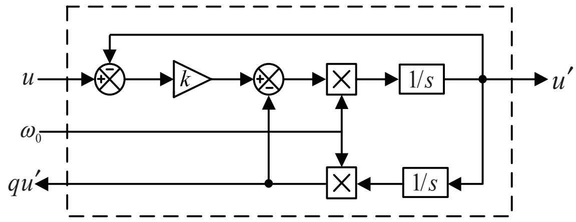


Fig.4 Method of SOGI constructing orthogonal component

The closed loop transfer functions of the orthogonal voltage to grid voltage are given by equations (4), (5).

$$D(s)=\frac{u'}{u}(s)=\frac{k\omega' s}{s^2+k\omega' s+\omega'^2} \tag{4}$$

$$Q(s)=\frac{qu'}{u}(s)=\frac{k\omega'^2}{s^2+k\omega' s+\omega'^2} \tag{5}$$

Furthermore, equations (4),(5) could be rewritten as equations (6),(7) illustrated,

$$u'=Du\begin{cases}|D|=\dfrac{k\omega\omega'}{\sqrt{(k\omega\omega')+(\omega^2-\omega'^2)^2}}\\ \angle D=\tan^{-1}(\dfrac{\omega'^2-\omega^2}{k\omega\omega'})\end{cases} \tag{6}$$

$$qu'=Qu\begin{cases}|Q|=\dfrac{\omega'}{\omega}|D|\\ \angle Q=\angle D-\dfrac{\pi}{2}\end{cases} \tag{7}$$

So no matter how ω', ω和k changes, the artificial sinusoidal signal u' and qu' has the precise 90° phase difference. And the phase angle of the PLL output follows the fundamental component precisely. Besides that, SSRF-SPLL output frequency is feed backed as the resonant frequency for grid frequency change situation.

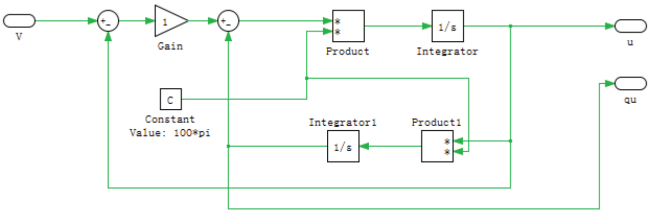


Fig.5 PLECS simulation model of SOGI block

Fig.5 further gives the simulation model of SOGI block and Fig.6 provides the PLL simulation model with PLECS software.Fig.7-10 show that the perfect performance of SOGI-SPLL, an accurate and fast detection of the frequency, phase angle of the grid voltage is achieved even utility distortions as harmonics, voltage sags, frequency variations occur.

And the control strategies of isolation and output part are introduced in author's another paper [10], which is eliminated here due to limited pages.

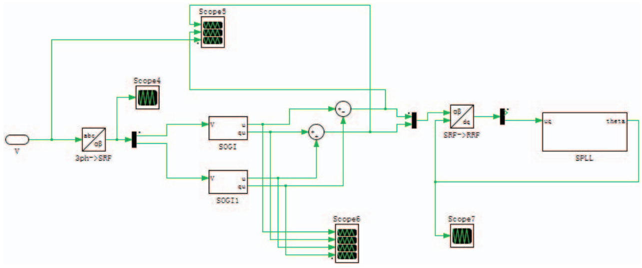


Fig.6 PLL Simulation results

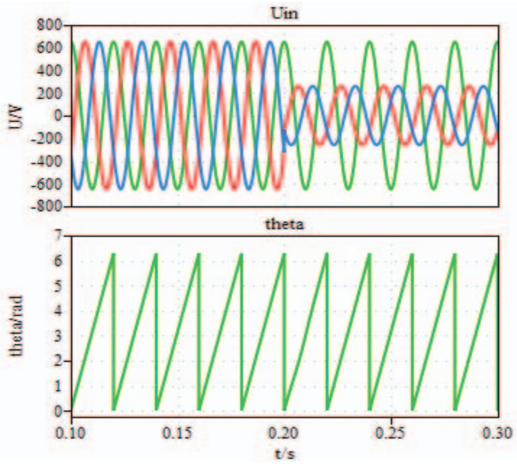


Fig.7 Simulation results of SOGI-SPLL under the condition of three-phase voltage imbalance

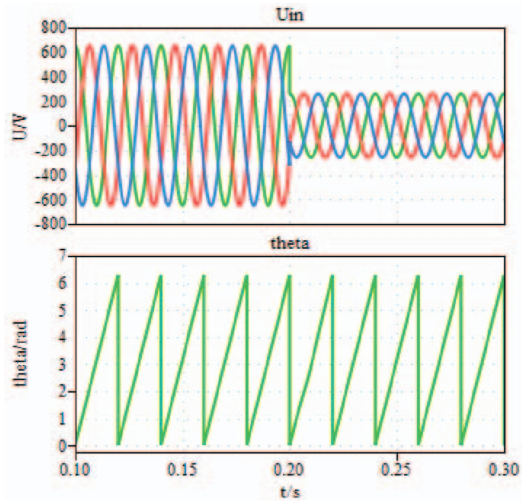


Fig.8 Simulation results of SOGI-SPLL under the condition of input voltage drop

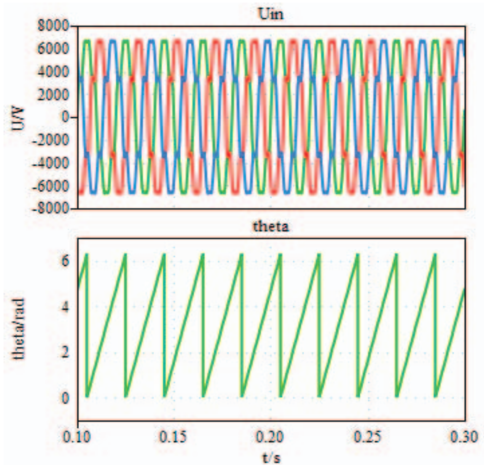


Fig.9 The simulation results of SOGI-SPLL with voltage harmonic input

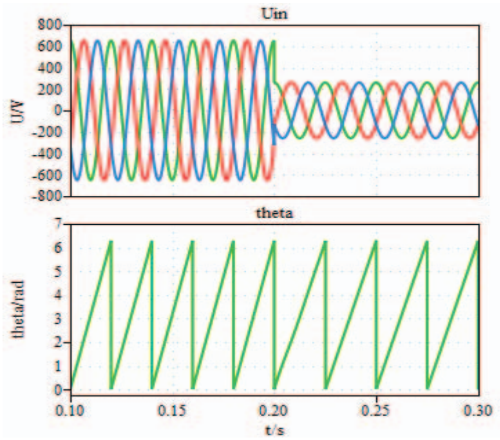
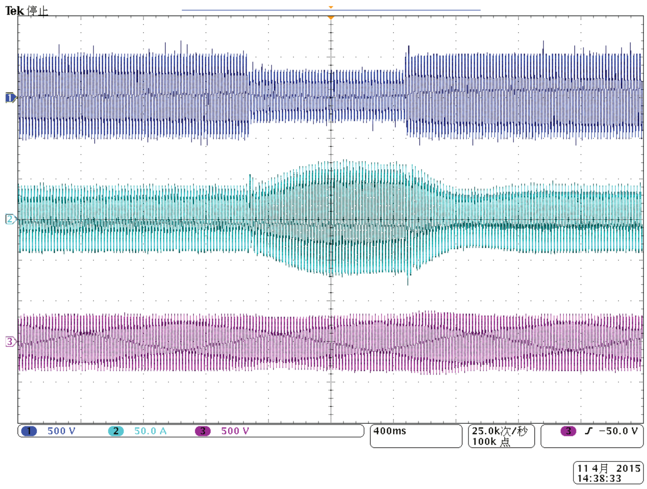


Fig.10 Simulation results of SOGI-SPLL with grid frequency fluctuations

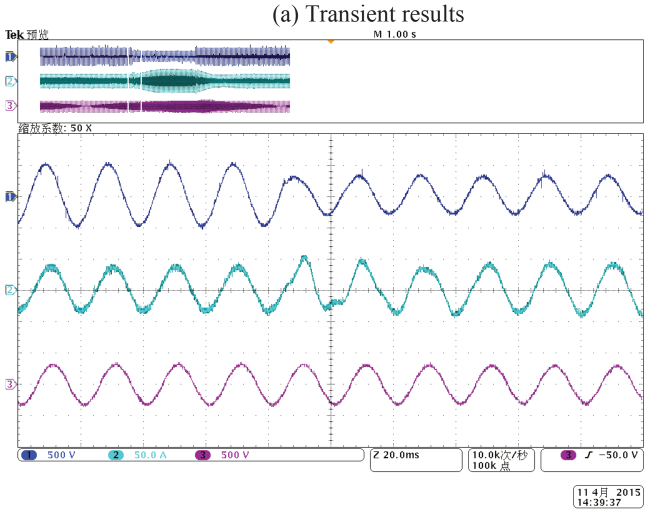
IV. Experimental Verification

In order to verify the key control Strategies of the solid state PET under voltage disturbance conditions, another PWM inverter the same to the front end converter of PET operates is chosen as a disturbance voltage source to emulate the grid.

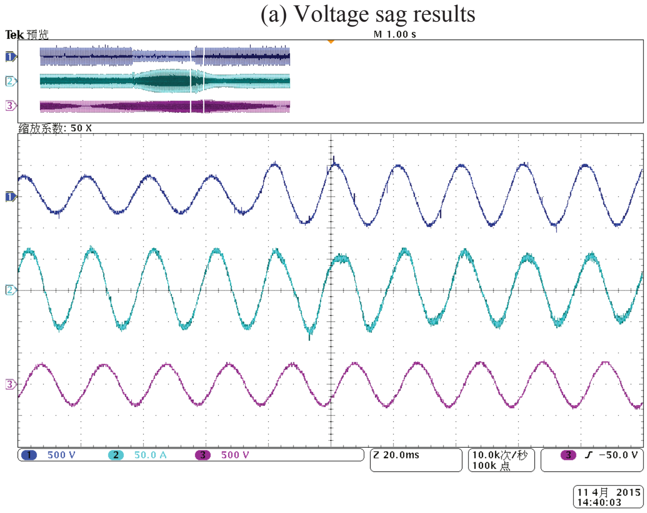
Due to limited pages, some critical tests results are selected and shown in Fig.11 and Fig.12 shown, where some utility distortions occurs at the same time. The voltage disturbance ride through of the PET with three phase 60% balance voltage sag and phase jump are shown in Fig.11, and voltage disturbance ride through of the PET with three phase 60% balance voltage sag, 50/40Hz frequency variation and phase jump in Fig. 12.It found that, no matter how the voltage changes, with the control strategy of this paper, especially the feedforward control, the input current and output voltage are both well regulated with fast dynamic response. The input power quality is only affected during two or three grid period. And the output voltage changes are not observed due to dc link buffer.



(a) Transient results

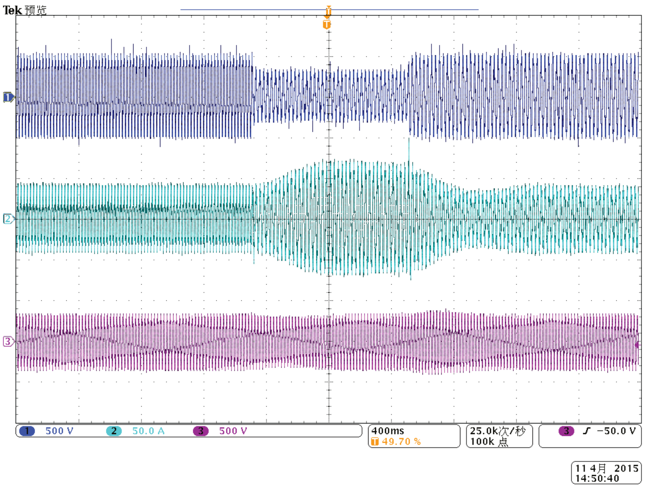


(a) Voltage sag results

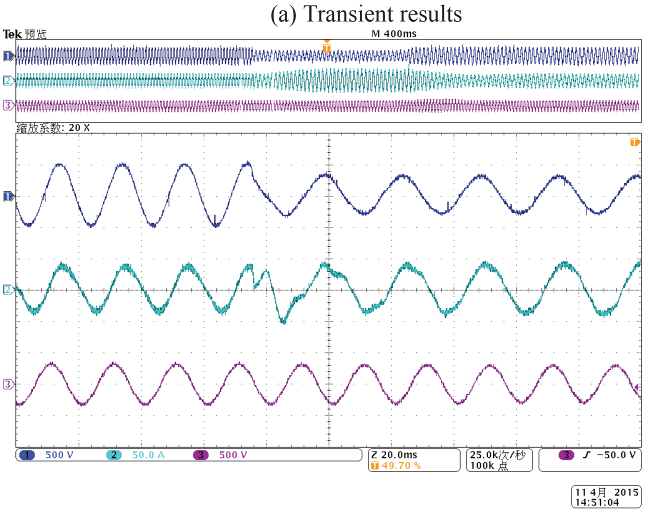


(a) Voltage recovery results

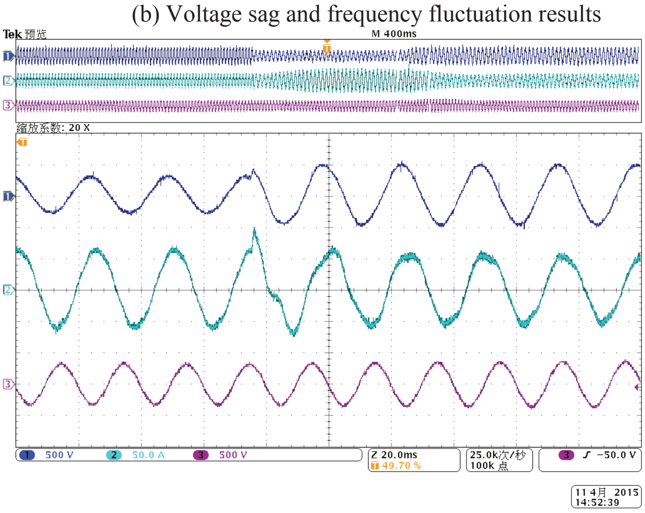
Fig.11Voltage disturbance ride through of the PET with three phase 60% balance voltage sag and phase jump(CH1: PWM rectifier line voltage v_{ab},CH2:PWM rectifier input current i_a,CH3:single phase inverter output voltage v_a)



(a) Transient results



(b) Voltage sag and frequency fluctuation results



(c) Voltage sag and frequency fluctuation recovery results

Fig.12 Voltage disturbance ride through of the PET with three phase 60% balance voltage sag , 50/40Hz frequency variation and phase jump(CH1: PWM rectifier line voltage v_{ab},CH2:PWM rectifier input current i_a,CH3:single phase inverter output voltage v_a)

V. Conclusion

This paper present the key control strategies of solid state PET for electrical distribution system application, especially under voltage disturbance conditions, including control principle of three phase PWM rectifier and phase-locked loop of grid voltage.

And the solid state PET prototype is tested and passed voltage disturbance ride through function, even voltage sag, frequency variation and phase jump occurs at the same time. The experimental results verify the PET power quality control abilities.

Reference

[1]. J. Wang, A. Huang, W. Sung, Y. Liu, and B. Baliga, “Smart Grid Technologies,” IEEE Industrial Electronics Magazine, 2009, 3(2): 16–23.

[2]. J. Zhao, “Simulation Study of a Power electronic transformer with Constant Output Voltage,” Automation of Electric Power Systems, 2003, 27(18):30-34, 46.

[3]. D. Wang, C. Mao, J. Li, “Auto Balancing Electronic Power Transformer,” Proceedings of the CSEE, 2007, 27(6):77-83.

[4]. G. Ortiz, J. Biela, and J. W. Kolar, “Optimized Design of Medium Frequency Transformers with High Isolation Requirements,” in Annual Conference of the IEEE Industrial Electronics Society (IECON), Glandale, 2010, pp. 631–638.

[5]. Z. Li, P. Wang, Z. Chu, et al, “Research on Medium and High Voltage Smart Distribution Grid Oriented Power Electronic Transformer,” Power System Technology, 2013, 37(9):2592-2601.

[6]. G. Wang, A. Huang, J. Wang, et al, “Comparisons of 6.5 kV 25A Si IGBT and 10-kV SiC MOSFET in Solid-State Transformer Application,” IEEE Energy Conversion Congress and Exposition (ECCE), 2010: 100-104.

[7]. C. Zhao, D. Dujic, A. Mester, et al, “Power Electronic Traction Transformer—Medium Voltage Prototype,” IEEE Transactions on Industrial Electronics, 2014, 61(7): 3257-3268.

[8]. D. Siemaszko, F. Zurkinden, L. Fleischli, et al, “Description and Efficiency Comparison of Two 25 kVA DC/AC Isolation Modules,” EPE Journal: European Power Electronics and Drives Association Journal, 2009, 19(LEI-ARTICLE-2010-002): 17-24.

[9]. G. Quartarone, M. Liserre, F. Fuchs, et al, “Impact of the Modularity on the Efficiency of Smart Transformer Solutions,” Annual Conference on IEEE Industrial Electronics Society (IECON), 2014: 1512-1518.

[10]. Q. Duan, J. Wang, C. Ma, B. Gu, B. Ji, P. Qiu, J. You, “Flexible Power Distribution Unit — A Novel Power Electronic Transformer Development and Demonstration for Distribution System,” Annual Conference on IEEE Industrial Electronics Society (IECON), 2015, submitted.

[11]. S. Thandi, R. Zhang, K Xing, et al, “Modeling, Control and Stability Analysis of A PEBB Based DC DPS [J]. IEEE Transactions on Power Delivery, 1999, 14(2): 497-505.