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THE RESEARCH ON SPECIAL ELECTRONIC POWER TRANSFORMER

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ABSTRACT

In many circumstances, three-phase AC power supply is not always the best choice for utility applications. In fact, there is a rating of three-phase to single-phase, three-phase to dual-phase and three-phase to multiphase transformers being in operation around the world, which are almost all made by general means. In spite of their huge cubage and weight, those transformers have other fatal characters for instance they can spread a fault current. EPT (Electronic Power Transformer, also called Power Electronic Transformer or Solid Transformer) has been proposed for years. In this paper, we use a module composed of the input three-phase PWM (Pulse Width Modulation) rectifier, medium frequency transformer and output single-phase inverters to structure a series of function SEPT (special EPT). We also discussed the modulation strategies of the SEPTs in this paper, and what's more, we expand the PARK transformation to four-phase and firstly proposed the transformation coefficients of four-phase AC system to dqg0 system. Several cases are being discussed in this paper, and the results of the simulation proved that SEPT has all the advantages EPT has, such as better steady-state, better waveforms, better power factor etc. compared with general special transformers.

Key words: *Special Transformer, Electronic Power Transformer, Four-phase to three-phase, Three-phase to multiphase, Power quality.*

1. INTRODUCTION

There have been years for people to use transformers for power transmission since it had been invented in 19th century by Nikole Tesla. Transformers are employed in power grid mostly for voltage transformation, isolation and noise decoupling [1]. Here isolation means isolation of different voltage ranks. In inherent those transformers let any AC waves through them, it means that they can't stop harmonics though them; can't stop fault current though them, which may cause more faults. When there is over load, they can't stop the voltage decline of the secondary side, which can cause a range of harmonics polluting the whole power grid. What's more, those special transformers being made in a general way, they are doomed to carry imbalance and nonlinear loads, those imbalance and nonlinear caused by the loads will eventually feedback to the power grid from their secondary side to primary side and vice versa. Although there are already several means being obtained to improve the performance of those transformers

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[2-4], it can make them work in a better way but can't solve the mentioned problems radically.

Special transformers are used in many occasions. As we all know, most high-speed railway systems around the world used single-phase source from a specific-substation transforming three-phase source to single-phase or dual-phase as power supply for trains. Since of the operation and running properties of the trains, there may be a lot of harmonics feedback to the power supply system through the special transformers of the substation, and also, the voltage change of the power system will affect the running trains, too. In many specific-substations for railways of China, there have been a lot of compensation equipments being in operation to improve the quality of the power supplied to the trains. Those equipments, since of their hypostasis, can't solve the problems well still.

In many plants, for instance a steel-making plant, they have many single-phase loads such as electric furnaces. Usually they have transformer's capacity in the same grade of their own. Consequently, they would cause a lot of harmonics as well as distorted voltage and currents feed back to the power grid.

Recently, three-phase to four-phase transformers have attracted many attentions for the rising of four-phase power transmission systems as well as the AT(autotransformer) feeding system in electric railways [5]. They both need clean and balance power supply.

Electronic Power Transformer (EPT) is a new type power transformer [6-9], it can be used in both transmission and distribution system [11-13]. Topologies and operating characteristics of EPT have been studied in many literatures [6-10, 13]. We try to apply the good quality of EPT to special transformers in this paper.

2. TOPOLOGY

To deal with all the conditions mentioned, we put forward the following scheme based on principle module of EPT, and named it SEPT (Special Electronic Power Transformer). The module of EPT is showed in fig.1.

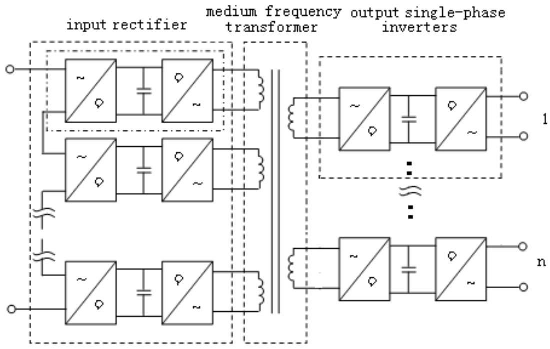

Figure 1. Module of EPT.

Fig.1 shows us a module transforming single-phase to single-phase or multiphase. In Fig.1, the input rectifier is cascaded by several cells to adapt to the voltage grade of the power source. The cell is composed of an AC/DC single-phase full-bridge controlled rectifier, a voltage-stabilizing capacitor and a DC/AC single-phase full-bridge inverter.

Since the electromotance of a transformer with other variable is given by equation (1) [14].

Where E_i denote the electromotance of the transformer; f denote the frequency of the transformer working; N_i denote the number of the windings of the transformer; $\dot{F}_m$ denote the main magnetic flux of the transformer. Here $\dot{F}_m$ has no relation with the stuff and size of the transformer. So when the frequency of the transformer has been increased, the number of the windings of the transformer will decreased to a very low level. So the transformer can be made in a small and light way. That's why we use a medium frequency transformer here.

$$E_i = - j\sqrt{2}p\, fN_i\dot{F}_m \qquad (1)$$

The medium frequency transformer has several windings both of its primary and secondary side according to the voltage grade of the power supply and the phase the load needs.

The output terminal of the module is made up of several single-phase inverters according to utility's demand. Every single-phase inverter has an AC/DC rectifier, a voltage-stabilizing capacitor and a DC/AC full-bridge inverter.

3. MODULATE STRATEGIES

The modulation signals of the AC/DC full-bridge controlled rectifiers in the input terminal are produced by a DC regulator. It uses voltage signals as its input signals. Firstly, it turns ABC system to dq0 system as Park's conversion coefficients regulated, then it modifies V_d through the feedback signal V_{dc} from the DC voltage-stabilizing capacitor, and at last, it turns dq0 system to ABC system in a same way, and the modified V_a V_b V_c are used as driving signals of a Discrete three-phase PWM Generator to produce modulation signals.

The DC/AC inverters followed use ideal switches as their power electronic device. They eventually turn the DC power to AC square wave power. Their modulation signals are simply produced by a pulse generator. The same thing happens on the AC/DC rectifier of the output terminal. It makes a little different that the pulse generators take the medium frequency transformer's output square wave as their control signals.

The modulated signals of the output DC/AC full-bridge inverter are produced by an output regulator. It takes the output voltage as its input variable. The per-unit quantity of the voltage is compared with 1 and then through a PI regulator and at last entrances a PWM generator to produce modulation signals.

4. SIMULATION AND RESULTS

The Simulink of Matlab is used for simulations here.

As the voltage source differs, the SEPT is made up of the same number of modules as the phases the source have. The output terminal of the SEPT has the same number of phases as the loads have. And to keep balance of the SEPT, both terminals of the SEPT are connected as astroids.

In all simulations, the line voltage of the voltage source is set to 20kV, according to the pressure resistance of the IGBT [15], the input rectifier is cascaded by 3 cells, and the line voltage of the loads is set to 400V. The voltage of the capacitor in the input terminal is set to 5000V, and the voltage of the capacitor in the output terminal is set to 500V. The frequency of the medium frequency transformer is set to 1000Hz.

To reduce the surging at the start, we set a startup device in the main circuit, and have a lag of 0.05 seconds.

Without special instruction, in all the following figures the units of time is seconds (s), and the units of voltage is V.

3.1. Three-phase to others

In this section, we simulated several cases: three-phase to single-phase, three-phase to dual-phase, three-phase to four-phase.

3.1.1. Undistorted and balanced conditions

For this situation, the input voltages are given by equation (2).

$$\left.\begin{aligned} V_a(t) &= \sqrt{2}V_m \sin(\varpi t) \\ V_b(t) &= \sqrt{2}V_m \sin(\varpi t - \frac{2\pi}{3}) \\ V_c(t) &= \sqrt{2}V_m \sin(\varpi t + \frac{2\pi}{3}) \end{aligned}\right\} \quad (2)$$

The results are provided in Fig.2, Fig.3 and Fig.4.

First is the result of three-phase to single-phase.

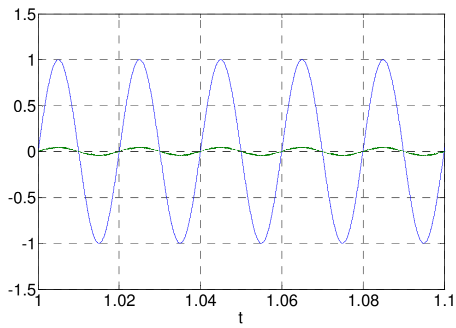

Figure 2. (a) Voltage and current of one phase of the source.

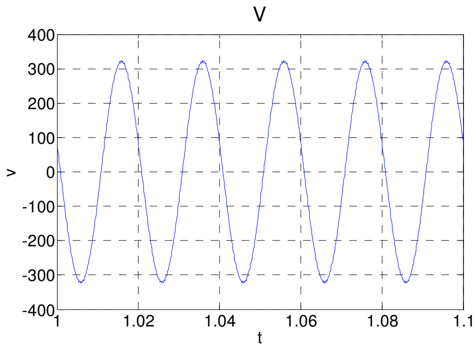

Figure 2. (b) Output voltage V .

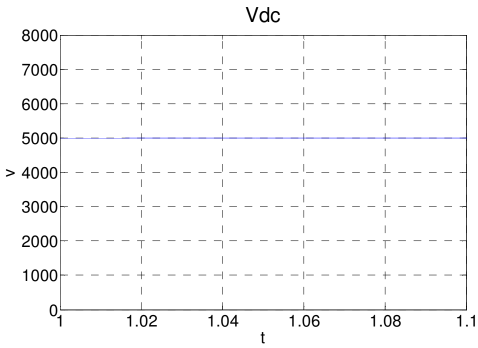

Figure 2. (c) Voltage of the first capacitor.

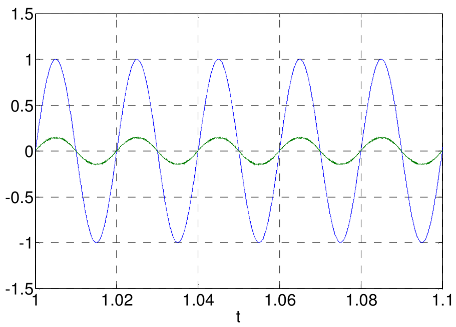

Figure 3. (a) Voltage and current of one phase of the source.

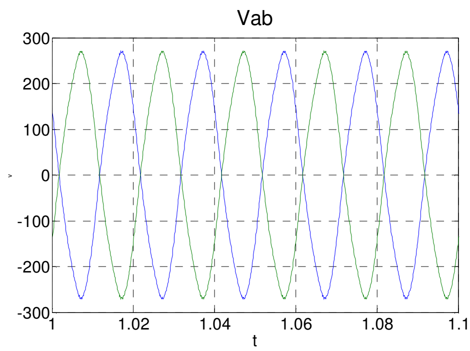

Figure 3. (b) Output voltage V_{ab} .

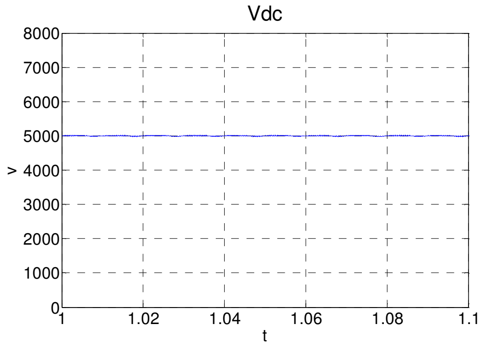

Figure 3. (c) Voltage of the first capacitor.

At last is the result of three-phase to four-phase.

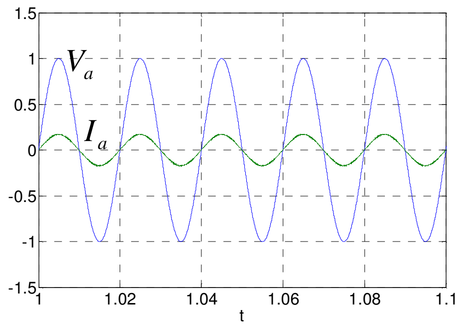

Figure 4. (a) Voltage and current of one phase of the source.

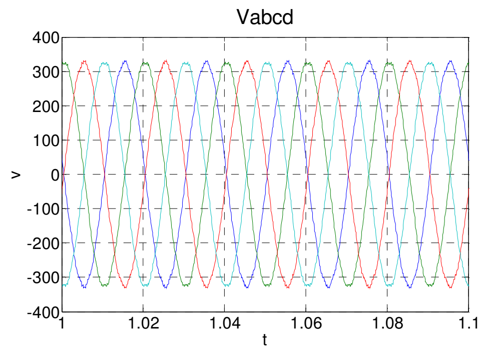

Figure 4. (b) Output voltage V_{abcd} .

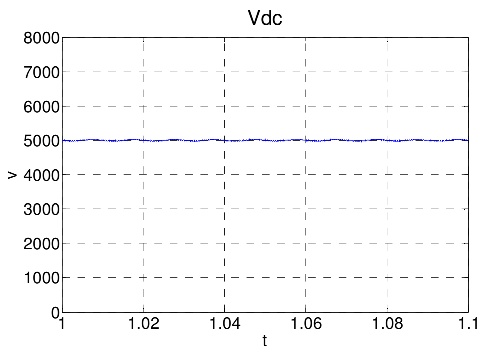

Figure 4. (c) Voltage of the first capacitor.

3.1.2. Distorted and unbalanced conditions

For this situation, we first let the input voltages given by equation (3).

$$\left.\begin{aligned} V_a(t) &= 1.3*\sqrt{2}V_m\sin(\varpi t-\frac{5\pi}{4})+0.25*\sqrt{2}V_m\sin(2\varpi t) \\ V_b(t) &= \sqrt{2}V_m\sin(\varpi t+\frac{\pi}{3})+0.2*\sqrt{2}V_m\sin(3\varpi t) \\ V_c(t) &= 1.2*\sqrt{2}V_m\sin(\varpi t-\frac{\pi}{2})+0.15*\sqrt{2}V_m\sin(4\varpi t) \end{aligned}\right\} \quad (3)$$

Here come the results of different SEPTs having the same voltage source given by equation (3):

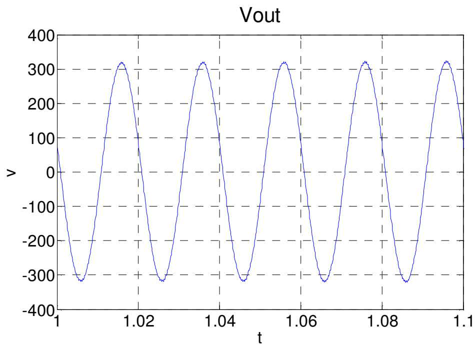

Figure 5. (a) Output voltage of three-phase to single-phase.

We use FFT to analyze the output voltage, and the result is showing in the following picture. In this picture, the vertical axis denotes the magnitude of each components, the horizontal axis denotes the frequency of each components. In order to show the detail of the harmonic waves, we just indicate the magnitude of the fundamental in the head, but don't show its all height. And the following homologous series pictures are in the same.

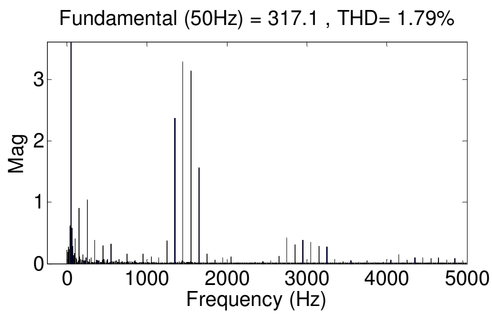

Figure 5. (b) FFT of the output voltage.

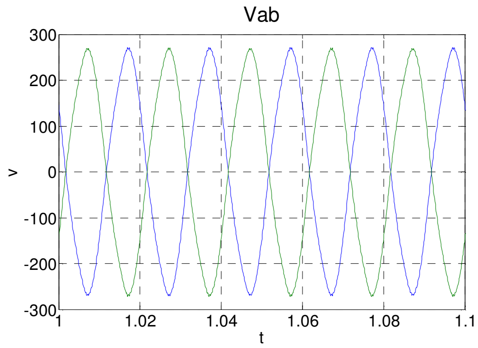

Figure 6. (a) Output voltage of three-phase to dual-phase.

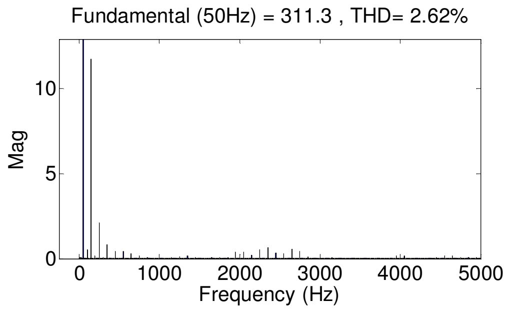

Figure 6. (b) FFT of the output voltage.

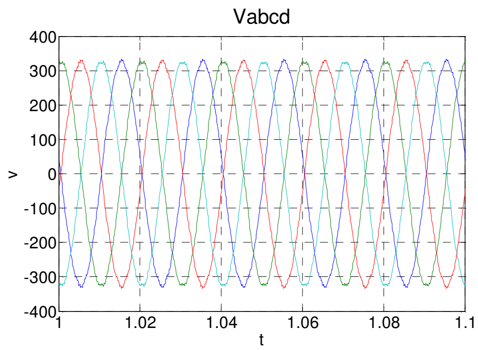

Figure 7. (a) Output voltage of three-phase to four-phase.

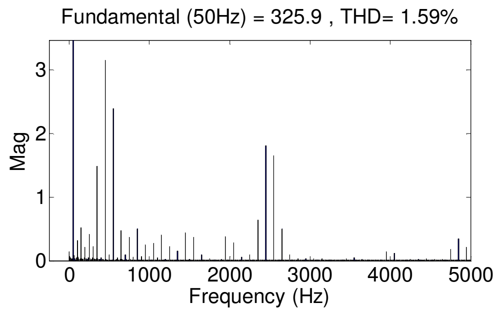

Figure 7. (b) FFT of the output voltage.

We can see that even under the distorted and unbalanced situations, the output voltage still have good waveforms.

And another situation, we let the load of the mentioned models have a harmonic wave given by equation (4) separately:

$$I_5 = 0.2 * I_1 \sin(5v\ ) \qquad (4)$$

The voltage and current waveform of one phase of the source in per unit are given in Fig.8:

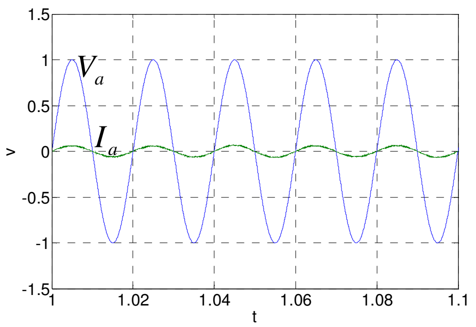

Figure 8. (a) Voltage and current of one phase of the source.

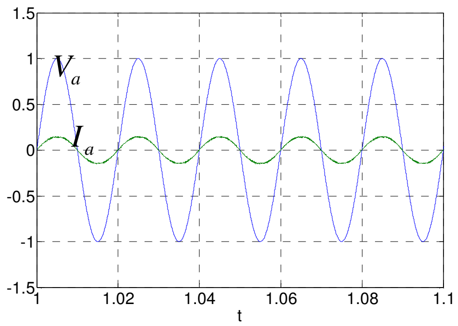

Figure 8. (b) Voltage and current of one phase of the source.

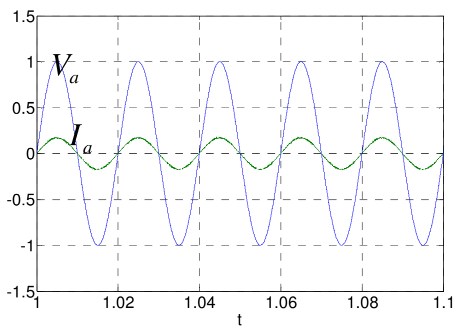

Figure 8. (c) Voltage and current of one phase of the source.

3.2. Four-phase to three-phase

Nowadays, because of the huge energy loss of power transmission, more and more people are searching for a better way to transmit power. Multiphase transmission is very flourish these years. Since quadriphase power transmission has an advantage in easy to rebuild the electric network and comparable simple modulation strategy, it has absorbed more attention. So we especially simulated this situation.

Since the input voltage is four-phase, the former DC regulator for the AC/DC full-bridge controlled rectifiers is not useful for this situation anymore. We try to expand the PARK transformation to four-phase so the regulator can use the feedback V_{dc} to regulate the modulation signals. We first proposed the transformation coefficients of four-phase AC system to dqg0 system, simulation results proved that it works well. The simplified coefficient is given here:

$$P = \frac{1}{2}\begin{bmatrix} \cos\alpha & \sin\alpha & -\cos\alpha & -\sin\alpha \\ -\sin\alpha & \cos\alpha & \sin\alpha & -\cos\alpha \\ \cos\alpha & \sin\alpha & \cos\alpha & \sin\alpha \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

And it's converse transformation:

$$P^{-1} = \frac{1}{2}\begin{bmatrix} \cos\alpha & -\sin\alpha & \cos\alpha & 1/2 \\ -\sin\alpha & \cos\alpha & \sin\alpha & 1/2 \\ -\cos\alpha & \sin\alpha & \cos\alpha & 1/2 \\ -\sin\alpha & -\cos\alpha & \sin\alpha & 1/2 \end{bmatrix}$$

We first let the voltage source given by equation (5):

$$\left.\begin{aligned} V_a(t) &= \sqrt{2}V_m \sin(\varpi t) \\ V_b(t) &= \sqrt{2}V_m \sin(\varpi t - \frac{\pi}{2}) \\ V_c(t) &= \sqrt{2}V_m \sin(\varpi t + \pi) \\ V_b(t) &= \sqrt{2}V_m \sin(\varpi t + \frac{\pi}{2}) \end{aligned}\right\} \qquad (5)$$

And the results of the simulation are provided in Fig 9.

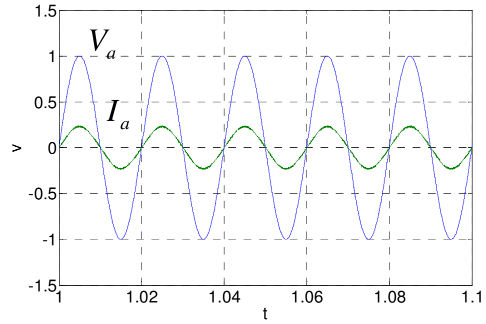

Figure 9. (a) Voltage and current of one phase of the source.

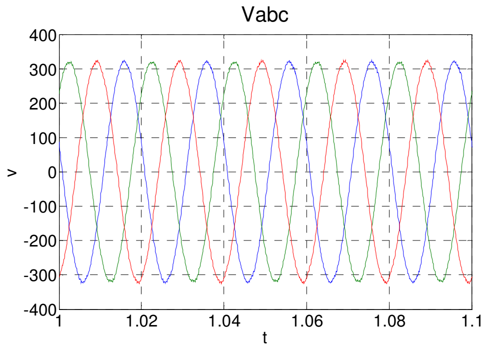

Figure 9. (b) Output voltage *Vabc* .

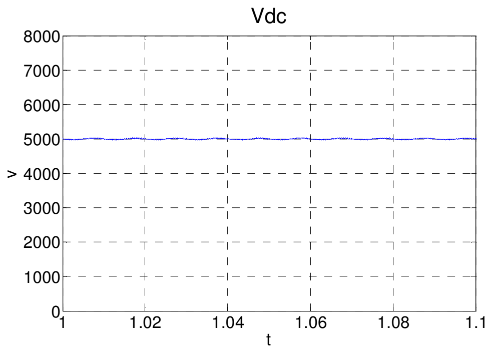

Figure 9. (c) Voltage of the first capacitor.

Then we let the SEPT work under distorted and unbalanced circumstances, the voltage source is given by equation (6):

$$\left.\begin{aligned} V_a(t) &= 1.3*\sqrt{2}V_m \sin(\varpi t - \frac{5\pi}{4}) + 0.25*\sqrt{2}V_m \sin(2\varpi t) \\ V_b(t) &= \sqrt{2}V_m \sin(\varpi t + \frac{29\pi}{36}) + 0.2*\sqrt{2}V_m \sin(3\varpi t) \\ V_c(t) &= 1.2*\sqrt{2}V_m \sin(\varpi t - \frac{\pi}{4}) + 0.15*\sqrt{2}V_m \sin(4\varpi t) \\ V_d(t) &= 1.1*\sqrt{2}V_m \sin(\varpi t - \frac{7\pi}{18}) + 0.3*\sqrt{2}V_m \sin(5\varpi t) \end{aligned}\right\} \tag{6}$$

And the output voltage and its FFT analysis are shown in Fig.10.

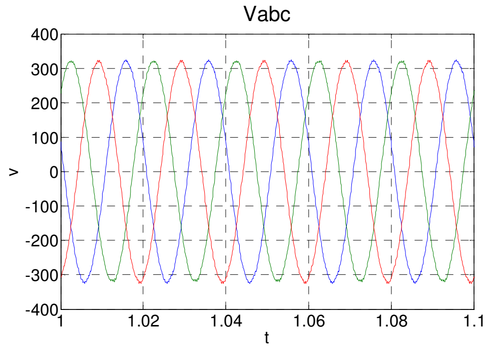

Figure 10. (a) Output voltage of three-phase to four-phase.

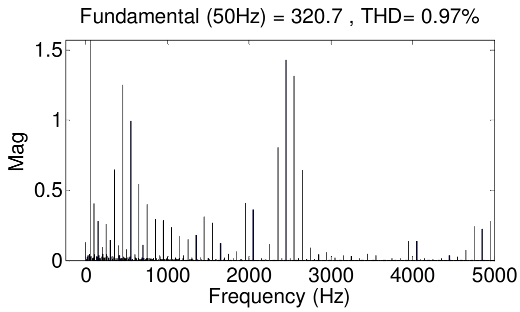

Figure 10. (b) FFT of the output voltage.

And when the load has a harmonic wave as equation (4) describes, the voltage and current in per unit of one phase of the source is in Fig 11:

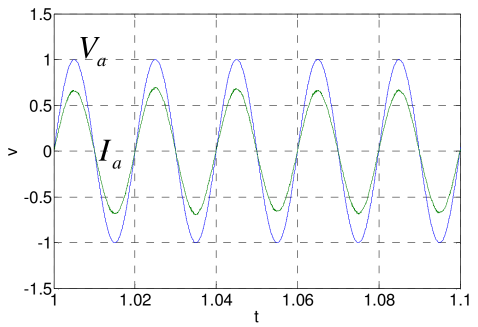

Figure 11. Voltage and current of one phase of the source.

5. CONCLUSIONS

Compared with other power supply used in same purpose, SEPT has the advantage in size, weight, efficiency and reliability, and has no environment pollution.

SEPT can guarantee that the primary side of it has very good waveform and can ensure the power factor be 1.

When the power supply is distorted and unbalanced, SEPT can ensure good waveform supplied to the load, and also, when the load has some harmonic waves, SEPT can also prove the power factor of the voltage source be 1. It also proved that the transformation coefficients of Park transformer transforming four-phase AC system to dqg0 system work well.

SEPT can provide DC power for utilities with good quality, since it has a DC export.

When there is a fault occurs, the switching devices can cut-off circuit very soon to prevent the fault's spreading.

6. ACKNOWLEDGMENT

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7. REFERENCE

[1] Nikola Tesla, "System of electrical distribution [P]", US Patent #381970, 1888.

[2] Zheng Qicun, "Electrified Railway and Balancing Transformer", *Transformer*, Vol:35 No.10, pp. 157-164, 1998.

[3] Zhang Zhi-wen, Wang Yao-nan, Liu Fu-sheng, Xiong Zhi-yao, Li Jian-ying, "Study on Operational Mode of Multi-function Balance Traction Transformer", *Proceedings of the CSEE*, Vol:24, No.4, pp. 125-132, 2004.

[4] Zhao Huifang, "Scott and Inverse Scott Connection Transformer used for Electrified Railway", *Transformer*, Vol:34, No.5, pp. 155-158, 1997.

[5] Gao Shibin, Chen Xiaochuan, "Principles of differential protection for three-phase to four-phase power transformer", *Developments in Power System Protection, 2004. Eighth IEE International Conferenc*, Vol:1, 5-8, pp. 339-342, 2004.

[6] E.R. Ronan, S.D. Sudhoff, S.F. Glover, D.L. Galloway, "Application of power electronics to the distribution transformer. Applied Power Electronics Conference and Exposition", *APEC 2000, Fifteenth Annual IEEE*, 2000, Vol:2, pp. 861-867.

[7] M.D. Manjrekar, R. Kieferndorf, G. Venkataramanan, "Power electronic transformers for utility applications[C]", *Conference Record of the 2000 IEEE-IAS Annual Meeting 2000*, 4, pp. 2496-2502.

[8] EPRI Report, Proof of the principle of the solid-state transformer the AC/AC switch mode regulator[R], *EPRI TR-105067, Research Project 8001-13, Final Report*, August, 1995.

[9] Mao Chengxiong, Fan Shu, Wang Dan, "Theory of Power Electronic Transformer and Its Applications" ,*High Voltage Engineering*, Vol:29, No.10, pp. 4-6, 2003.

[10] Wang Dan, Mao Chengxiong, Lu Jiming, "The Research on Characteristics of Electronic Power Transformer for Distribution System", *2005, IEEE/PES Transmission and Distribution Conference & Exhibition: Asia and Pacific Dalian*, China.

[11] Mao Chengxiong, Fan Shu, Huang Yiyu, Lu Jiming, “Theory of Power Electronic Transformer and Its Applications”, *High Voltage Engineering*, Vol:29, No.12, pp. 1-3, 2003.

[12] Shu Fan, Chengxiong Mao, Luonan Chen. “Optimal coordinated PET and generator excitation control for power systems,” *International Journal of Electrical Power & Energy Systems*, Vol:28, No.3, pp. 158-165, 2006.

[13] Wang Dan, Mao Chengxiong, Lu Jiming, “Master and Slave Control for Parallel Operation of EPTs”, J*ournal of Electrical and Electronics Engineering*, pp. 189-195, 2006.

[14] Chenglin Gu Qiaofu, Chen Yongqian Xiong, *Electromechanics*, Wuhan, Huazhong University of Science and Technology Press., 121-124, 2001.2.

[15] Jian Chen, *Power Electronics*, High Education Press, 45-47, 2004.12.

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Chengxiong MAO received his B.S., M.S. and Ph.D. degrees in electrical engineering, from HUST, Hubei China, in 1984, 1987 and 1991 respectively. Presently, he is a professor of HUST. His fields of interest are power system operation and control, the excitation control of synchronous generator and applications of high power electronic technology to power system.