Symmetrical Components Definition and Analyze for Power Electronic Converters in Non-sinusoidal Conditions

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Abstract: - As symmetrical components are very useful tools for power system analyzing in unbalance condition and defining phasor is hard for power electronics because of their switching behaviors, Time variable phasor is defined for power electronic wave forms at the first. Then some methods are proposed and evaluated for defining symmetrical components for power electronic converters. These methods are developed for zero, positive and negative circuits of a three phase half wave rectifier.
The final proposed method satisfies ABC to ZPN transform and vice versa and is tested with harmonics in voltage source. This study is started and has many steps to complete in future.

Key-Words: -Symmetrical components, non-sinusoidal condition, power electronic converters.

1 Introduction

Zero, Positive and Negative (ZPN) symmetrical components transform have this advantage that it transform a three phase system to a three decoupled (independent) system and it simplifies unbalance fault analyses. This transform is introduced by C. L. Fortescue in 1918[1].

Current and voltage wave forms are not sinusoidal in presence of nonlinear equipments like power electronic converters and they are time variable, But they are periodic. Using symmetrical component has problem in this situation because this transform is defined base on phasor and steady state condition and there is not a global accepted definition in non sinusoidal periodic states [2].

As switching is done with symmetrical and balance conditions in power electronic converters in steady state and wave forms are periodic, they can be defined as summation of some sinusoidal components base on Fourier transform theory. Therefore, it seems that symmetrical component theory can be used with a little change for power electronic converters, then analyzing of fault and unbalance condition will be easy [2-8].

Defining symmetrical ZPN circuit for non sinusoidal periodic wave forms is the goal of this paper. Then it is possible analyzing unbalance faults of power electronics converters with using these circuits. Many usages are imaginable for the result of this paper like power electronic converters fault detections and protection schemes [5-14].

In the first, a phasor must be defined for time variable wave forms in power electronic converters. This definition must satisfy ABC to ZPN transform and vice versa and also must fulfill power equation in ABC and ZPN domain. At the second, the proposed method must be usable for definition of zero, positive and negative equal circuit. For this propose, a three phase full wave rectifier as shown in Fig.1 is chosen for analyzing and modeling. It can be considered as two half wave rectifiers as shown in Fig.2.

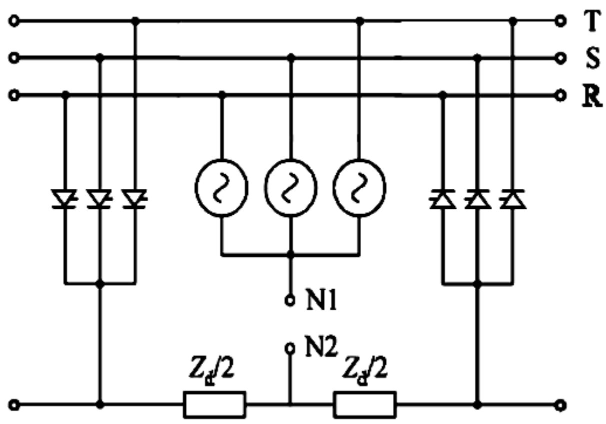

Fig 1. A full wave three phase rectifier as two half wave rectifier

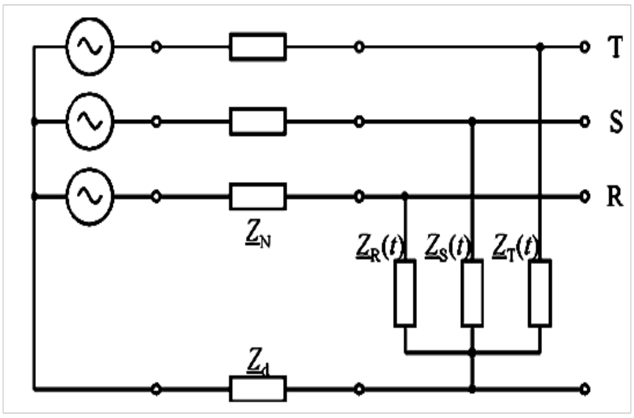

Fig 2. Modelling of a three pahse half wave rectifier

Three phase currents for a three phase rectifier are shown in Fig.3.

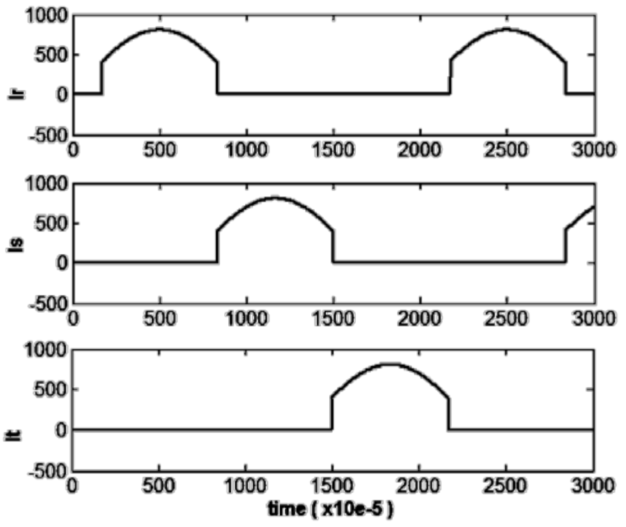

Fig 3. Three pahse half wave rectifier currents

As shown in Fig.3, three phase currents are periodic, in 120 degree phases and equal amplitude. Therefore, they are symmetrical but they are not sinusoidal.

The main question is that what is the zero, positive and negative components of these three phase wave forms? As symmetrical components are not defined for phasor and sinusoidal wave forms, the answer of this question is hard. Some answers are proposed and analyzed in this paper for this question.

2 First Method-RMS

It is possible to transforming the wave forms to harmonic components with Fourier transform. Then zero, positive and negative components were defined for each harmonic component. Therefore, Fourier transform of wave forms are done and the results are shown in Table 1.

Table 1. Harmonic Domains and phases

Freq.	$\lvert I_r \rvert$	φ_r	$\lvert I_s \rvert$	φ_s	$\lvert I_t \rvert$	φ_t	ZPN
0	58%	90^0	58%	90^0	58%	90^0	Z
50	100%	0^0	100%	240^0	100%	120^0	p
100	58%	270^0	58%	30^0	58%	150^0	n
150	15%	180^0	15%	180^0	15%	180^0	z
200	12%	270^0	12%	150^0	12%	30^0	p
250	15%	180^0	15%	-60^0	15%	60^0	n
300	3%	90^0	3%	90^0	3%	90^0	z
350	7%	180^0	7%	60^0	7%	-60^0	p
400	8%	90^0	8%	210^0	8%	-30^0	n
450	1%	0^0	1%	0^0	1%	0^0	z
500	5%	90^0	5%	-30^0	5%	210^0	p
550	6%	0^0	6%	120^0	6%	240^0	n

As shown in Table 1, different harmonic components belong to one of the zero, positive or negative components. A important point in Table 1. is that the similar symmetrical components have different phase for example 0, 150 and 300 hertz components are zero sequence but they have different phase 90, 180 and 90 degrees. Another point is that all 3n components are zero components, all 3n+1 components are positive and 3n+2 components are negative components. Another order seems in Table 1 that equal components have a sequence of 0, 270, 180 and 90 degrees in their phases. On this result, a quadruplet group can be defined as Table 2.

Table 2. Quadruplet Of ZPN Components

Iz	φ_z	In	φ_n	Ip	φ_p
12n-9	180^0	12n-10	270^0	12n-11	0^0
12n-6	90^0	12n-7	180^0	12n-8	270^0
12n-3	0^0	12n-4	90^0	12n-5	180^0
12n	270^0	12n-1	0^0	12n-2	90^0

The first answer to this paper question can be summing RMS of all similar components as (1).

$$I_F = \sqrt{\frac{1}{m}\sum_{i=1}^{m} I_{P_i}^2}, P = z, p, n \quad (1)$$

This method gives a scale for ZPN components but it does not seem correct because of different phase of different components. The result of (1) will not satisfy the inverse transform of ZPN to ABC. Also this method is not proper for developing zero, positive and negative equal circuits.

3 Second Method-Vector summation

The second method is vector summation of similar components as (2). The results are shown is Fig.4.

$$\vec{I}_{zero} = \sum_{i=1}^{m} \vec{I}_{zi}, \vec{I}_{pos} = \sum_{i=1}^{m} \vec{I}_{pi}, \vec{I}_{neg} = \sum_{i=1}^{m} \vec{I}_{ni} \quad (2)$$

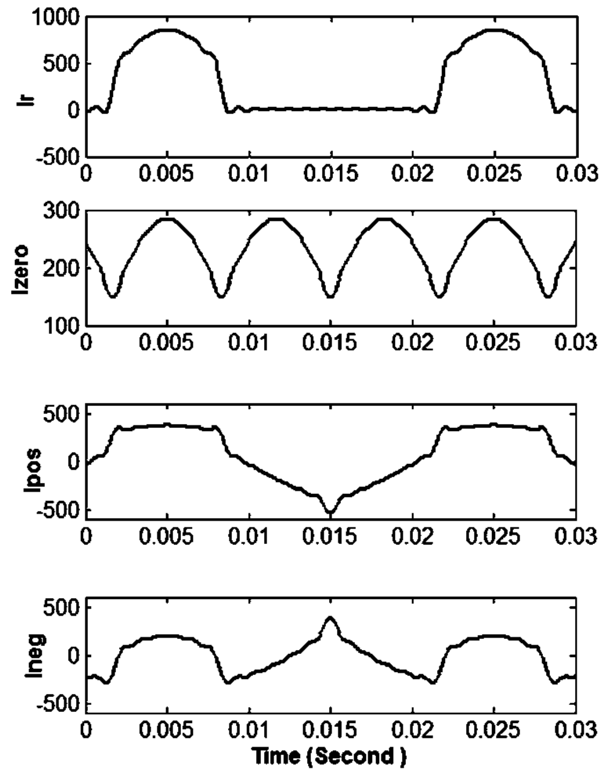

Fig 4. Zero, Positive and Negative components base on second method

As shown in Fig.4, The Ir will obtain with summation of ZPN components but Is and It will not obtain by inverse transform. The ZPN to ABC transform is done base on this method and the results are shown in Fig.5. Therefore, this method is not reversible and useful.

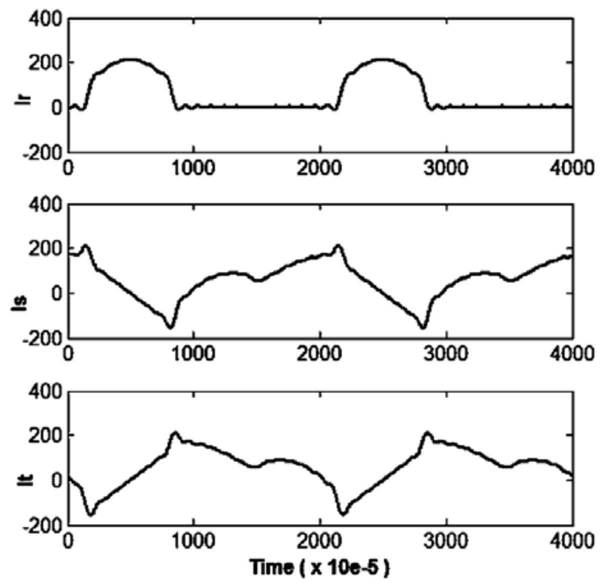

Fig 5. Invers transform for Fig.4

4 Third Method-new phasor definition

A phasor with time variable domain can be defined as (4) base on phasor definition as (3). The Ir wave form can be written as (4). The results are shown in Fig.6.

$$ASin(\omega t+\varphi)\Rightarrow Ae^{i\varphi} \quad (3)$$

$$A(t)Sin(\omega t+\varphi)\Rightarrow A(t)e^{i\varphi} \quad (4)$$

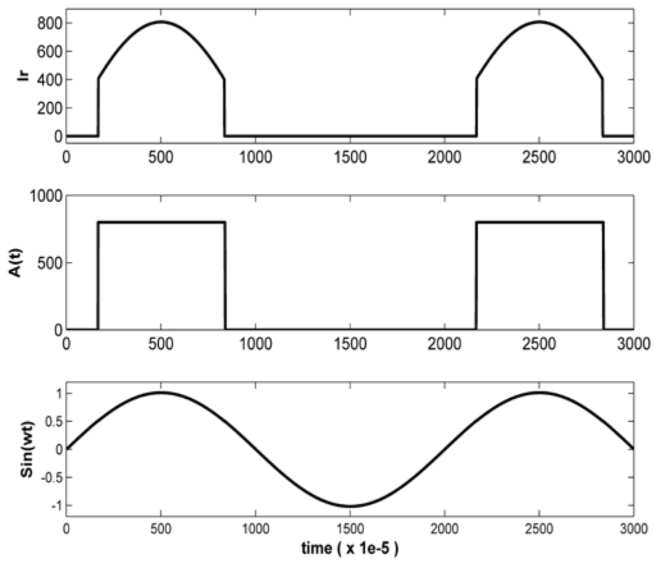

Fig 6. New phasor defination with time variable domain

Therefore, three phase currents can be written as (5) base on (4). Ar(t), As(t) and At(t) are shown in Fig.7.

$$\vec{I}_r = A_r(t)e^{i\varphi}, \vec{I}_s = A_s(t)e^{i(\varphi-\frac{2\pi}{3})}, \vec{I}_t = A_t(t)e^{i(\varphi-\frac{4\pi}{3})} \quad (5)$$

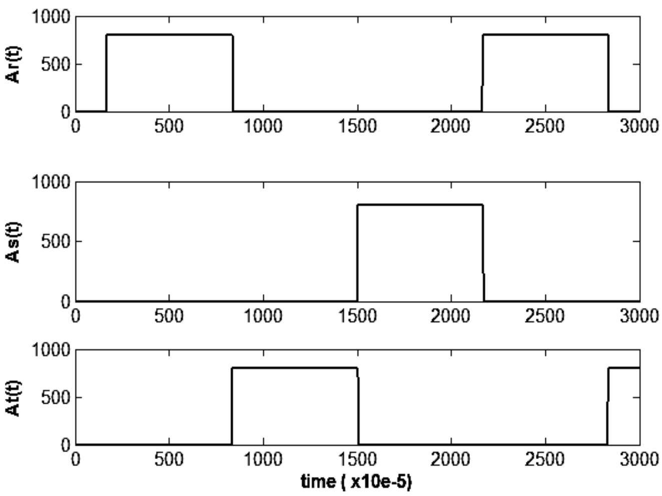

Fig 7. Ar(t), As(t) and At(t) domains

Equation (5) can be written as (6) for three phasors.

$$\begin{aligned}\vec{I}_r &= A(t)e^{i\varphi}\\ \vec{I}_s &= A(t-\tfrac{2\pi}{3})e^{i(\varphi-\frac{2\pi}{3})}\\ \vec{I}_t &= A(t-\tfrac{4\pi}{3})e^{i(\varphi-\frac{4\pi}{3})}\end{aligned} \tag{6}$$

Now, symmetrical components can be defined as (7).

$$\begin{aligned}I_z &= A(t)e^{i\varphi} + A(t-\tfrac{2\pi}{3})e^{i(\varphi-\frac{2\pi}{3})} + A(t-\tfrac{4\pi}{3})e^{i(\varphi-\frac{4\pi}{3})}\\ I_p &= A(t)e^{i\varphi} + A(t-\tfrac{2\pi}{3})e^{i\varphi} + A(t-\tfrac{4\pi}{3})e^{i\varphi}\\ I_n &= A(t)e^{i\varphi} + A(t-\tfrac{2\pi}{3})e^{i(\varphi+\frac{2\pi}{3})} + A(t-\tfrac{4\pi}{3})e^{i(\varphi-\frac{2\pi}{3})}\end{aligned} \tag{7}$$

The ZPN components can be defined according to (4)-(7). The result is shown in Fig.8.

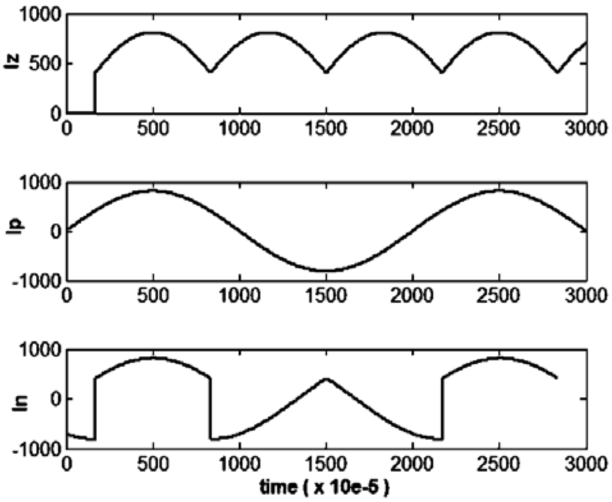

Fig 8. The ZPN components base on third method

This method satisfies the ZPN to ABC transform. The result for inverse transform is shown in Fig.9.

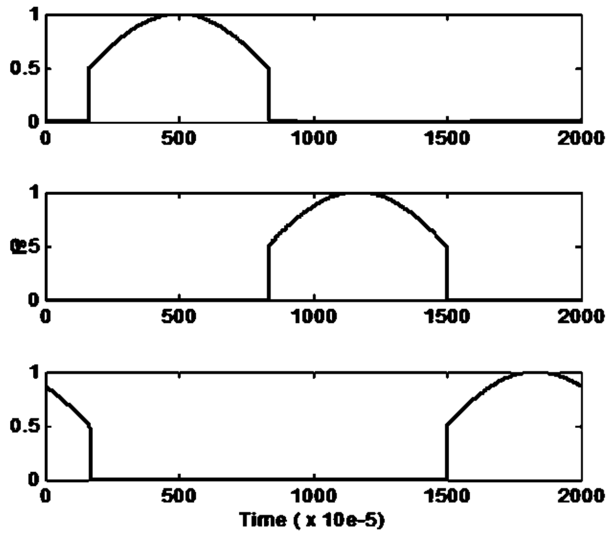

Fig 9. The inverse transoform base on third method

This method work correctly. The next step for analyzing the power electronic converters is defining of zero, positive and negative component circuits in faulty conditions. For this propose, impedance matrix of three phase rectifier is defined as (8) and (9) base on Fig.2 and Fig.10.

$$\begin{bmatrix}V_R(t)\\ V_S(t)\\ V_T(t)\end{bmatrix} = \boldsymbol{Z}_C(t)\begin{bmatrix}I_R(t)\\ I_S(t)\\ I_T(t)\end{bmatrix} \tag{8}$$

$$\begin{aligned}\boldsymbol{Z}_C(t) &= \begin{bmatrix} z_1(t) & z_d & z_d\\ z_d & z_2(t) & z_d\\ z_d & z_d & z_3(t)\end{bmatrix}\\ z_1(t) &= z_N + z_d + z_R(t)\\ z_2(t) &= z_N + z_d + z_S(t)\\ z_3(t) &= z_N + z_d + z_T(t)\end{aligned} \tag{9}$$

These matrixes are shown in Fig.10.

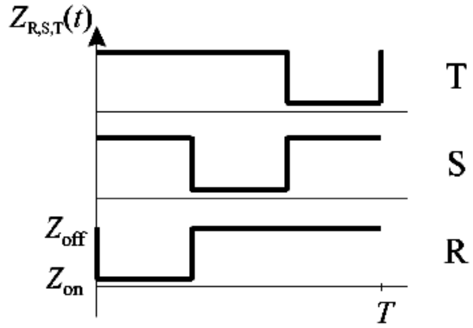

Fig 10. The Zrst(t) matrixes

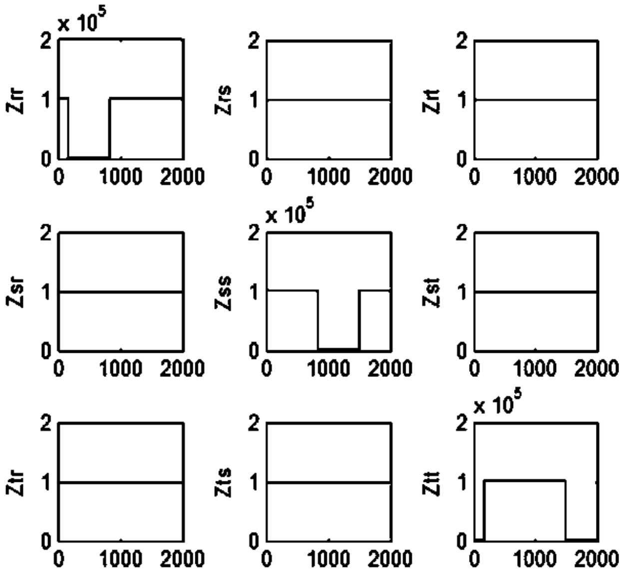

Fig 11. The rst network matrix

If this matrix is written as phasor then it transform to ZPN components, the non diagonal components will be constant and they can be written as $A\angle-\omega t$. The diagonal components will be converted to phasor as (5). For example, the $z_1(t)$ will convert to phasor as (10).

$$(Z_d + Z_N + Z_{off})\angle(-\omega t) - S_r(t)\angle 0 \tag{10}$$

The $\boldsymbol{Z}_C(t)$ impedance is drawn in Fig.11 and ZPN network matrix is obtained as Fig.12.

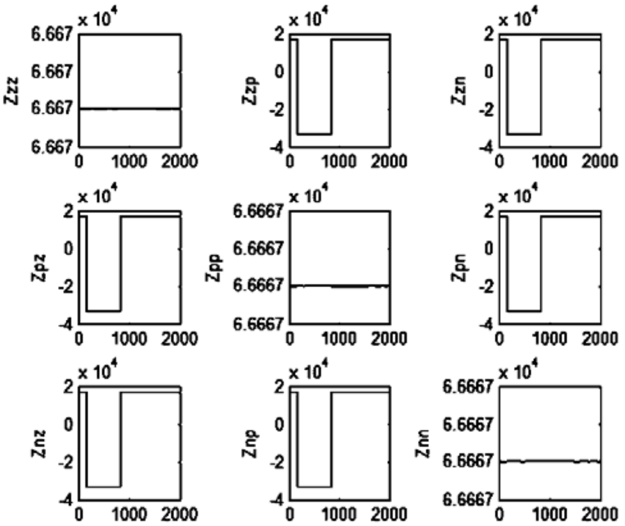

Fig 12. The ZPNetwork marix

Although this method works correctly in ABC to ZPN and vice versa, but the ZPN matrix is not decoupled and there is not definition for harmonic components. Therefore, the forth method is proposed.

5 Fourth Method-New Harmonic Definition

Transform matrix of ZPN to ABC and vice versa can be written as (11) for harmonic components. This transform is shown in Fig.13. And table 1. modified to Table 3 base on this definition.

$$A(h)=\begin{bmatrix}1 & 1 & 1\\ 1 & a(h)^2 & a(h)\\ 1 & a(h) & a(h)^2\end{bmatrix}, a(h)=e^{j\frac{2\pi h}{3}}$$

$$A^{-1}(h)=\frac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & a(h) & a(h)^2\\ 1 & a(h)^2 & a(h)\end{bmatrix} \quad (11)$$

Table 3. Harmonic Domains and phases base on (11)

Freq.	$\lvert I_z \rvert$	φ_z	$\lvert I_p \rvert$	φ_p	$\lvert I_n \rvert$	φ_n
0	58%	90^0	58%	90^0	58%	90^0
50	0%	0^0	110%	0^0	0%	0^0
100	0%	0^0	58%	270^0	0%	0^0
150	15%	180^0	15%	180^0	15%	180^0
200	0%	0^0	12%	270^0	0%	0^0
250	0%	0^0	15%	180^0	0%	0^0
300	3%	90^0	3%	90^0	3%	90^0
350	0%	0^0	7%	180^0	0%	0^0
400	0%	00^0	8%	90^0	0%	0^0
450	1%	0^0	1%	0^0	1%	0^0
500	0%	00^0	5%	90^0	0%	0^0
550	0%	0^0	6%	0^0	0%	0^0

Table 3 shows that each harmonic component is not belong to exact ZPN components and the 2, 5 and 8 components belong to positive components in conflict with Table 1. This method is defined as shown in Fig.13. The calculation results of this method are shown in Fig.14.

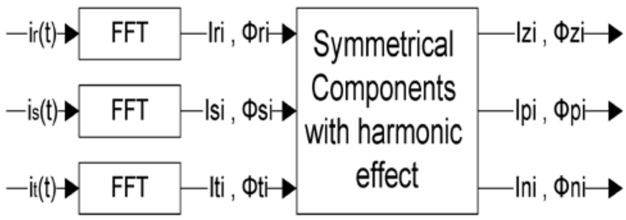

Fig 13. The ZPN harmonic transform

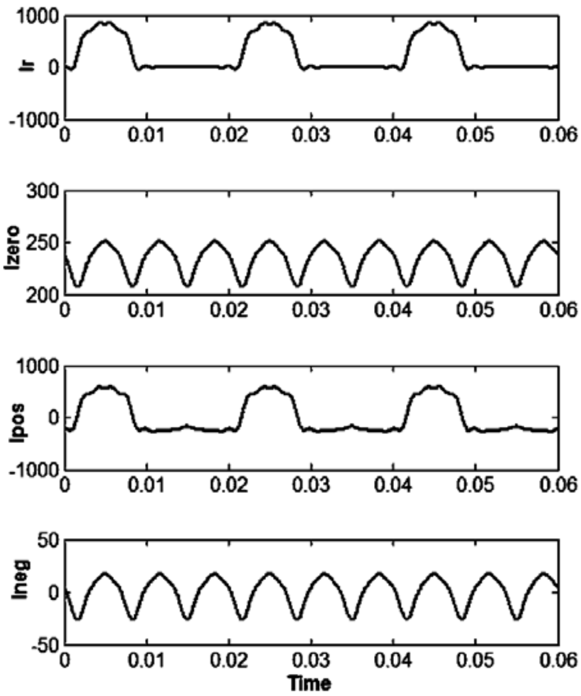

Fig 14. The ZPN components of Ir wave form

The ZPN components of current wave forms are shown Fig.14 and inverse transform is shown in Fig.15.

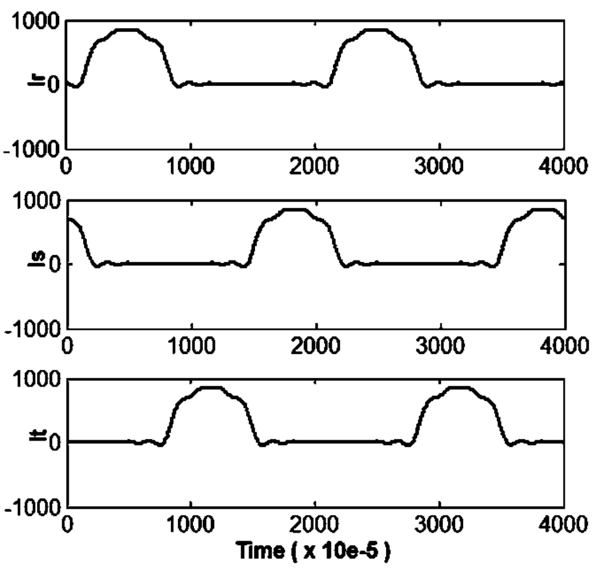

Fig 15. The inverse of ZPN components of Ir, Is and It

This method also transforms ABC to ZPN and vice versa correctly like third method.
The performance of this method is evaluated when 10% of 5th harmonic is added to source voltage. The current harmonics are as Table 4 for this case.

Table 4. Harmonic Domains and phases base of three phse currents with 10% 5th harmonic on voltage source

Freq.	$\|I_r\|$	φ_r	$\|I_s\|$	φ_s	$\|I_t\|$	φ_t	ZPN
0	245	90^0	210	90^0	211	90^0	z
50	419	0^0	360	237^0	361	122^0	p
100	243	270^0	213	24^0	212	155^0	n
150	59	180^0	57	165^0	55	195^0	z
200	50	267^0	41	153^0	42	24^0	p
250	60	178^0	54	-67^0	53	64^0	n
300	12	90^0	15	64^0	14	118^0	z
350	32	175^0	25	61^0	27	-66^0	p
400	34	86^0	31	201^0	30	-25^0	n
450	4	3^0	8	-32^0	7	39^0	z
500	23	83^0	18	-30^0	19	203^0	p
550	23	-6^0	22	109^0	21	243^0	n

The rectifier currents are shown in Fig.16 and the ZPN components are shown in Fig.17 for this case.

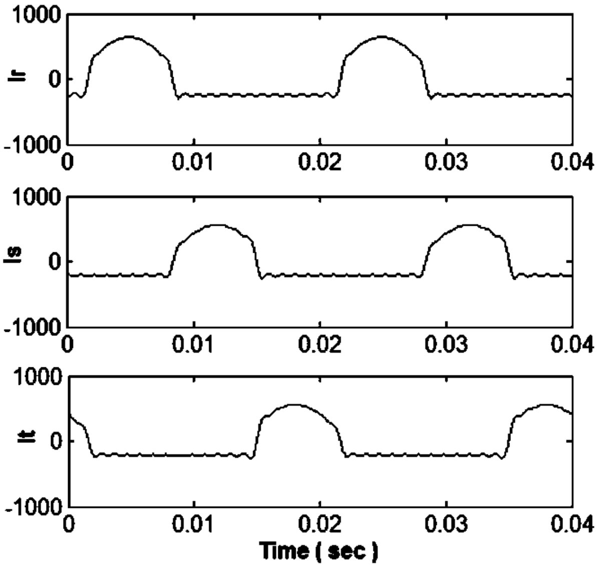

Fig 16. The rectifier current witj 10% 5th harmonic on voltage source

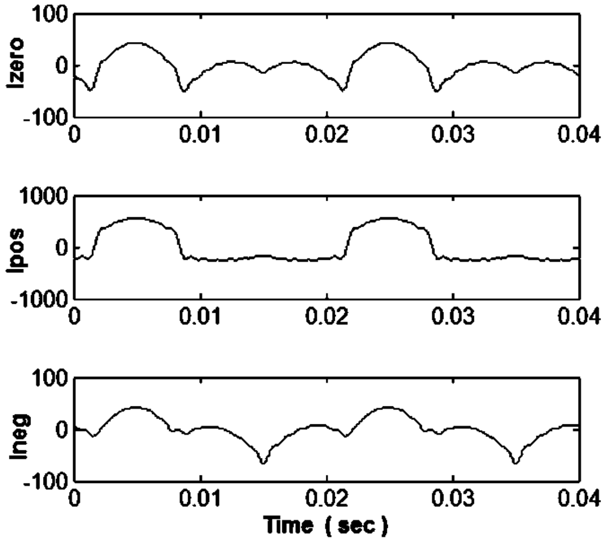

Fig 17. The ZPN components of Fig.15

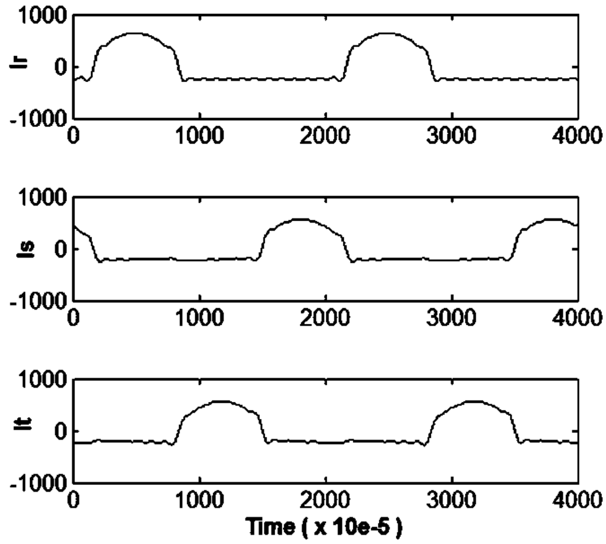

Fig 18. The rectifer current form inverse transform of proposed method

6 Conclusion

Some methods are proposed and analyzed in this paper for creating zero, positive and negative symmetrical components for power electronic converters. It was shown that the proposed methods can be developed for unbalance and faulty condition of power electronics converters.
The next step of this research is decoupling of the obtained ZPN components for comfortable analyzing and defining ZPN equivalent circuits for different power electronic converters. The proposed method was tested with one switch open fault in simulation. The third and fourth method was tested for power equation transform.

This study is started and has many steps to complete in future.

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