2009 3rd International Conference on Power Electronics Systems and Applications

More General Definition of Energy Factor and Its Application in Isolated Converters

Zhanghai SHI[1] K.W.E. CHENG[1] S.L. HO[1] Wei XU[2]
[1]Department of Electrical Engineering, the Hong Kong Polytechnic University, Hong Kong
[2]Faculty of Engineering and Information Technology, University of Technology, Sydney
E-mail:ee.zhhshi@polyu.edu.hk, eeecheng@inet.polyu.edu.hk, eeslho@polyu.edu.hk, wxu@eng.uts.edu.au

Abstract- Energy factor proposed as a goodness factor for dc system is reviewed in this paper. More general definitions of energy storage and energy factor are presented based on the analysis of energy process. By these new definitions, energy factor and energy storage can be extended into ac system. They can be used to compare the performance of different topologies of dc converters. The investigation of transformer's energy storage indicates that transformer has important influence to the characteristics of whole circuit. It depends on the way that transformer operates. If the transformer run as inductor (like Flyback converter), then it will improve the energy factor of the whole converter. But if the transformer run as a real transformer, then it will increase the non-active power consumption and make the energy factor worse. Simulation results explain BuckBoost and Flyback converter absorb the same amount of non-active power from front-end power supply. But the latter has better inner characteristics. Both input and inner characteristics of Buck converter are better than those of its isolated version which is Forward converter.

Keywords – Energy factor, energy storage, flyback converter, forward converter.

I. INTRODUCTION

During the operation of dc power converters, the energy was stored in the energy-storage components and delivered to the output stage or other terminals periodically with the switching frequency. This inherit property has been not explored thoroughly for the converter property especially the storage energy with aspects to the power throughput. The storage energy of the reactive components as compared with the output energy can be a method to measure how the effectiveness of the power is handled by DC systems.

A similar concept for DC drive systems has been proposed by Lawrenson[1] for the switched reluctance motor where it is termed the goodness factor. Energy factor as a goodness factor in dc converters was firstly put forward by Cheng in reference [2, 3]. In these papers, storage energy of inductor and capacitor is defined as the difference between maximum energy and minimum energy in one cycle. Energy factor is defined as the ratio of storage energy to output energy in one cycle. On the other hand the application of storage energy to control for dc converters has been developed[4, 5]. These new concepts provide a new measurement on the characteristics of dc converters. But those definitions of the new concepts can't be extended into ac system. So they are not general and systematical enough for electrical system. This paper explains the concepts proposed in [2, 3] based on the Fryze theory. The gap between the application of these concepts in ac and dc systems is filled in this paper.

To analyze the energy process for electrical system, the concepts of active power and reactive power are put forward and widely used. Active power is the average value of instantaneous power. It is based on physical energy balance that is the reason why it has not any controversy in the past. But reactive power has lots of developments from the initial definition since it was extended into non-sinusoidal systems for compensation research[6-14]. These developments of reactive power are mainly based on time-domain or frequency domain method. For the convenience of measurement, time-domain method has got lots of progress. Nowadays power electronic devices are widely used in power control. The systems including these devices are nonlinear systems. This means the currents in system may include the components with frequency which doesn't appear in input voltage. It is necessary to develop a concept to depict the energy process in power electronics devices especially in dc power converter.

As early as 1930, Fryze had proposed that the input current can be divided into two orthogonal components. One is in phase with the input voltage and has the same wave shape as that of input voltage. It is called the active component as it is responsible for the supply of the active power P. Another component is obtained by subtracting the active component from the main input current and is called reactive component. Based on this theory, this paper redefined the concepts proposed by Cheng. Through the definition in this paper, energy factor can be extended into ac system. And based on this definition, energy factor and energy storage are applied to evaluate the characteristics of isolated converters in this paper.

II. DEFINITION OF ENERGY STORAGE AND ENERGY FACTOR

The notes in this paper are listed as follows:

p: instantaneous power
P: active power
Q: non-active power
S: apparent power

The definition of energy storage and energy factor in this paper can be applied not only on reactive components but also any electrical circuits. The considered circuit can be

applied not only on reactive components but also any electrical circuits. The considered circuit can be regarded as one port network as Fig. 1. u and i are input voltage and current.

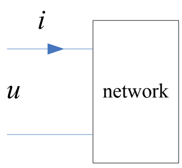


Fig. 1. One port network

According to Fryze theory, input current i can be decomposed into two components, active current i_a and non-active current i_q.

$$i_a = k \cdot u \quad (1)$$

$$i_q = i - i_a \quad (2)$$

$$k = \int_0^T uidt \Big/ \int_0^T u^2 dt \quad (3)$$

$$P = \frac{1}{T}\int_0^T uidt = \frac{1}{T}\int_0^T ui_a dt \quad (4)$$

$$q = u \cdot i_q \quad (5)$$

Obviously P is the active power. The quantity q can be regarded as instantaneous non-active power. When q is positive the circuit absorbs energy. Otherwise the circuit releases energy. The average value of q in one cycle of voltage must be zero. That means the energy absorbed and released by the circuit are equal. Then the energy absorbed or released by the circuit in one cycle T is defined as ***energy storage***. It is denoted by E_s . And its formula can be obtained as:

$$E_s = \frac{1}{2}\int_0^T |q| dt \quad (6)$$

The ratio of energy storage to the active input energy in one cycle of the whole considered system is defined as ***energy factor***. It is denoted by F_E which in reference [2] is MSEF (Maximum Storage Energy Factor). The formula of F_E can be obtained as:

$$F_E = \frac{E_s}{P \cdot T} \quad (7)$$

Two examples of E_s and F_E are presented as follows. One is for AC system, another is for DC system.

Example 1. AC system

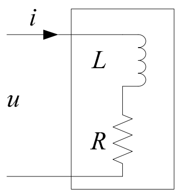


Fig. 2. The considered AC system

The circuit is as Fig. 2. Input voltage is

$$u = \sqrt{2}U\cos(\omega t) . \quad (8)$$

Then

$$i = \sqrt{2}I\cos(\omega t - \varphi) . \quad (9)$$

φ is the impedance angle. $T=2\pi/\omega$. According to Fryze theory, $k=I\cos\varphi/U$, then

$$i_a = k \cdot u = \sqrt{2}I\cos\varphi\cos(\omega t) , \quad (10)$$

$$i_q = i - i_a = \sqrt{2}I\sin\varphi\sin(\omega t) , \quad (11)$$

The input instantaneous and average active power are respectively:

$$p_{in} = u \cdot i_a = 2UI\cos\varphi\cos^2(\omega t) \quad (12)$$

$$P_{in} = \frac{1}{T}\int_0^T p_{in} dt = UI\cos\varphi \quad (13)$$

The input instantaneous non-active power

$$q_{in} = u \cdot i_q = UI\sin\varphi\sin(2\omega t) \quad (14)$$

It can be found that the traditional reactive power is in fact the amplitude of instantaneous non-active power. So energy factor can be viewed as another measurement of non-active power which is different from power factor.

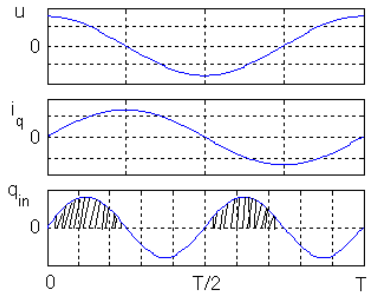


Fig. 3. The waveforms of input voltage, non-active current and non-active instantaneous power for AC system

The waveforms of input voltage u , input non-active current i_q and input non-active instantaneous power q_{in} are as Fig. 3. The shadow area in the waveform of q_{in} is the whole circuit's stored energy E_s . Then it can be proved that

$$E_s = 2LI^2 . \quad (15)$$

If the whole circuit is the considered system, then the whole circuit's energy factor

$$F_E = \frac{E_s}{P_{in} \cdot T} = \frac{2L}{RT} . \quad (16)$$

From equation (15), we can find that, the stored energy absorbed from source increases when the value of inductor increases.

For specified component in system, there is also corresponding energy factor. The stored energy of inductor and resistor in Fig. 2 can be calculated by above method.

It can be proved that $k = 0$ for inductor. If the considered system is still the whole circuit, then

$$E_{sL} = 2LI^2 \quad (17)$$

$$F_{EL} = \frac{E_{sL}}{P_{in} \cdot T} = \frac{2L}{RT} \quad (18)$$

$$E_{sR} = 0 \quad (19)$$

$$F_{ER} = 0 \quad (20)$$

It can be found that this circuit has the conversation of the energy storage and energy factor.

Example 2. DC system

The reactive components operating in dc system will have dc offset component besides alternated component. Here uses buck converter as example. Fig. 4 is the circuit of Buck converter

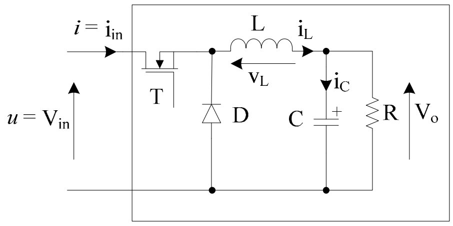


Fig. 4. The Buck converter

According to Fryze theory, $k = I_{in} / V_{in}$, I_{in} is the average value of input current.

$$i_{ina} = I_{in} \tag{21}$$

$$i_{inq} = i_{in} - I_{in}, \tag{22}$$

$$P_{in} = V_{in} \cdot I_{in} \tag{23}$$

$$q_{in} = V_{in} \cdot i_{inq} \tag{24}$$

The waveforms of input voltage V_{in} , i_{inq} and q_{in} are shown in Fig. 5

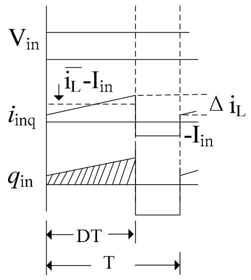


Fig. 5. The waveforms of input voltage, non-active current and non-active instantaneous power for AC system

The shadow area in q_{in} is the stored energy E_s . Then $E_s = (1-D)V_{in}I_{in}T$. If the whole circuit is the considered system, then the whole circuit's energy factor

$$F_E = \frac{E_s}{P_{in} \cdot T} = 1 - D \tag{25}$$

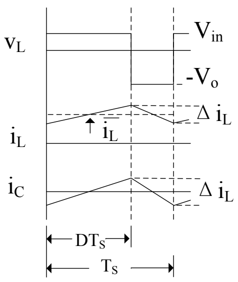


Fig. 6. The waveforms of Buck converter in CCM

Through the above method, the stored energy of inductor, capacitor and resistor in Fig. 4 can be calculated. It can be proved that $k = 0$ for inductor. If the considered system is still the whole circuit, then

$$E_{sL} = \int_0^{DT} v_L i_L dt = (1-D)V_{in}I_{in}T \tag{26}$$

$$\tfrac{1}{2}Li_{L\max}^2 - \tfrac{1}{2}Li_{L\min}^2 = (1-D)V_{in}I_{in}T \tag{27}$$

It is interesting that in dc system the definition of energy storage proposed in this paper is the same with energy storage defined by Cheng in reference [2, 3]. This coherence can be also proved for capacitor in Fig. 4. But the definition proposed by this paper can be extended into AC systems，and it is more general than the definition in [2, 3].

$$F_{EL} = \frac{E_{sL}}{P_{in} \cdot T} = 1 - D \tag{28}$$

$$E_{sC} = \frac{1-D}{4K} V_{in} I_{in} T \tag{29}$$

$$F_{EC} = \frac{E_{sC}}{P_{in} \cdot T} = \frac{1-D}{4K} \tag{30}$$

$$E_{sR} = 0 \tag{31}$$

$$F_{ER} = 0 \tag{32}$$

In the above equations, $K=2L/(RT_S)$. We can also compute the energy storage and energy factor for Buck converter under discontinuous mode. The results are as TABLE I.

TABLE I
ENERGY FACTOR FOR WHOLE CIRCUITS AND EACH COMPONENTS OF BUCK CONVERTER

mode	F_{Ein}	F_{EL}	F_{EC}	F_{ER}
CCM	$1-D$	$1-D$	$\frac{1-D}{4K}$ *	0
DCM	$\frac{(2-D+DM)^2}{4(1-M)}$	$1-M$	$(1-\frac{D}{2M})^2$	0

* $K=2L/(RT_S)$

M is the voltage conversion ratio. Under discontinuous mode,

$$M = (1+\sqrt{1+4D^2/K})/2 \tag{33}$$

It can be found that the energy factors of inductor and capacitor in TABLE I are the same with those in reference [2]. The reason of this result is as follows. In fact, at steady state the active power of inductor and capacitor are zero. That means the power through them is non-active power. So their energy variation which is the difference between maximum energy and minimum energy is their energy storage. And then the energy factor of inductor and capacitor are same under these two definitions.

Besides inductor and capacitor, the energy factor of the whole circuit and resistor can be also presented by the definition proposed in this paper. Special attention should be paid on that the energy factor of the whole circuit is not simple the sum of each component's energy factor. It is just like that whole circuit's power factor is not equal to the sum of each component's power factor.

III. THE ENERGY FACTOR OF SOME BASIC ISOLATED CONVERTERS

For isolated DC converter, there is one kind of vital component, which is transformer. In fact transformer is multiport component. The transformer in Fig. 7 has 1 primary side and m secondary sides.

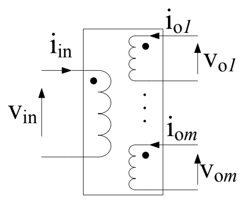


Fig. 7 The multi-output transformer

If we just look into the transformer from the primary side, we can use the input voltage and current to calculate the total input energy storage and energy factor of the whole transformer and its after loads. But if we separate the transformer and its after loads and view it as a single unit, then we can calculate the energy storage and energy factor for only transformer. The method is as follows.

The transformer in Fig. 7 can be viewed as *n+1* ports network. The positive direction of each port's voltage and current are shown in Fig. 7

The total instantaneous injected power is

$$p = v_{in}i_{in} + \sum_{n=1}^{m} v_{on}i_{on} \quad (34)$$

$$k_{in} = \frac{\int_0^T v_{in}i_{in}dt}{\int_0^T v_{in}^2 dt} \quad (35)$$

$$k_{on} = \frac{\int_0^T v_{on}i_{on}dt}{N_n^2 \int_0^T v_{in}^2 dt},\ n=1,\cdots,m \quad (36)$$

Then

$$q_{in} = v_{in}(i_{in} - k_{in}v_{in}) \quad (37)$$

$$q_{on} = v_{on}(i_{on} - k_{on}v_{on}),\ n=1,\cdots,m \quad (38)$$

$$q = q_{in} + \sum_{n=1}^{m} q_{on} \quad (39)$$

Then the energy storage and energy factor for the transformer alone are:

$$E_{s\_total} = \frac{1}{2}\int_0^T |q_{total}|dt \quad (40)$$

$$F_{E\_total} = \frac{E_{s\_total}}{PT} \quad (41)$$

P is the considered system's average input active power.

So to calculate the energy storage and energy factor, we only need to examine the total instantaneous injected power's waveform.This method is suitable for not only transformer but also any other multiport network.

If we only consider the magnetizing inductance for a transformer, but neglect all resistance and the leakage inductance of both primary and secondary side, then the calculation may be simplified. In this case, below equations must be satisfied

$$\frac{v_{on}}{v_{in}} = N_n,\ n=1,\cdots,m \quad (42)$$

$$P_{tr} = \int_0^T pdt = 0 \quad (43)$$

By some math operation, it can be proved that

$$q = p \quad (44)$$

This means in the case of neglecting leakage resistance and inductance, the transformer's power is thorough non-active power. Substitute (34) and (42) into (44), we can get

$$q = v_{in}(i_{in} + \sum_{n=1}^{m} N_n i_{on}) \quad (45)$$

This equation shows that we can use equivalent voltage and current to calculate the non-active power of transformer. v_{in} is the equivalent voltage. The equivalent current is the sum of input current and all output currents referred to the primary side。Then we can acquire the energy factor through the waveform of non-active power.

Further, if the magnetizing inductance is neglected, then the transformer becomes ideal transformer. Its currents should satisfy

$$i_{in} + \sum_{n=1}^{m} N_n i_{on} = 0 \quad (46)$$

Then

$$q = p = 0 \quad (47)$$

This means ideal transformer doesn't absorb not only active power but also non-active power. So its energy storage and energy factor are zero.

1. Flyback converter

Flyback converter is one of the most commonly used converters. It is very popular for a small power isolated converter because of its simple configuration. In fact it is the isolated version of Buck-Boost converter.

The circuit and typical CCM operation waveform of flyback converter are shown as Fig. 8.

a) The total input energy factor F_{Ein}

According to (3) and Fig. 8, we can get

$$k_{in} = DI_{mp}/V_{in} \quad (48)$$

$$i_{inq} = i_{in} - DI_{mp} \quad (49)$$

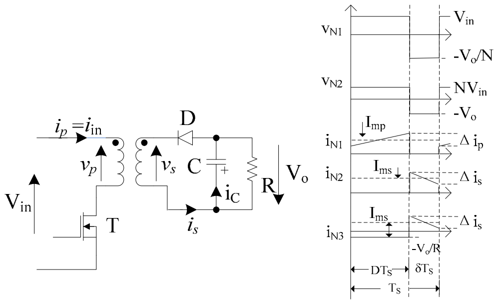
$$q_{in} = V_{in}i_{inq} \quad (50)$$

$$I_{in} = DI_{mp} \quad (51)$$

then

$$E_{s\_in} = (1-D)V_{in}I_{in}T_s \quad (52)$$

$$F_{Ein} = 1-D \quad (53)$$



(a) (b)

Fig. 8 (a) Flyback converter, (b) operation waveform of Flyback

b) Each component's energy factor

Flyback converter has only two reactive components. One is transformer, another is capacitor.

The transformer's energy factor can be acquired by the method in section III. Here we only consider the magnetizing inductance in the model of transformer. The leakage impedance and magnetizing resistor are neglected. So as mentioned previously, the equivalent voltage is the primary voltage. The equivalent current of transformer is the sum of input current and all output currents referred to the primary side.

The results of energy storage and energy factor of Flyback converter are as follows:

$$E_{s\_tr} = DV_{in}I_{in}T_s \quad (54)$$

$$F_{E\_tr} = D \quad (55)$$

$$E_{sC} = DV_{in}I_{in}T_s \quad (56)$$

$$F_{EC} = D \quad (57)$$

2. Forward converter

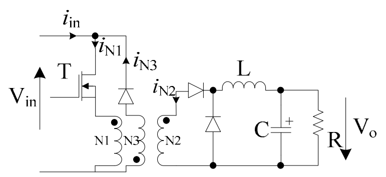
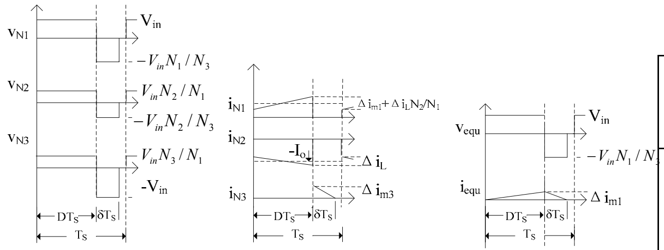


Fig. 9 forward converter

The circuit of forward converter is shown as Fig. 9 During the off time, the third winding must reset the flux. The resetting time is δT_s.

$$\delta = DN_3 / N_1 \quad (58)$$

Again, here we only consider the magnetizing inductance in the model of transformer. Assume the magnetizing inductance is L_M referred to the primary side.



(a) (b) (c)

Fig. 10 (a) the waveform of voltage, (b) the waveform of current, (c) equivalent waveform for the transformer

a) The total input energy factor F_{in}.

The input current of the whole circuit is the sum of the first and third winding's current. Then the following equation can be derived from Fig. 10.

$$i_{inq} = i_{in} - I_{in} \quad (59)$$

$$I_{in} = DI_oN_2 / N_1 \quad (60)$$

$$E_{s\_in} = (1-D)V_{in}I_{in}T_s + \frac{1}{2}V_{in}\Delta i_{m1}DT_s \quad (61)$$

$$F_{Ein} = 1 - D + (\frac{N_1}{N_2})^2 / K_M \quad (62)$$

K_M=2L_M/(RT_s)

b) Each components energy factor

Forward converter's reactive components include a three-winding transformer, an inductor and a capacitor.

For the transformer, according to the method in section III, the waveforms of equivalent voltage and current can be derived from Fig. 10 (a) and (b). Then the energy storage is

$$E_{s\_tr} = \frac{1}{2}V_{in}\Delta i_{m1}DT_s \quad (63)$$

$$F_{E\_tr} = \frac{E_{s\_tr}}{V_{in}I_{in}T_s} = (\frac{N_1}{N_2})^2 / K_M \quad (64)$$

And the energy storage and energy factor of the inductor and capacitor can be easily calculated from Fig. 10. They are as follows.

$$E_{sL} = (1-D)V_oI_oT_s \quad (65)$$

$$F_{EL} = 1 - D \quad (66)$$

$$E_{sC} = \frac{1}{8}(1-D)V_o^2T_s^2 / L \quad (67)$$

$$F_{EC} = (1-D)/(4K) \quad (68)$$

K=2L/(RT_s).

IV. The Comparison of Some Basic Isolated Converters by Energy Factor

TABLE II lists the input energy factors of Buck, Buckboost and their isolated versions under continuous mode.

TABLE II
INPUT ENERGY FACTOR OF BUCK, BUCKBOOST, FLYBACK AND FORWARD CONVERTER

Input energy factor	Buck	Buckboost	Flyback	Forward
F_{Ein}	$1-D$	$1-D$	$1-D$	$1-D+(\frac{N_1}{N_2})^2/K_M$

*K_M=2L_M/(RT_S)

From TABLE II, We can find that the energy factors of Buckboost and Flyback converter are same. Fig. 11 is their characteristic curve. These results are reasonable because as well known the transformer in Flyback converter is in fact an inductor. It is like the inductor in Buckboost converter. From this point these two topologies have the same structure. So their energy storage and energy factor are also same.

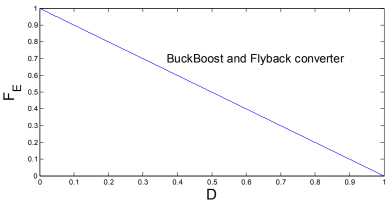


Fig. 11 energy factor of BuckBoost and Flyback converter

Fig. 12 is their characteristic curve of energy factors of Buck and Forward converters. The circuits' parameters are same for these converters. They are R=10Ω, L=50μH, L_M=150 μH, C=47μF, f_s=100kHz. These values can make sure the converters operate under continuous mode.

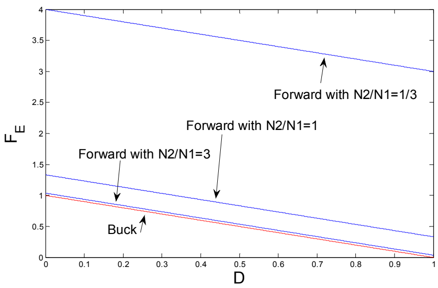


Fig. 12 energy factor of Buck and Forward converter with different turn's ratio

From Fig. 12 we can find that forward converter's energy factor is always bigger than Buck converter's energy factor. As mentioned before, energy factor can be viewed as a measurement of non-active power. So Fig. 12 shows that transformer will increase the non-active power absorbed from front-end supply. The energy factor of forward converter depends on the turn's ratio and increases rapidly along with the decrease of turn's ratio. This is reasonable. Because the increased part of non-active power of forward converter refer to buck converter is in fact consumed by magnetic inductor. If the turn's ratio decreases, the circuit parameters and duty ratio are kept invariable, then the input average current will also decrease. But the non-active current absorbed by magnetic inductor does not change. Then the ratio of magnetic inductor's non-active current to the input average current will increase. So the energy factor will also increase.

TABLE III lists each component's energy factors of Buck, Buckboost and their isolated versions under continuous mode.

TABLE III
EACH COMPONENT'S FACTOR OF BUCK, BUCKBOOST, FLYBACK AND FORWARD CONVERTER

component	Buck	Buckboost	Flyback	Forward
inductor	$1-D$	1	-	$1-D$
capacitor	$\frac{1-D}{4K}$ *	D	D	$\frac{1-D}{4K}$ *
transformer	-	-	D	$(\frac{N_1}{N_2})^2/K_M$ *
sum	$1-D+\frac{1-D}{4K}$	$1+D$	$2D$	$1-D+\frac{1-D}{4K}+(\frac{N_1}{N_2})^2/K_M$

* $K=2L/(RT_S)$, $K_M=2L_M/(RT_S)$

Fig. 13 shows the characteristics of the sum of all components' energy factors against duty ratio. The circuits' parameters are same for these converters. They are N_2/N_1=5, R=10Ω, L=50μH, L_M=150 μH, C=47μF, f_s=100kHz. These values can make sure the converters operate under continuous mode.

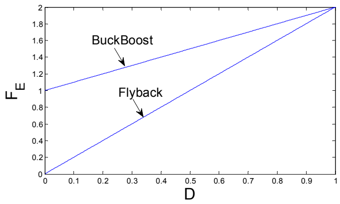


Fig. 13 the sum of all components' energy factors of BuckBoost and Flyback converter against duty ratio

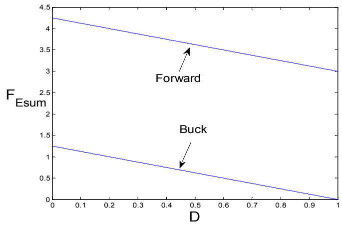


Fig. 14 the sum of all components' energy factors of Buck and Forward converter against duty ratio

Components' energy factors can reflect the characteristics of inner non-active energy circulating inside the converters. The non-active energy circulating inside the converters will cause power loss and the loss of voltage conversion ratio. The sum of all components' energy factors in a converter represents the amount of the inner non-active circulating energy in this converter. Fig. 13**Fig. 14** shows the sum of all components' energy factors of the BuckBoost and Flyback converters under CCM respectively. From Fig. 13 we can find that BuckBoost converter has more amount of inner non-active circulating energy than Flyback converter. This means from the angle of energy factor Flyback converter has a better inner characteristic. This is reasonable because Flyback converter is derived from BuckBoost converter by replacing the inductor with transformer. This transformer consumes less non-active power than inductor.

Similarly, Fig. 14 shows the sum of all components' energy factors of the Buck and Forward converters under CCM respectively. From Fig. 14 we can find that the Forward converter has more amount of inner non-active circulating energy than Buck converter. This means from the angle of energy factor Forward converter has not only worse input characteristic but also worse inner characteristic than Buck converter.

V. CONCLUSION

The new terminology of energy factor which is originally proposed for dc converter in reference [2, 3] is discussed from a new angle based on non-active energy process in circuits. The more general and more sophisticated definitions of energy storage and energy factor are proposed. By the proposed definition in this paper, energy storage and energy factor can be extended from dc system into ac system. The energy process analysis shows that the energy storage and energy factor are different from traditional reactive power and power factor. Energy storage and energy factor can be also as measurement of performance of electrical system.

Transformer is the key component for isolated converters. It has impact to energy storage and energy factor of DC converters. If the transformer run as inductor (like Flyback converter), then it will improve the energy factor of the whole converter. But if the transformer run as a real transformer, then it will increase the non-active power consumption and make the energy factor worse. Two basic isolated converters' energy factor has been researched in detail. Calculation results explain BuckBoost converter and its isolated version which is Flyback converter has the same input energy factor. But the latter has a better inner characteristic. Simulation results show that both input and inner total energy factor of Buck converter are small than those of it isolated version which is Forward converter.

VI. FUTURE WORK

The future research will clarify the influence of input energy factor to the front-end equipments. And the influence of the sum of components' energy factors in a converter to the efficiency and the voltage conversion ratio is to be researched quantitatively. The application of energy factor in the control of DC power supply is also need to be discussed.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support of the Research Grants Council (RGC) of Hong Kong (PolyU5136/06E) and The Hong Kong Polytechnic University (B-Q02W) for this project.

REFERENCES

[1] P. J. Lawrenson, S. J.M., B. P.T., C. J., and N. N. Fulton, "VARIABLE-SPEED SWITCHED RELUCTANCE MOTORS," IEE Proceedings, Part B: Electric Power Applications, vol. 127, pp. 253-265 1980.

[2] K. W. E. Cheng, "Storage energy for classical switched mode power converters," IEE Proceedings: Electric Power Applications, vol. 150, pp. 439-446, 2003.

[3] K. W. E. Cheng and Y. Lu, "Formulation of the energy-storage factor for isolated power convertors using integrated magnetics," IEE Proceedings: Electric Power Applications, vol. 152, pp. 837-844, 2005.

[4] F. L. Luo and H. Ye, "Energy factor and mathematical modelling for power DC/DC converters," IEE Proceedings: Electric Power Applications, vol. 152, pp. 191-198, 2005.

[5] F. L. Luo and H. Ye, "Small signal analysis of energy factor and mathematical modeling for power dc-dc converters," IEEE Transactions on Power Electronics, vol. 22, pp. 69-79, 2007.

[6] C. H. Page, "Reactive Power in Nonsinusoidal Situations," Instrumentation and Measurement, IEEE Transactions on, vol. 29, pp. 420-423, 1980.

[7] Chester and H. Page., "Reactive Power in non sinusoidal situations," IEEE Transactions on Instrumentation and measurement, vol. IM-29, pp. 420-423, 1980.

[8] L. S. Czarnecki, "Considerations on the Reactive Power in Nonsinusoidal Situations," Instrumentation and Measurement, IEEE Transactions on, vol. 34, pp. 399-404, 1985.

[9] L. S. CZARNECKI, "What is Wrong with the Budeanu Concept of Reactive and Distortion Power and Why It Should be Abandoned," IEEE Transactions on Instrumentation and Measurement vol. IM-36, pp. 834-837, 1987.

[10] M. Depenbrock, "The FBD-method, a generally applicable tool for analyzing power relations," Power Systems, IEEE Transactions on, vol. 8, pp. 381-387, 1993.

[11] J. Itoh and K. Fujita, "Novel unity power factor circuits using zero-vector control for single-phase input systems," IEEE Transactions on Power Electronics, vol. 15, pp. 36 - 43, 2000.

[12] N. L. Kusters and W. J. M. Moore, "On the Definition of Reactive Power Under Non-Sinusoidal Conditions," IEEE Transactions on Power Apparatus and Systems, vol. PAS-99, pp. 1845-1854, 1980.

[13] M. Saitou and T. Shimizu, "Generalized theory of instantaneous active and reactive powers in single-phase circuits based on Hilbert transform," presented at Power Electronics Specialists Conference, 2002. pesc 02. 2002 IEEE 33rd Annual, 2002.

[14] D. SHARON, "Reactive-power definition and power-factor improvement in nonlinear systems," IEE Proc., vol. 120, pp. 704-706, 1973.