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Review

A review of energy losses in power electronics converters and developments in related application fields

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Abstract: In recent years, the world has been paying more and more attention to the power electronics converter in the power system. The power electronics converter has made great development in its own structure and control strategy, but there are still concerns of significant energy consumption and insufficient energy saving in many fields of application, the purpose of this paper is to let researchers grasp the current situation of the power electronics converter research and advance the development of the industry. Firstly, we review and evaluate some relevant methods that can evaluate the energy consumption of power electronic converters and introduce several cases of improving the topology in order to achieve energy saving. Afterwards, we introduce and summarize the development and application of power electronic converters in specific scenarios. The review and discussion presented in this paper concludes with some limitations and concerns in the current development of power electronics converters.

Keywords: switch losses; conduction losses; modular approach; topology; case study

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1. Introduction

In recent years, developing and emerging economies have undergone significant industrialization, leading to concurrent progress in their economic and industrial sectors. This development has been accompanied by a notable increase in the demand for electric energy. To meet the growing need for electric energy in industrial production, a reliable and uninterrupted power supply is essential. Against the backdrop of dwindling fossil fuel reserves, the investigation of innovative energy generation methods has gained considerable attention. Presently, although new energy generation cannot fully meet global electricity demands, it does contribute significantly to addressing the rising electricity consumption [1].

A decade ago, certain Scandinavian countries, notably Denmark, established a substantial presence in wind power generation, surpassing their entire electricity consumption [2]. Many nations are now strategizing to significantly augment their reliance on new energy sources, including solar and wind power. For instance, the United States has outlined plans for the next decade to markedly enhance the deployment of wind and solar power generation as a replacement for coal-based electricity generation, as depicted in Figure 1[3]. The integration of new energy generation technologies is intrinsically linked to discussions on power systems, particularly concerning electronic power technology [4-6]. Power electronics converters have gained increasing attention from researchers and hold substantial potential for the future, as indicated by the expanding market depicted in Figure 2[7]. While the application of power electronics converter s is well-established in certain domains such as electric aviation and the widespread adoption of hybrid and electric vehicles [8-11], notable challenges persist. Foremost among these are the optimization of converter structures and control strategies to mitigate excessive energy losses. Precisely analyzing losses across all facets of these systems poses a considerable challenge. This paper aims to provide targeted analyses that can offer valuable insights in addressing these concerns.

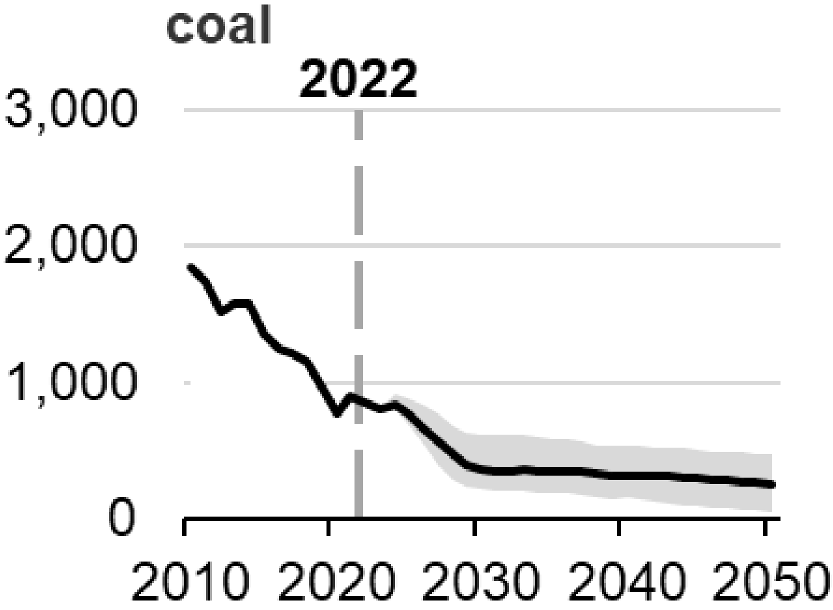

Figure 1. U.S. electricity generation by coal (Projected from 2022 onwards), from [3], data from the U.S. Energy Information Administration, Annual Energy Outlook 2023 (AEO2023)

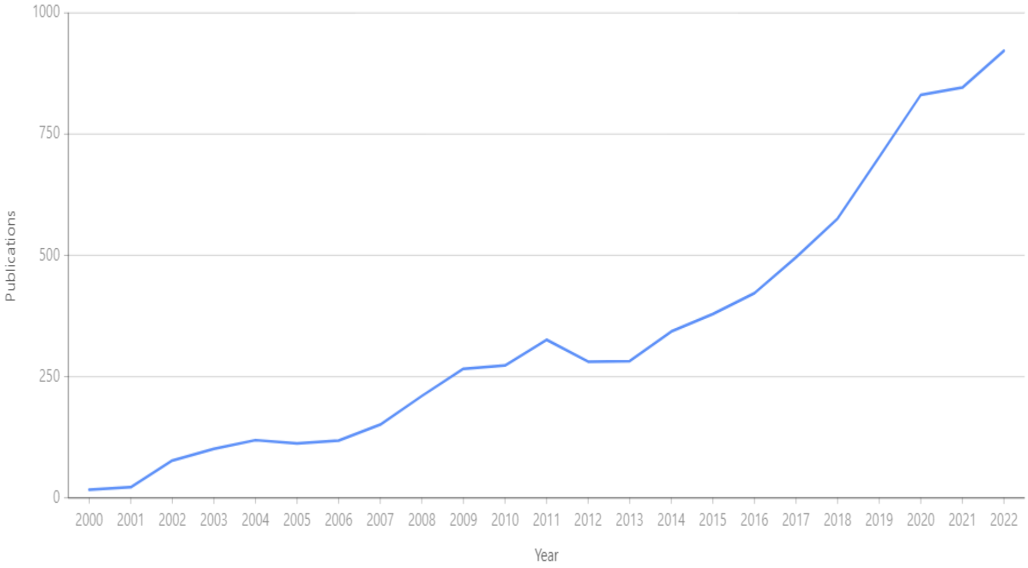

Figure 2. The number of power electronic converter research publications in the Web of Science from 2000-2022

This paper aims to provide a precise and specific examination of the energy consumption associated with individual components of power electronics converters. Such an analysis serves the dual purpose of elucidating the current state of electronic power technology development and facilitating the identification of optimization avenues for researchers. The primary methodology employed herein involves offering a comprehensive overview of pertinent literature concerning the structure and energy consumption aspects of power electronics converters. The research's significance is multifold: (1) By engaging in discussions and analyses based on the energy dissipation equation model of converters, this paper enhances comprehension of the variables influencing losses, thus providing valuable guidance for research and development efforts concerning novel converters. (2) The research experience introduced two typical converter application domains serves as a reference point for guiding future advancements in electronic power technology.

The paper's structure is organized as follows:

In the second section, converter losses will be described. Power electronics converter losses are categorized into different types, including conduction losses, switching losses, gate losses, capacitance losses, and others. The section evaluates the significance and analytical utility of each loss category. Specifically, it discusses conduction and switching losses, employing a blend of theoretical and practical approaches. Additionally, this paper also discusses the issue of energy consumption and energy saving in terms of converter topology through some cases. The third section concentrates on converter applications within renewable energy conversion systems and new energy networks. It consolidates ongoing research progress and findings in this area. The final section addresses deficiencies and shortcomings in energy consumption modeling and its practical applications.

2. Energy loss analysis of power electronic converters

Provide sufficient details to allow the work to be reproduced by an independent researcher. Methods that are already published should be summarized, and indicated by a reference. If quoting directly from a previously published method, use quotation marks and also cite the source. Any modifications to existing methods should also be described.

2.1 Analyzing losses from specific circuit components

2.1.1 The big picture of losses

In order to be able to clarify the energy losses of a power electronics converter, it is obviously important to identify the specific power losses of each module. There are many factors affecting the power loss of a power electronics converter, such as switching loss and conduction loss generated by semiconductor devices such as transistors and diodes, the loss of passive components such as inductors and capacitors, which are common in typical DC transformers such as DC/DC, the energy loss brought about by the core of the magnetic components and the gate drive loss.

Dušan Graovac et al. of Infineon Technologies AG proposed a model of equation (1), which effectively illustrates the part that considers semiconductor power loss under practical application conditions of normal accuracy, where P_l represents the power loss in the semiconductor, which generally has two major components, conduction loss P_c, and switching loss P_{sw}, while the third component leakage loss P_b is often neglected in the study of loss problems, considering the first two parts of the sum can be [12].

$$P_l = P_c + P_{sw} + P_b \approx P_c + P_{sw} \tag{1}$$

In contrast, U. Badstuebner discusses the losses in power electronic converters more precisely, especially under the requirement of high precision estimation. The weights of the three different losses, conduction loss ($P_{cond,MOS}$), switching loss($P_{zvs,off,A}$, $P_{zvs,off,B}$), and gate loss(P_{gate}), on the overall semiconductor losses of the power electronics converter are given in equation (2) below[13].

$$\mathbf{P_{semi} = 2\left(P_{zvs,off,A} + P_{zvs,off,B}\right) + 4P_{cond,MOS} + 2P_{cond,rect} + 4P_{gate}} \tag{2}$$

After reviewing the two ways of calculating losses above, in the following expressions related to the consideration of energy losses, the focus will be on the switching and conduction losses generated by semiconductor components, and the losses of passive device inductors and gate losses will be discussed briefly, and other losses, such as leakage losses, will no longer be included.

2.1.2 Switching and conduction losses

Switching and conduction losses in power electronics converter s will be discussed mainly in terms of losses associated with typical transistors (e.g. IGBT, MOSFETs) and diodes of different materials. Some typical mathematical models of the paper will be presented and discussed here to effectively and comprehensively evaluate the associated losses.

Poopak Roshanfekr et al. in designing an IGBT active rectifier for permanent magnet synchronous generator (PMSG) applied in wind power generation gives the on-state and switching losses in the IGBTs and diodes, respectively, and the following equations (3)-(6) show the specific formulas for the calculation of the formulae, where P_{swD}, $P_{swIGBT}$are the diode and transistor switching power consumption, respectively. $P_{onstateIGBT}$represents the conduction loss of the IGBT transistor loss , $P_{onstateD}$represents the conduction loss of the diode, I_{ref}represents the current level in the transistor, φ is the power factor angle, cosφ represents the size of the power factor, which can be seen that the power factor is also an important influencing factor When the power factor is larger, the conduction loss of the IGBT will increase, on each branch module, $V_{CC}$and V_{ref}represent the actual voltage and the theoretical reference voltage, $E_{sw}$and E_{swD}represent the switching energy loss under the theoretical reference voltage, and $\widehat{I_1}$represents the maximum value of the current, since the modules are connected in parallel with each other, for the current on the stator will be distributed to each branch module, M is the modulation factor, f_{sw}represents the switching frequency, $V_{CE0}$and V_{F0}represent the voltage bias, and $K_i$and $K_v$take different values in diode and IGBT transistors, 0.6, and 0.6 (for diode), 1, and 1.35 (for IGBT), respectively. For different PMSG performance parameters, the voltage bias values obtained by the calculation are different. r_{CE} and r_F are also related to the parameters of the specific PMSG and represent the resistance of the semiconductor [14].

$$P_{swD} = f_{sw} E_{swD} \left(\frac{1}{\pi} \cdot \frac{\widehat{I_1}}{I_{ref}}\right)^{K_i} \cdot \left(\frac{V_{CC}}{V_{ref}}\right)^{K_v} \tag{3}$$

$$P_{swIGBT} = f_{sw} E_{sw} \left(\frac{1}{\pi} \cdot \frac{\widehat{I_1}}{I_{ref}}\right)^{K_i} \cdot \left(\frac{V_{CC}}{V_{ref}}\right)^{K_v} \tag{4}$$

$$P_{onstateIGBT} = \left[\frac{1}{2\pi} + \left(\frac{M\cos\varphi}{8}\right)\right] V_{CE0} \cdot \widehat{I_1} + \left[\frac{1}{8} + \left(\frac{M\cos\varphi}{3\pi}\right)\right] r_{CE} \cdot \widehat{I_1}^2 \tag{5}$$

$$P_{onstateD} = \left[\frac{1}{2\pi} - \left(\frac{M\cos\varphi}{8}\right)\right] V_{F0} \cdot \widehat{I_1} + \left[\frac{1}{8} - \left(\frac{M\cos\varphi}{3\pi}\right)\right] r_F \cdot \widehat{I_1}^2 \tag{6}$$

From the above expressions for switching loss and conduction loss, it is clear that if the higher the current flowing through the stator, the higher the current passing through a single module, the higher the conduction power loss on either the transistor or the diode. According to the formula (3)-(4) the actual voltage of the IGBT and switching losses are positively correlated, an actual voltage of the IGBT and diode will often lead to switching losses, and in addition, the frequency of the switch itself is also a factor affecting its loss.

The previous review of Eqs. (3)-(4) shows that different switching frequencies are the influencing factors of power loss, and that for special semiconductors such as IGBTs, pulse width modulation (PWM) is commonly involved in converter control [15-22].

For PWM, two kinds of waveforms, harmonics and interharmonics, are generally generated in a certain range, and in general, if the harmonic percentage of the output is high, it will not only affect the quality of the output, but also more importantly, it will affect the loss of the whole machine.

In order to better analyze the effects brought by PWM accurately, M. Elsied et al. have taken a more interesting index to investigate the power loss in DC/DC and DC /AC converters in terms of power loss by proposing the total harmonic distortion factor (THD) [23], which is illustrated in the following equation (7),

$$THD = \sqrt{\sum_{h=2,3,\ldots}^{\infty} \left(\frac{V_h}{V_1}\right)^2} \tag{7}$$

From the point of view of the expression, when h takes different values, it represents different harmonic voltages with different root mean square values V_h, the total harmonic distortion factor THD is essentially an operation in which the ratio of V_h to the root mean square of the fundamental voltage V_1 is squared and summed up and then finally squared again. M. Elsied discusses two types of DC/AC converters, namely, a five-level converter with a small number of switching elements such as diodes and a conventional level converter, and simulates them separately, showing that when the converter is in the medium-to-high switching frequency range, the simpler, higher-level converter will be more advantageous. The validity of THD measure of energy loss reduction is also shown.

For power electronics converters can be divided into two types of voltage source (VSC) and current source (CSC) converters are categorized and analyzed separately, for the general voltage source converter, the load current satisfies the functional relationship of equation (8-9)

$$\mathrm{i(t) = I_m \sin(\omega t + \varphi)} \tag{8}$$

where $\mathrm{I_m}$ represents the maximum value of the load current, which can also be written in phase form in (8) for the same load current of ω:

$$\dot{\mathrm{I}} = \frac{\mathrm{I_m}}{\sqrt{2}} \angle \varphi \tag{9}$$

Eqs. (8-9) are expressions for the load current from a general mathematical point of view, in electronic power technology, the parameters ω, φ have special meanings, representing the angular frequency and the initial phase of the load current, respectively. M.H. Bierhoff has given the relevant calculations of conduction and switching losses for these two types of converters (Eqs. 10-12) [24].

$$\mathbf{P_{sv} = \frac{6}{\pi} f_s \left(E_{on,I} + E_{off,I} + E_{off,D}\right) \frac{V_{dc}}{V_{ref}} \frac{I_m}{I_{ref}}} \tag{10}$$

$$\mathrm{P_{cv,I}} = \frac{\mathrm{V_{CE,0} I_m}}{2\pi} \int_0^{\pi} \sin(\omega t) \frac{1+\mathrm{M(t)}}{2} \mathrm{d}(\omega t) + \frac{\mathrm{r_{CE} I_m}^2}{2\pi} \int_0^{\pi} (\sin(\omega t))^2 \frac{1+\mathrm{M(t)}}{2} \mathrm{d}(\omega t) \tag{11}$$

$$\mathbf{P_{cv,D}} = \frac{\mathbf{V_{F,0} I_m}}{\mathbf{2\pi}} \int_{\mathbf{0}}^{\boldsymbol{\pi}} \mathbf{sin}(\boldsymbol{\omega}\mathbf{t}) \frac{\mathbf{1+M(t)}}{\mathbf{2}} \mathbf{d}(\boldsymbol{\omega}\mathbf{t}) + \frac{\mathbf{r_F I_m}^2}{\mathbf{2\pi}} \int_{\mathbf{0}}^{\boldsymbol{\pi}} (\mathbf{sin}(\boldsymbol{\omega}\mathbf{t}))^2 \frac{\mathbf{1+M(t)}}{\mathbf{2}} \mathbf{d}(\boldsymbol{\omega}\mathbf{t}) \tag{12}$$

Obviously, when the switching frequency does not change with time (it can also be assumed that the waveform generated by the PWM control strategy is mathematically continuous and there are no discontinuities), the overall switching losses of the VSC are influenced by the conduction$\mathrm{E_{on,I}}$,the turn-off losses $\mathrm{E_{off,I}}$ of the IGBTs, the turn-off losses generated by the diodes $\mathrm{E_{off,D}}$, the switching itself frequency $\mathrm{f_s}$, the ratio of the actual voltage to the theoretical reference voltages $\mathrm{V_{dC}}$, and $\mathrm{V_{ref}}$and the ratio of the alternating current amplitude to the reference current. For the conduction losses of the IGBT and the diode, both expressions have two terms with some symmetry and regularity, both of them contain an integral of the load current over the time, as well as a time-invariant unity-abstract modulation function M (t), and are related to the respective threshold voltages, resistors $\mathrm{r_{CE}}$, $\mathrm{r_F}$and the maximum value of the load current.

While the related analysis for current source converter (CSC) is more complicated, T. Halkosaari et al. proposed expressions for calculating the total loss $\mathrm{P_{d,loss}}$ and conduction loss $\mathrm{P_{c,loss}}$ of CSC as shown in (13)-(14) below [25]

$$\mathrm{P_{d,loss}} = \frac{1}{\mathrm{T}} \int_0^{\mathrm{T}} \mathrm{u_d(t) i_d(t) dt} \tag{13}$$

$$\mathrm{P_{c,loss} = 2 I_{DC} (u_{onD} + u_{onIGBT})} \tag{14}$$

For the formula (13), from the CSC total loss expression is a general expression for calculating power loss, for the product of current$\mathrm{i_d}$ and voltage $\mathrm{u_d}$ in a period of integration, and then divided by the average length of time, mapping the average power over a period of time, from a theoretical point of view, it has a strong generality. However, in practical problems, voltage, current sinusoidal expression are more complex, in practical applications when calculating the conduction loss in order to avoid abstract, complex functional expressions, T. Halkosaari proposed a bold assumption, first assuming that the converter are ideal switches, the link current is kept constant, so that the conduction loss of the CSC can be roughly estimated. For Eq. (14), it can be analyzed through Eq.(14) The conduction loss of the CSC is difficult to be reduced by improving the topology of the converter, because in the whole process even the current flowing through the IGBT and the current distribution of the series diode are known, the switching element current sum $\mathrm{I_{DC}}$remains unchanged, hence, only the IGBT ($\mathrm{u_{onIGBT}}$) and the diode ($\mathrm{u_{onD}}$) voltage can be considered for optimization, you may choose a specific semiconductor material, when the current passes through the potential to land as little as possible.

As for the switching loss of CSC, it is generally more complicated, in the theory of M.H. Bierhoff , he describes its principle in detail, and gives an expression for the Fourier series to measure the average total switching loss ($\mathrm{P_1}$,$\mathrm{P_2}$) and the conclusion is given here (15-16), in short, the principle is based on the different control strategies of PWM for segmented discussion, and determine whether it is a turn-off loss or a turn-on switching loss by the positive or negative voltage at the next stage when the switch is turned on. The principle is simply to discuss the different control strategies of PWMs in segments and to determine whether the switching loss is turn-off or turn-on by the positive or negative voltage at the turn-on switch in the next stage. When discussing the magnitude of the switching loss, it is determined by the periodicity of the commutation voltage and the regular phase relationship with the phase angle φ of the load current, where δ represents the special angle, which is related to the PWM control strategy, and in practical applications in industrial field applications, the special angle is usually given directly as a known quantity.

$$P_1 = \frac{3}{\pi} f_s\left(E_{on,I} + E_{off,I} + E_{off,D}\right) \frac{V_{line}}{V_{ref}} \frac{I_{dc}}{I_{ref}} \left[\frac{4}{3}\frac{8}{\pi}\sum_{\mathrm{k}=2}^{\infty}\left(\frac{\cos[k(\varphi+\delta)]}{k\left(k^2-1\right)}\right)\sin\left(\frac{k\pi}{3}\right)\right] \tag{15}$$

$$P_2 = \frac{3}{\pi} f_s\left(E_{on,I} + E_{off,I} + E_{off,D}\right) \frac{V_{line}}{V_{ref}} \frac{I_{dc}}{I_{ref}} \tag{16}$$

In the previous analysis of the expression of M.H. Bierhoff et al. we can obviously conclude that the increase of switching frequency will increase the switching loss at the same time, and it is necessary to inhibit the increase of switching frequency to control the loss, but this conclusion makes it obvious that it is too one-sided.

In order to be able to accurately assess this, M. Janicki et al. proposed a method to combine the energy efficiency with the power factor in the process of studying boost converter. and others in the study of the boost converter proposed a method to multiply the energy efficiency and power factor, the following equation (17) in which k represents the efficiency, from this measure it can be seen that appropriately increased switching frequency facilitates a better utilization of energy [26].

$$\text{Power loss coefficient} = \mathrm{k}\cos\varphi \tag{17}$$

For other semiconductor materials such as GaN and SiC , they can make the energy loss of semiconductors lower, and at the same time have a lower manufacturing cost in industry, which is quite promising[27-30].Robson Mayer et al. proposed the calculation of the conduction loss of special transistor MOSFETs, according to equation (18), which has two components, represented by the passage of the current ($\mathrm{I_{DSrms}}$) and channel impedance($\mathrm{R_{DSon}}$), which mainly allows the calculation of the losses brought by a cycle, whether in the PFC rectifier made of GaN and SiC materials discussed in this paper or in other cases, calculating the conduction loss of MOSFETs will constitute an important component of the total loss. [31].

$$\mathrm{P_M} = (\mathrm{I_{DSrms}})^2\mathrm{R_{DSon}} \tag{18}$$

In addition to improving the energy conversion efficiency of the converter through the improvement of the material itself, the thermal loss brought about by the current also occupies an important part of the energy loss, therefore, some researchers stand on the electro-thermal point of view to study the energy consumption of the converter. Part of the energy stored in the power electronics converter to inhibit hardware temperature rise, to meet both the application for the demand for power and focus on the control of electric heat, Wayne Weaver et al. proposed a kind of multi-objective planning problem with constraints, in order to satisfy the objective function to achieve the minimum power loss at the same time, the converter will be kept stable for the operation of the temperature requirements and other relevant factors will be used as boundary conditions or constraints, which will be more effective in evaluating the energy consumption of power electronics converter [32-35].

2.1.3 Losses on inductors

A brief discussion of losses in inductors, as shown in the figure 3 below, Amruta V. Kulkarni et al. classified the losses in non-ideal inductors into two main types of losses: core losses, and resistive losses (ACR losses, DCR losses), which can be supplied by the manufacturer [36].

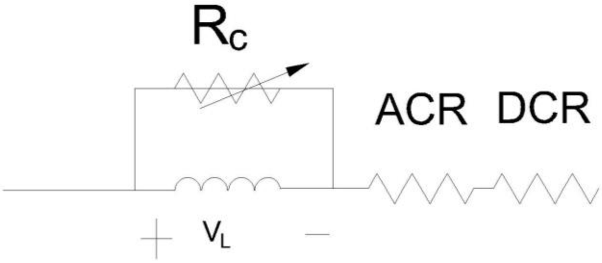

Figure 3. Circuit diagram with inductors

Lingyin Zhao et al. used the Steinmetz equation (19) for calculating the losses for a specific kind of material[37], and similarly, which is also effective in estimating the core loss of an inductor, where P_{core} is the core loss, and it can be seen that the magnitude of the core loss in an inductor is equal to the product of the frequency of the sinusoidal excitation waveform, f, the flux density of the core, B, and the volume of the core, V.

$$P_{core} = Kf^{\alpha}B^{\beta} \quad (19)$$

The above Steinmetz equation is a kind of simplified consideration for the ideal situation that the current waveform and excitation waveform flowing through the inductor are sinusoidal waveforms, even if it is a relatively complex waveform, it can be decomposed into the superposition of countless sinusoidal waveforms through the means of Fourier analysis to consider the loss problem, but in the actual problem, the core is in the magnetic field, which is not a sinusoidal waveform, and the core loss will become a nonlinear problem. There is obviously no way to decompose the superposition of the method, many researchers work for this practical nonlinear problem, which take a variety of Steinmetz equation for the improvement and transformation, this paper will not be discussed that in detail [38-45].

2.1.4 Gate losses

Finally, for the gate drive losses, an important factor is the gate capacitance. For different converters, the geometry and specific parameters of the gate capacitance will vary, and the capacitance value and the final power loss will also be different.

U. Badstuebner et al. have made a lot of efforts to improve the efficiency of converters in order to meet the power requirements of electronic devices in the field of telecommunication, and they have designed several special DC-DC converters with a target efficiency around 95% within the constraints, and in order to keep the energy at the output higher than the permitted value, the gate loss is taken into account in the design of the converter module [46-47].

J. Biela et al. in designing an optimization procedure to optimize the design of the converter to obtain higher efficiency, the gate loss is also considered in the process of considering the losses and the efficiency value is higher than 99% [48].

S. Musunuri et al. studied the maximum efficiency problem in the very low power range by taking into account the converter gate losses and conducted experiments on the transistors [49].

Toru Takayama et al. developed a loss model taking into account the gate drive losses to model CMOS which requires very high accuracy [50].

Mehran Mirjafar et al. elaborated on how to consider gate loss in a particular problem and summarized a table for calculating gate drive loss [51].

In fact, for most of the power electronics converters in practical applications, there are some good reasons to reduce the importance of considering gate losses. On the one hand, it would complicate this optimization problem, for example, there are some converters where the gate capacitance changes with the overall loading conditions would be a difficult problem, and on the other hand, although the weight of the gate loss in the previous expression is large, for most of the converters that are not so demanding, the gate loss does not contribute significantly to the total loss.

2.2 Discussion of losses from the topology of the converter

2.2.1 The significance of topology in power electronics

Topology abstracts entities into "points" independent of their size and shape, and the lines connecting them into "lines", and then represents the relationship between these points and lines in the form of a diagram, which aims to study the connection between these points and lines. In electrical circuits, the circuit topology, also known as the diagram of the circuit, is a collection of branches and junctions that are abstracted again. Further from the circuit diagram, which discusses the connectivity of the circuit and its properties, i.e., the connections between branches and nodes. The application of topology to the design of power electronic converters is an important research method.

2.2.2 Some specific case study about topology to reduce power loss

With regard to the basic operating principle and power transfer characteristics of the basic dual-edge bridge isolated DC/DC converter, Peng Zhu specifically analyzes the topology, equivalent circuit and average model of the four-port isolated DC/DC converter QAB, and quantitatively analyzes the power expression, soft-switching characteristics, and reactive power duty ratio of the QAB converter under the single-shifted SPS control strategy. Subsequently, the CHB-QAB converter is modeled, its discretization and digital control implementation methods are summarized, and a three-phase cascaded power electronic transformer based on four-port DC/DC converter isolation is constructed as a small-power experimental platform, which experimentally verifies the effectiveness of the proposed control strategy for the suppression and elimination of the secondary ripple voltage on the DC side with a low capacitance value of filtering capacitors. Energy losses has been sharply and significantly decreased in the converter [52].

Gan Yanqi, in his study of new electronic power transformers for MMC and DC-DC converters, analyzes the topology of PET isolated stage DC-DC converter in terms of PET rectifier stage MMC converter. The isolation stage is the key link for PET to realize the voltage conversion, which generally adopts the DAB converter, and with the help of the topology of the DAB converter, it is optimized to obtain the topology of the DABSRC, i.e., the resonant converter structure, which not only possesses the advantages of the DAB converter, but also has a ZVS operation range that can be extended under the traditional phase-shift control. In addition, the introduction of resonant capacitors can suppress the DC component in the DABSRC, limiting the fault current, filtering the DC component in the transformer, and avoiding saturation. Reasonable calculation of the relevant parameters of the resonant link of the DABSRC can realize the ZVS operation, reduce the loss of the converter, and improve efficiency [53].

Xueyin Zhang has intensively studied the topology and control of hybrid frequency conversion cascaded PETs to reduce the complexity of the topology while making the structure more compact and more conducive to engineering, ensuring high output power and energy efficiency and lowering the material and processing costs. In the context of energy internet, the MRCC-PET topology is proposed for grid applications, the evolution of topology and the design of circuit parameters are investigated, and an in-depth study of the control strategy and the design of ZVS parameters as well as a detailed analysis and comparison of the topology performance is carried out for the hard-switching mode of operation and ZVS mode of operation of the MFCC-PET.

The concept of hybrid frequency conversion is proposed in Xueyin Zhang's research, and the MFCC-PET type topology is proposed for the first time, so that the number of switching devices in the power electronics converter can be reduced to achieve the purpose of compact structure and cost reduction. There are two ways of realizing the mixed frequency conversion, and the study explains the working mechanism of the hard-switching operation mode and the ZVS operation mode, and Xueyin Zhang's research proposes the design method of the circuit parameters in the two modes to guarantee the stable and reliable operation of the MFCC-PET [54].

2.2.3 Some considerations for further research on topologies based on cases

Based on 2.2.2, there are still some shortcomings that need to be optimized and improved, and the following will be a brief overview to provide research ideas for future researchers:

- How to ensure that the system can operate stably when the power electronics converter cannot be rectified as a passive system.
- Passive control has more advantages in improving stability compared with traditional PI control, but there is still overshoot in the transition process, and further optimization solutions are needed.
- In the circulating current suppression of pet rectifier MMC, the research on the suppression of high-order harmonics needs to be strengthened.
- For the ZVS operation mode of MFCC-PET, the method of parameter setting and on-line calibration needs further experimental verification.

3. Applications related to power electronic converters

In this section, we will focus on the optimization process of EPC design, in order to achieve higher energy efficiency, and discuss two main directions of EPC applications in sustainable energy conversion systems and new energy networks.

3.1 Sustainable energy conversion systems

Currently, the application of renewable energy conversion systems is becoming more and more widespread. For energy conversion systems, it is worth studying how to maximize the absorption and storage of energy from the input side as well as the highest efficiency of energy conversion. For example, Fernando A. Inthamoussou et al. optimized a power electronics converter in a photovoltaic conversion system by proposing a novel control algorithm that allows the system to operate consistently near the power peak and reduces the energy loss, ensuring efficient and sustainable hydrogen production [55]. Sanka Liyanage et al. designed a power supply system SPEED, a system for emergency situations, which contributes to the autonomous operation of the entire power supply system by controlling it in both grid-connected and islanded modes through multiple power electronics converter s as part of the constituent system [56].

This part will focus on a typical new energy source with high interest in the field of energy harvesting - dielectric electroactive polymers (DEAP), which have many advantages over other energy sources, such as low cost of manufacturing DEAP, high mechanical strain under external forces, high energy density, and overall light weight, so DEAP materials have a very wide range of applications, such as in the manufacture of new generators, wave energy converters (WEC), humanoid walking robots, artificial muscles and haptic feedback [57-65].

In order to have an accurate understanding of the process of DEAP generator to convert the external energy to collect electrical energy as well as for the optimized design of power electronics converter in DEAP generator, the following will briefly review the current information about the energy storage capacity of DEAP as well as the mechanical model related to DEAP.

In the practical application of DEAP generator, the capacitance of DEAP can be regarded as an infinitely large parallel-plate capacitor by considering a single DEAP sheet and the capacitance value of DEAP satisfies a functional relationship with the deformation that occurs due to the mechanical external force, according to equation (20-21):

$$\mathrm{C(t)} = \mathrm{k}\delta^2 \tag{20}$$

$$\delta_\mathrm{x} = \mathrm{l}_1/\mathrm{l}_0 \tag{21}$$

Where the value of k represents the intrinsic capacitance value of DEAP when it is not subjected to deformation such as stretching and compression. In Eq (20-21) describe the specific meaning of δ elongation, for example, the ratio of the elongated length $\mathrm{l}_1$to the original length $\mathrm{l}_0$of the DEAP subjected to an external force in the x-direction, and similarly for the y-direction and z-direction.

Phan Cong Binh et al. provided a kinetic analytical model of DEAP, according to the equation (22) ,which is characterized by an additional mass ($\mathrm{M_{eq}}$) so that four forces will be applied in the direction of deformation of the material, namely electrostatic force ($\mathrm{F_{me}}$), elastic restoring force of the DEAP itself ($\mathrm{F_{el}}$), mechanical external force ($\mathrm{F_{ex}}$) and its own gravitational force (P) respectively, and based on the above analysis the kinetic equations in one direction are proposed[66]

$$\mathrm{M_{eq}l_0}\frac{\mathrm{d^2y}}{\mathrm{dx^2}} = \mathrm{F_{ex}(t)} + \mathrm{P} + \mathrm{F_{me}}(\delta) - \mathrm{F_{el}}(\delta) \tag{22}$$

Phan Cong Binh et al. proposed a specific analysis method about the mechanical elastic force due to the DEAP material strain (cannot exceed the maximum strain) and the operating frequency has a limitation, and the electrical conductivity fluctuation related to the objective environment and the fluctuation of the temperature change are not take into account, and assuming that the volume of this incompressible material V of the DEAP in the deformation process to satisfy the dV = 0. Among the three main material mechanics models, the quasi-linear model of Mooney - Rivlin strain energy is selected to describe the relationship between force and deformation of DEAP materials. For the effect and influence of electrostatic force, the capacitance of DEAP sheet will change due to tensile deformation under the action of electric field. The results discussed are similar to the methods and results of changing the capacitance under mechanical external force. [67]

And since the DEAP material itself is passive, which leads to the impossibility of DEAP to transform energy by conventional means. DEAP converts the collected mechanical energy into electrical energy through a special method of active bias in the energy collection cycle. Therefore, if the energy collection cycle is not well grasped, it will become meaningless to discuss the transformation of energy forms.

Phan Cong Binh et al. described the energy harvesting cycle process in detail, which is generally divided into four stages, namely the pre-stretching process, charging process, relaxation process and discharge process [68]. Rick van Kessel also described the three ideal harvesting cycles occurring in the DEAP [69], compared to the maintenance of the constant-field cycle for the conversion of energy, although it is the most efficient, but Rick van Kessel also gives the relationship between the efficiency of the power electronics converter and the conversion efficiency of the energy in an ideal harvesting cycle, as shown in Fig. (4), In Fig. 4, λ represents the strain as well as the previously mentioned δ. When the same degree of strain occurs in the material, increasing the efficiency of the converter(ηpeu) by 1%, the efficiency of the energy conversion will have a significant increase, and at the same time, it can be seen that the energy conversion efficiency of the DEAP material requires high efficiency of the converter, even under the relatively loose strain limitation, high converter efficiency is still required for energy conversion. And the more the requirement of small deformation, the higher the requirement of converter efficiency, every small part of the converter efficiency leads to a small part of the conversion efficiency increase, so it is necessary to reasonably design the structure of the power electronics converter in order to achieve the specified level of efficiency.

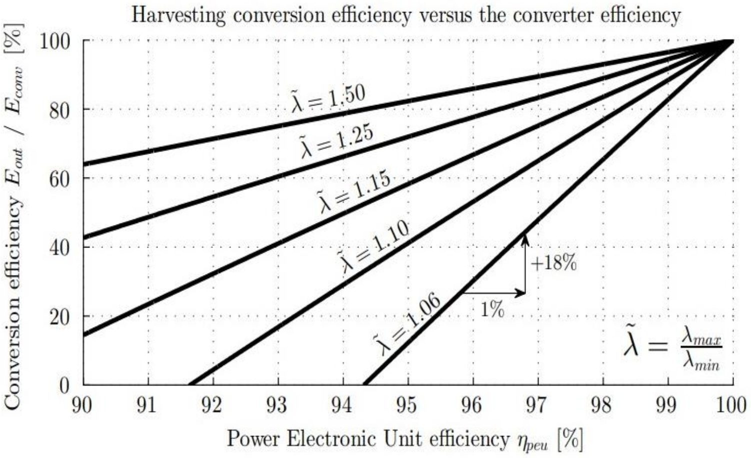

Figure 4. Relationship between power electronics converters and cycle conversion efficiency, from [69].

In order to be able to meet the relatively high energy conversion efficiency of DEAP generators, Emmanouil Dimopoulos et al. proposed an energy harvesting system which contains a unique bidirectional tapped inductive buck-boost converter as shown in Fig. 5, where three MOSFET transistors with the same structure are used instead of the original high voltage devices needed at the buck switching end, and several DEAP Generators are mounted together on the disk to form an energy harvesting system, this system can meet the current flowing over a period of time to maintain a low average value while the amplitude is large[70]. Finally, experimental simulation was carried out, from the results of the 60% strain experiments, DEAP generators perform the energy harvesting at the same time, the input side of the DEAP, namely the mechanical energy required by the DEAP is significantly reduced significantly, more than 85%.

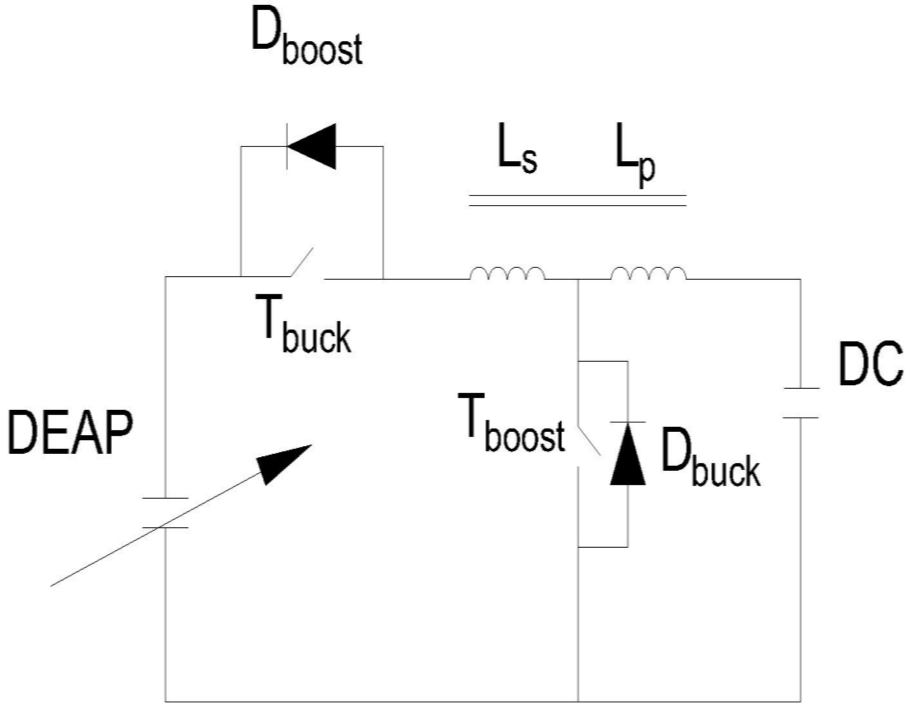

Figure 5. A Unique Bidirectional Tapped Inductor Buck-Boost Converter.

In the actual application of DEAP equipment in the industrial field, considering the need to maintain a high level of safety and long service time after completion, the strain range will be strictly limited when selecting materials at the design level, Todor Todorčević et al. optimized the topology and control technology of the power electronics converter for the DEAP collection, and proposed a new type of multilevel DC/DC converter that can effectively improve the efficiency of the converter while δ is small, and is expected to be able to be used in DEAP energy conversion in bulk[71].

There is a unique idea of using DEAP generators to convert flow energy, such as wind and water, into electricity, which was considered by Thorben Hoffstadt et al. and R. Heinze et al. A novel DEAP generator was proposed to induce a cylindrical cylinder to oscillate vertically within a certain range when the oscillation frequency differs from the intrinsic frequency by a very small amount, and at the same time, a fixed square cylinder can be used as a generator. It is also possible to increase the amplitude by fixing the square cylinder downstream, in this way both the energy stored in the cylinder can be effectively converted into electrical energy, ensuring a certain energy gain, and on the other hand, the continuity of energy collection is ensured by means of oscillation [72-73].

3.2 Research and application of electronic power conversion in new energy networking

Since the last century, the use of energy has been developing from the field of traditional fossil energy to new energy sources such as electricity, wind and solar energy. New energy become environmentally friendly and low-carbon, with less damage and impact on the environment, basically not affecting people's normal life and new energy are also highly renewable, low cost, characterized by sustainable development. According to the current international mainstream electric power in the application of new energy, are wind power and solar power generation seem to be common, some countries or regions relay on marine power generation. From per capita share of new energy power generation point of view, China has great prospects in-field of new energy development in the world [74]. China has proposed "carbon peak" and "carbon neutral" goals which let new energy development and other policies receiving great attention [75]. Compared with the traditional energy generation technology, the new energy generation technology has been improved to a certain extent and developed into a certain scale of industry, but there are still many problems that need to be solved, such as the promotion of new energy generation system, the transformation of electromechanical-led power generation to electronic power-led power generation [76].

Power electronic converters play a very important role in the new energy generation system, combined with the application of power electronic converters, the development of new energy efficiency continues to improve. The grid connection, transmission and consumption of new energy introduces more power electronic equipment at the source network and load side, and the power system shows a significant power electronic development trend, and the electromechanical steady state process dominated by rotating motors is transformed into a transient process dominated by power electronic equipment.

3.2.1 Optimized design of power electronics converters

Power electronics converter is an important part of the new energy grid. Nowadays, the continuous development of the grid has led to a large number of power quality control equipment incorporated into the grid for real-time monitoring, control of harmonics and voltage fluctuations and other issues. Power electronics converter as its main equipment, its own operating state determines the overall output performance of the equipment, the quality of the product, the grid's operating loss, the loss of electrical equipment and safety issues, so the distribution network requires the power electronics converter in the power quality control equipment to have sufficient response speed, which called the rapidity of the electronic power converter [77].

In many existing electronic power control methods for realize rapidity, there are still potential stability problems. For example, in PI control, the control parameters are the proportional coefficient and the integral coefficient. It is usually chosen to reduce the integral coefficient to accelerate the response speed, while increasing the proportional coefficient to realize the accurate tracking of the reference signal [78]. This parameter selection means that somewhere exists a large amount of overshooting in the process of dynamic regulation of the converter output and the converter external "equivalent impedance" decreases. When it is reduced to the external negative impedance in the process of grid-connected operation. Some phenomenon like oscillation and instability will occur [79-80]. Therefore, the stability of the power electronics converter is particularly important.

Sun et al. found that passive control can ensure the stable operation of the power electronics converter, but the parameters need to be set reasonably to meet the fast response. In the AC grid-connected power electronics converter, based on the theory of passivity, the control link is designed and the mathematical model under the dq axis is deduced. The system is rectified to be a passive system to ensure the intrinsic stability of the device. Under his research, the transfer function characteristics of the power electronics converter part are analyzed. Moreover, optimization method of the passive control parameter to meet the requirement of quickness has been verified through simulation and comparison. The composed power electronic converter AC grid-connected system is shown in Figure 6 below.

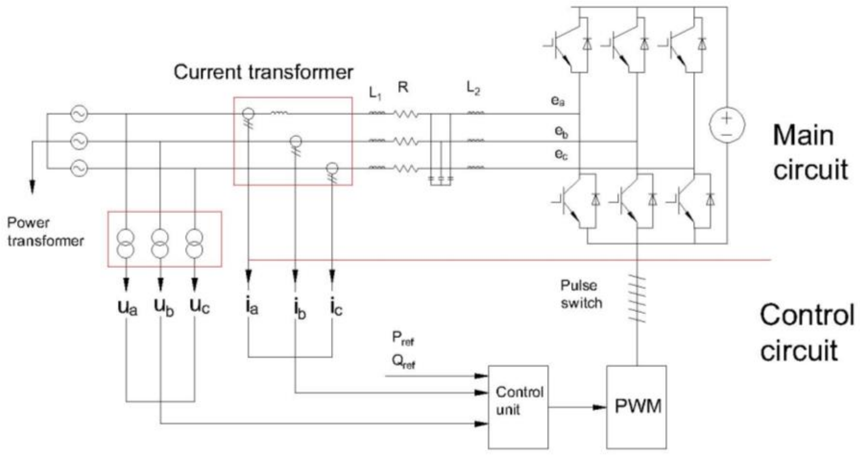

Figure 6. A special power electronic converter AC grid-connected structure diagram

The transfer functions between output active power, output reactive power and input reference current in dq form are as follows (23-26):

$$\frac{\Delta P(s)}{\Delta i_{Ldref}(s)}=\frac{1.5u_d K_r[K_M s+K_R+K_r]}{(K_M)^2 s^2+2K_M(K_R+K_r)s+[(K_R+K_r)^2+(K_J)^2]} \tag{23}$$

$$\frac{\Delta P(s)}{\Delta i_{Lqref}(s)}=\frac{1.5u_d K_r K_J}{(K_M)^2 s^2+2K_M(K_R+K_r)s+[(K_R+K_r)^2+(K_J)^2]} \tag{24}$$

$$\frac{\Delta Q(s)}{\Delta i_{Ldref}(s)}=\frac{1.5u_d K_r K_J}{(K_M)^2 s^2+2K_M(K_R+K_r)s+[(K_R+K_r)^2+(K_J)^2]} \tag{25}$$

$$\frac{\Delta Q(s)}{\Delta i_{Lqref}(s)}=\frac{-1.5u_d K_r[K_M s+K_R+K_r]}{(K_M)^2 s^2+2K_M(K_R+K_r)s+[(K_R+K_r)^2+(K_J)^2]} \tag{26}$$

where ΔP(s) is the output active power, ΔQ(s) is the output reactive power, $\Delta i_{Ldref}(s)$, $\Delta i_{Lqres}(s)$are the reference values of the currents flowing through $L_1$and L_2 in the dq coordinates, and $u_d$is the voltage at the merging point.

Before introducing the four coefficients $K_{M,}K_J, K_{r,}$First we elicit the expressions for these four important matrices (27-30):

$$M_C=\begin{bmatrix}K_M & 0\\ 0 & K_M\end{bmatrix} \tag{27}$$

$$J_C=\begin{bmatrix}0 & -K_J\\ K_J & 0\end{bmatrix} \tag{28}$$

$$R_C=\begin{bmatrix}K_R & 0\\ 0 & K_R\end{bmatrix} \tag{29}$$

$$r_C=\begin{bmatrix}K_r & 0\\ 0 & K_r\end{bmatrix} \tag{30}$$

M_C, J_C, R_C, and $r_C$above represent the inertia matrix, the interconnection matrix, the dissipation matrix, and the injection damping matrix respectively

K_M is the parameter of the inertia matrix, K_J is the parameter of the interconnection matrix, K_R is the dissipation matrix parameter, and K_r is the injection damping matrix parameter. The parameters of all four coefficient matrices can be adjusted, and the parameter adjustment strategy is as follows:

- The inertia matrix parameter K_M reacts to the size of the system's "inertia". When the parameter K_M increases, the system's "inertia" becomes larger. In the dynamic regulation process, the oscillation amplitude of the system output power decreases and the speed of oscillation decays becomes slower, which results a longer time for the transition to a new stable operating state. Moreover, oscillation waveform becomes slower.
- The interconnection matrix parameter K_J reacts to the "coupling" of the system. When K_J becomes larger, the more obvious the phenomenon of "coupling" of the system appears obviously. When the input d-axis reference current is changed, the amplitude of the coupled output reactive power oscillation is larger; when the input q-axis reference current is changed, the amplitude of the coupled output reactive power oscillation is larger. When the operating conditions changes, the oscillation frequency remain and the time required to transition to a new stable operating state are both basically unchanged.
- The sum of the dissipation matrix and damping matrix parameters reflects the dissipation of the system. The larger the parameter becomes, the greater the system "dissipation" appears. When the operating condition changes, the oscillation amplitude of the system output power decreases, the speed the oscillation decay becomes faster. However, the oscillation frequency is basically unchanged.
- When the above parameters are unchanged, changing the damping matrix parameter K_r will have an additional impact on the amplitude gain of the transfer function. Under the condition of the same input, the larger K_r, the larger the output changes which means the oscillation waveform to reach the peak value faster [77].

3.2.2 Design and application of power electronics converters in new energy networks

There are four basic types of power electronic converters, namely, rectifiers, inverters, choppers, and inverters. Rectifiers convert AC into fixed or adjustable DC; inverters convert DC into AC; choppers convert fixed voltage DC into set voltage DC; and inverters use the on-off action of power semiconductor devices to convert an industrial frequency power into a specific frequency [74].

Yang Zhenquan et al combined with the new energy power generation network of grid-connected control model parameter analysis in order to realize the application of power electronic converter topology technology in new energy power generation network. Through the photovoltaic array and inverter control scheme, they built the new energy power generation network of the outer ring voltage and the inner ring current proportional integral control model and established the AC side of the filter transfer [81]. The transformer, generator and transmission lines were used as the differential harmonic control model to obtain the mathematical model of the new energy power generation network.

Yang Haihua on this basis combined with power electronic converter and a large number of power electronic components of the coupling correlation control technology, putting forward the new energy power generation network program based on the joint design of the soft grid connection and the hard grid connection in order to improve the stability of the new energy power generation network output and anti-interference ability. Transformer, generator and transmission lines and other components are used as a differential harmonic control model, combining with the relay protection and the second harmonic parameters to realize power electronic converter topology control [82].

In the battery energy storage system, Wu Jing et al. compared the power electronics converter according to two categories: centralized energy storage system and modular energy storage system. They analyzed and summarized the advantages and problems of various grid-connected structures and their used DC/AC converters. Finally, they summarized the development of the grid-connected structure of power electronic converter in the grid-connected battery energy storage system and the trend in the future [83].

4. Discussion

The above study reviews the energy consumption indexes that relate to the design and applications of power electronics converters, discussing the application of the renewable energy conversion system and new energy networking in detail. However, some of the above discussions are too ideal. In the actual production and design of the converter to achieve the process of reducing energy losses often need to consider other factors, the following part will focus on improving and optimizing the loss and analysis of the relevant application of the research which still exists problems and deficiencies, to a certain extent, increasing the practicability and reference.

Under normal circumstances, through the analysis of each module based on the converter in Section 2, the energy consumption of the converter can be clearly understood, when the actual use of the converter there may be an unexpected state, the power loss in the time of the fault may become extremely high, from a period of time to consider a significant reduction in the efficiency of the converter, so it is necessary to considerate the converter's fault-tolerant capability [84]. There are some expressions for analyzing and evaluating the impact of a system experiencing a fault, but they are far from sufficient and still need to be further optimized [85].

For the fault tolerance of the immediate corresponding is also quite important. Generally speaking, it means that abnormalities can be detected immediately after the fault occurs, diagnosing and repairing in a short time. Compared with the relevant mentioned loss model, from a period of time can reduce the total output power reduction, improving the efficiency of reducing energy consumption [86]. For the development of related detection systems, improving punctuality and accuracy will play a significant role in the future research.

In the process of using some other tricky issues arise. It is not difficult to find that as time goes by, the overall converter efficiency will reduce, and the corresponding loss will also increase. A reliability function respect to time is currently proposed. By graphing the image of the function, lifetime of the components can be easily observed. The lifetime of the whole system will be used as an important constraint when considering the problem of energy consumption. [87].

From the point of view of the manufacturer, the investor and the overall project engineering, the pursuit of extremely low loss may not be reasonable. It is critical to ensure high energy output while reducing production costs. In some aspects, the pursuit of lower losses helps to reduce costs. For a given input power, increasing the output power or decreasing the energy input and keeping the output power the same can be an effective way to save this cost. There are also some cases that two considerations are contradictory. For example, replacing a two-level converter with a low-harmonic multi-level converter in a DC/AC converter is quite common, but the extra number of components raises the overall expense of the converter from the perspective of cost [88-89]. Using a more complex control strategy such as the MPPT technique would be better to achieve an accurate control of the system, while the complexity of the controller design also affects the cost [90]. How to balance energy saving and cost in practical problems will be a tricky and significant problem in the future research.

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