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Cooling and insulation design of power electronic transformers

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Abstract. In the case that the usage of power electronic transformers (PETs) has become a trend, research on minimizing the energy loss of PETs is imperative. Meanwhile, the miniaturization of PETs was considered a meaningful way to relief the problem to the maximum extent. And in the problems of miniaturization, the insulation design and the cooling-down design was considered the head of the problems because these two problems could result in an increase of energy loss, which is conflict with the goal of miniaturization. The basic requirement for insulation design is to keep the circuit from the damage of incidents like arc, which brought this job a status of the key to the miniaturization. But what made this trickier is that the design should also satisfy the demand of miniaturization. For the cooling-down design, a design could undertake the task but with smaller volume and lower cost would be favorable for users, but the change of circumstance could lead to different optimum design. Therefore, a study on these two fields is critical, in this essay, the insulation design would be firstly introduced and then the cooling-down design. Due to the status of the two problems mentioned above, the study showed in this paper would have a great value for the research and application of miniaturization of PETs.

Keywords: power electronic transformers, cooling down design, insulation design.

1. Introduction

PETs have long been an important part of industrial productivity and daily civilian life. But the energy waste due to the flaw of design and semi-conductors could take up to 8% of the total energy it receives [1]. Therefore, the study of improving the efficiency continued for a long period and many ways regarded as possible solutions had been put on the table, among dozens of solutions, the miniaturization of PET showed the greatest potential among the competitors.

Due to modern semiconductor technology [2], the efficiency of typical PETs was greatly improved, which makes it possible for electronic engineers to design and manufacture the same circuit in a smaller package. But meanwhile, the insulation design and cooling-down design became a more serious problem under these circumstances because a narrower space would significantly increase the chance of insulation breakdown, decrease heat radiation efficiency, and many more problems. As the advantages brought by miniaturization are significantly greater than the by-products, it would be an important topic to study in the related field which can potentially solve the problems.

Among the related fields that could lead to problems, what have been considered focuses are insulation design and cooling-down design, the ones that have chances of leading to serious accidents, and as the reason of resulting in the greatest energy loss. Therefore, a special discussion may provide solutions to these two areas is necessary when applying the miniaturized design to PETs while keeping it safe to use and capable of undertaking the same tasks as the previous designs.

For insulation design, traditional approaches like polymer coating and build-in transformers are still playing an important role in the fields nowadays. Innovative measures like optical measures are gaining more ground due to their special performance under special circumstances.

For cooling-down design, if the volume of the device was not strictly limited, a combination of an active system and a media with perfect thermal feature would be ideal to undertake the task of high power of heat dissipation. If not, passive heat sink built by good materials would also be a good choice.

Several possible approaches to solving the problems in the two fields mentioned above were discussed in this essay, and a combination of measures discussed in this essay could lead to a better design [3]. And of course, it would be wise to choose different combinations to satisfy the demands of different scenarios.

2. Insulation design

Insulation design was a relatively complicated topic due to the multiple scenarios mentioned in this essay, therefore, multiple available measures would be mentioned and the features like advantages and the suitable scenarios will be discussed separately.

2.1. Polymer coating

Though coating has long been considered an effective, cost-saving, and long-lasting measure to undertake the electrical insulation task, but the shortcomings of this time-tested tech would be revealed greatly when it comes to the circumstances like PETs, especially the PETs with a small volume due to the characteristic of Power electronics.

First, the fast-switching working conditions would cause repetitive voltage pulses, which results in a high value of dv/dt. Therefore, the partial discharge would corrupt the coating greatly due to the fast-switching electric field. Second, the conflict between preventing tip discharge from happening and cooling requirements. A thinner coating would be in favor of cooling down. But meanwhile, the thinner the coating is, the sharper its geometric edge would be, which would result in a worse tip discharge condition.

Therefore, the coating requires a stable chemical property under poor conditions, good thermal conductivity, and good surface property to prevent tip discharge and corona. Fortunately, with the help of nano coating and the right material, all requirements could be satisfied by one.

Polyimide film has been widely used in Power electronic equipment. due to its excellent heat resistance. Compared with ordinary polyimide, the electrical, thermal, and mechanical properties of nano-polyimide coating have been greatly improved. Moreover, the interface dissipation zone and high conductivity of the nano-film reduce the discharge's thermal effect and the nano-composite film's corrosion. At the same time, due to the enhancement of surface charge attenuation, the average discharge of nano-film is significantly smaller than that of the ordinary film [4].

2.2. Optimizing the geometrical features of elements

Partial discharge, ionization of air, and flashovers are also great challenges when designing the shape of elements, but there are hundreds of mature solutions to those problems. One simple approach to those problems is to optimize the geometry of the device.

Due to the feature of partial discharge, making a design with every corner rounded and all surfaces smoothen would be a good decision to make the conditions tougher for discharge [5], because it would homogenize the electric fields around them [6] and minimize the chance of occurring the phenomenon under every circumstances.

The essence of arcing phenomena is air breakdown, therefore, two possible approaches to the problem would be maximizing the distance between the poles and replacing the medium between the poles. For the output poles, pulling out the two poles with well-insulated wires could avoid the problem to a great extent. For the insulation between the device and the ground, placing a piece of material with good insulation performance like concrete or engineering polymer between or simply rise the height of the device from the ground would improve the insulation feature greatly. And for the insulation between devices and devices, a Faraday cage with a rounded shape and a properly designed distance, which could satisfy the demands of insulation and miniaturization, would be a good choice for preventing arc from happening. Moreover, when it comes to designing a PET of a small volume, a completely enclosed sealing could also be a good choice because it could keep all elements from the effect of the change of physical index of the air like a shift of humidity.

2.3. Build-in transformers

Obviously, under circumstances that need to supply both the controlling circuit and the main circuit, supplying both by the same power source would be risky since the impact caused by the power grid surge would result in the high value of dv/dt, and the controlling elements like chips, which are highly sensitive to these factors, could be badly influenced and have a potential of being permanently damaged. Therefore, a transformer, which is an electrically isolated, independent, ungrounded safety system could prevent the worst condition from happening.

Therefore, a step-down transformer excluding Autotransformer would be a perfect candidate for this task. Thanks to its special feature of delivering energy without any electrical connection, it can keep the input voltage waveform of the controlling circuit stable even if the main circuit was interrupted greatly. This advantage could make the damping feature of the auto-controlling system stay stable under any circumstance and avoid element breakdown.

This technique was already widely applied to multiple scenarios like the voltage step-down process of ultra-high voltage transmission [7].

2.4. Optical measures

Since the phototransistors carry the electrical features that are related to the light irradiated, a combination of phototransistors and a specific electromagnetic wave generator that can generate specific light could be used as the trigger of relays, and the whole system could perform as the insulation unit for controlling system. Thus, the complete electrical isolation between the controlling circuit and the main system gave this unique technique extremely high reliability and the strong ability to resist interference when the environment was filled with severe electromagnetic interference. This is an essential feature for special circumstances like controlling the power source of communication buses and the substations in residential areas. Moreover, the fast-responding and fast-recovery feature is also suitable for scenarios like controlling servo motors and responding units of power distribution systems. Since a light signal generator with a power of 5w was adequate to run the controlling system steadily, a programmed chip with basic functions would complete the task perfectly even if the users require the system to complete the more complicated tasks like PWM control or shift the output with time [8]. Therefore, it could save a lot of space compared with the Analog control circuitry and showed great potential of cutting down the cost of production and maintenance of the whole system due to the feature of a smaller number of elements required.

3. Cooling down design

3.1. Air-cooled passive radiator

As a time-tested measure of giving away heat, these kinds of systems have the easiest structures. A typical passive radiator would have a main body, multiple fins to extend the surface area. Furthermore, a kind of alloy could make all this device with excellent thermal conductivity. The whole design would radiate the heat by the air, so it got a natural size advantage over all other designs. Moreover, thanks to mature thermodynamic theories, a design of an unbelievable small volume could undertake the task of heat radiation well as it costs little. Which allows it to be applied on householding scenarios.

Meanwhile, as the design that carries the easiest structure, this kind of design could have a complicated geometrical structure without having significant impact on the effect of heat radiation [9]. Which is extremely suitable for special situations like the design that used in the smartphones.

3.2. Oil/other media actively cooling-down

Since it is not hard to find a kind of liquid with good insulation and thermal conduction performance, users have multiple choices to soak the device in to improve the thermal conduction efficiency. The power of heat radiation would be significantly higher than the passive cooling down since the package of elements is mostly made of plastic nowadays. Moreover, suppose a pump with a media piping system could be applied to the system, which could actively push the media from the heat generating area (the transistor) to the heat radiation area (usually the area with a fan or heat sink). In that case, the heat conduction efficiency could be greatly improved again compared with the passive media cooling down system, which means it would have the ability to satisfy the cooling down the requirement for more integrated circuits.

For most conditions, mineral oil will be the first option for this measure due to its low price and safety, moreover, it is a proven technology with thousands of successful cases for referring. Meanwhile, a variety of halogenated hydrocarbons are also good choices due to the higher cooling down efficiency because the process may involve the phase transitions of matter. It does not need any active system to perform as well as the oil media system with a pumping system. Therefore, it could undertake the task of conducting more elements with a smaller volume. But these halogenated hydrocarbons are either toxic or have the potential of polluting the atmosphere, some of them may carry the feature of both. Considering the price and all the factors mentioned above, mineral oil is still the top option nowadays even if the conducting performance is worse than other substitutes and it would consume more energy to perform as good as users want.

Another outstanding feature of this design is that it could perform as a part of insulation design as well due to the media used are usually far harder to breakdown compared with air, which is a good way to satisfy two goals at one time.

But at the same time, the media inside may be influenced by temperature, therefore, the oil should be in motion state to decrease the dispersion of insulation weaknesses [10].

3.3. Evaporative cooler

The essence of this kind of device is the phase shift of matter would cause the shift of energy, therefore, a combination of a thin-walled vessel and a certain amount of liquid which could be easily vaporized (usually be called as heat pipes) would be ideal for giving away heat.

Since the cost of metal finishing was greatly cut down and the minimum size of the elements was significantly reduced over the last decade, it is possible for users to treat heat pipe as a general solution of cooling-down design if the volume wasn’t restricted. And at the same time, the field of heat transfer media has been well studied thanks to the air-conditioning industry, which means it would be easy to find a media that could have all the favourable feature like low corrosion, low cost, and environmentally friendly.

With the factors mentioned above, the cost of this kind of device could be the lowest among the devices that could give away heat at the same power, but out of the same reason, the device may not be suitable for a complicated shape because the flow of the media may be interrupted, and the efficiency would be heavily influenced [11].

What made the designing work of this kind of elements tougher is that the thickness of vessel should be decided after taken all factors like the resistance to physical impact and the power of heat radiation.

3.4. Media-media cooling-down system

As an alternative solution to media cooling system, this kind of system holds two kinds of media within the system, which could bring the efficiency to another level. If combined with an active system, this kind of design could giveaway heat at a rate that is not possible for any other design mentioned above.

But meanwhile, the volume and the complicity of the system would also become unimaginable. But if take the factor of more concentrated elements of PETs into account, this technique still has a good potential of reducing the size of the entire element.

Though this kind of device have multiple drawbacks, it is still widely used in various scenarios that remains stationary and have a high demand of heat radiation like main substations and reactors [12].

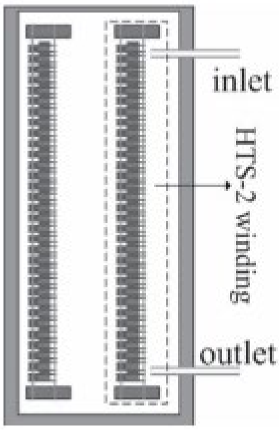

Figure 1. A possible schematic of cooling system for reactors [12].

4. Conclusion

Though choosing from the options mentioned above when designing PETs could be confusing and it could be also a tough task optimizing the design to have a good balance between the cost of element and power loss, there are still a couple of principles could be drawn from this analysis to simplify the work. Suppose the volume of the device wasn't strictly restricted and power of the device is high, like the circumstances faced in the transformer substation. In that case, a combination of optical measure and active media cooling-down could be a good choice due to the outstanding ability of heat radiation and extremely low chance of element breakdown. But when designing the volume sensitive PETs like the ones used in the smartphones, passive radiator and a polymer coating with fixed outfit would be ideal due to the requirement of volume. Meanwhile, a design followed this principle could have the potential of being massively and cheaply produced. And for the devices that have a stable supply of all resources and not sensitive to weight, a build-in transformer and a media-media active cooling-down system could have the ability to satisfy any tricky situation and could significantly reduce the cost of power loss. Optical measures with evaporative cooler could be a wise choice for the designs that are highly sensitive to weight due to the extremely low weight and relatively better performance compared with the designs that carry the same weight.

Obviously, there are also principles that should be followed by all designs like optimizing the geometrical features of elements, which is a universal way of preventing arc from happening for all PETs.

As the situation varies, it is not likely to draw a universal design that could meet all the demands, choose different combination under different situations may be the only solution to all problems.

For a future glance, media with better performance could help a lot increasing the efficiency. Meanwhile, materials with a better mechanics performance and a better process could also benefit the cooling device from structural view. With all these improvements, it is obvious that the performance of the coolers could be significantly improved.

References

[1] Zhiqiang, F., Zhengming, Z., Bochen, S., Zhujun, Y., & Jialin, Z. (2023). Loss analyses of multi-port power electronic transformers based on DSIM simulations. J Tsinghua Univ (Sci & Technol), 63(1), 94-103.
[2] Jiajian, L., Jungyun, L., Archana, V., Jingjing, C., Zongqing, R., & Jaeho, L. (2022). Dynamic

Thermal Management of Power Transistors using Holey Silicon-Based Thermoelectric Cooling. 2022 21st IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (iTherm), 1-7.

[3] Zhongqing, Y., Sheng, Z., Liujun, H., & Shuanghan, L. (2022). Analysis and Improvement of Completely Shut Down Circuit of Nuclear Power Main Transformer Cooler. 2022 2nd International Conference on Electrical Engineering and Mechatronics Technology (ICEEMT), 198-203.

[4] Peng, W., Zhengjia, Z., Xueshan, L., Qun, Z., Yong, L., & Wei, W. (2018). Electrical Insulation Problems in Power Electronics Devices. High Voltage Engineering, 44(7), 2309-2322.

[5] Zhang, J., Hu, Y., & Xue, F. (2020). Characteristic Analysis of Point Discharge Current Pulse Using Numerical Simulation Based on Fluid Dynamics Model. *2020 8th International Conference on Condition Monitoring and* Diagnosis (CMD), 149–153. https://doi.org/10.1109/CMD48350.2020.9287187.

[6] Zhao, C., Dujic, D., Mester, A., Steinke, J. K., Weiss, M., Lewdeni-Schmid, S., Chaudhuri, T., & Stefanutti, P. (2014). Power Electronic Traction Transformer—Medium Voltage Prototype. *IEEE Transactions on Industrial Electronics*, *61*(7), 3257–3268. https://doi.org/10.1109/TIE.2013.2278960.

[7] Wang, D., Tian, J., Mao, C., Lu, J., Duan, Y., Qiu, J., & Cai, H. (2016). A 10-kV/400-V 500-kVA Electronic Power Transformer. *IEEE Transactions on Industrial Electronics*, *63*(11), 6653–6663. https://doi.org/10.1109/TIE.2016.2586440.

[8] Imran, M., Collier, M., Landais, P., & Katrinis, K. (2016). Software-Defined Optical Burst Switching for HPC and Cloud Computing Data Centers. *Journal of Optical Communications and Networking*, *8*(8), 610. https://doi.org/10.1364/JOCN.8.000610.

[9] Kim, C., Jeong, M.-W., Kim, S., Oh, S.-H., Lee, S.-Y., Joo, Y.-C., Shen, H., Lee, H., Yoon, J., & Joo, Y. (2020). Planar-Radial Structured Thermoelectric Cooler for Local Hot Spot Cooling in Mobile Electronics. *2020 IEEE 70th Electronic Components and Technology Conference (ECTC)*, 2242–2246. https://doi.org/10.1109/ECTC32862.2020.00349.

[10] Sun, J., Zhang, S., Xu, Z., Wu, C., Yu, X., Qiu, Y., & Gao, Z. (2017). Oil-paper insulation characteristic and maintenance measures of oil-immersed transformer in cold environment. *2017 IEEE 19th International Conference on Dielectric Liquids (ICDL)*, 1–5. https://doi.org/10.1109/ICDL.2017.8124667.

[11] Xingli Zhong, Bin Zhang, & Bo Zhang. (2012). The flow numerical simulation and optimization for evaporative cooler. *IET International Conference on Information Science and Control Engineering 2012 (ICISCE 2012)*, 2.25-2.25. https://doi.org/10.1049/cp.2012.2338.

[12] Shen, S., Tang, Y., Ren, L., Wang, Z., Chen, L., & Shi, J. (2016). Design of Cryogenic Cooling System of a 35-kV/3.5-MVA Single-Phase HTS-Controllable Reactor. *IEEE Transactions on Applied Superconductivity*, *26*(4), 1–4. https://doi.org/10.1109/TASC.2016.2522186.