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Comparative Analysis and Evaluation of High Voltage Power Generation Architectures

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***Abstract*—This paper introduces the high voltage generation architectures derivation methodology and comparative evaluation of high voltage power generation architectures based on the key performance items such as efficiency, power density, high voltage pulse speed, high voltage pulse ripple, HV insulation and scalability for different output voltage and output power ratings. Based on comparative evaluation of high voltage generation architectures with single inverter configuration, high voltage generation architecture with single inverter, multiple high voltage transformers and multiple stage voltage multiplication circuits overall outperforms other high voltage generation architectures based on architecture performance comparative analysis and evaluation at 100kV/10kW output rating as case study.**

Keywords—HV generator; modular architecture; LCC resonant converter; equivalent circuit model

I. INTRODUCTION

In recent years, the high voltage(HV) generators are widely used in applications, such as HV capacitor charger, X-ray generation, ESP (electrostatic precipitation), plasma generator, and many other pulsed power areas [1-6]. Usually, these high voltage generators convert low dc voltage to high dc voltage which typically can be as high as several hundred kilovolts. Generally, the high frequency high voltage generator is composed of high frequency DC-AC inverter, resonant tank, high voltage transformer and high voltage rectifier. There are various high voltage generator architectures for different output voltage and output power ratings [1-6]. However, the state-of-the-art works don't summarize the existing HV generator architecture. There is lack of a clear picture to evaluate the performance for HV generator architectures and provide the guideline to select the best HV generator architectures to achieve good performance such as high power density, high efficiency, and good HV pulse quality, etc.

From the typical HV generation circuit diagram shown in Fig.1, inverter, HV transformer and HV rectifier are 3 key power building blocks subcomponents for HV generator main circuit. The resonant tank includes series resonant inductor, series resonant capacitor and parallel resonant capacitor for LCC topology illustrated in Fig.1. The parasitic components of HV transformer are used as series resonant inductor, and parallel resonant capacitor, or part of resonator. The series resonant capacitor is typically packaged together with inverter low voltage enclosure. So, resonant tank is not identified as one of power building block separately. The HV transformer and HV rectifier are usually packaged together in the HV insulated enclosure which are called HV tank.

However, the influence of different architectures on the performance and comparative evaluation of architectures have not yet been done. The comparative evaluation of different high voltage power generation architectures is not investigated yet. The major contribution of this paper is to introduce the systematic high voltage generation architectures derivation methodology, and provide comparative evaluation and selection guidelines of high voltage power generation architectures for different output voltage and output power ratings in various applications.

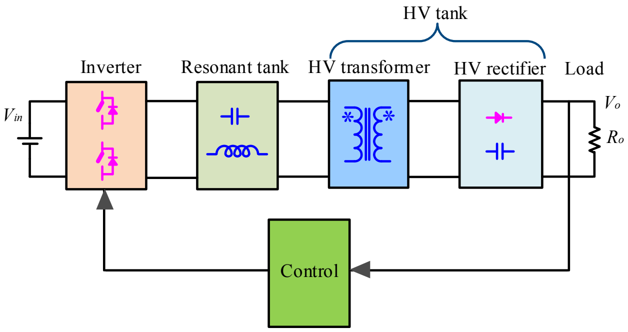

Fig. 1 HV generator circuit diagram

II. HIGH VOLTAGE POWER GENERATION ARCHITECTURES

The benefits of distributed sub-components of the high voltage generation system will lead to low electrical and insulation stress on the sub-components, easy for power and high voltage generation scalability. There are different high voltage generation architectures according to the level of modularity of the main sub-components of the high voltage generation system (inverter, transformer, rectification) as shown in Table I. The definition of modularity level of rectifier can be found in the following: rectifier/doubler is

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TABLE I. HIGH VOLTAGE GENERATION ARCHITECTURE DERIVATION

	Inverter	Transformer	Rectifier	Key feature
Architecture-1	single	single	single	basic architecture
Architecture-2	single	single	multiple	voltage multiplication
Architecture-3	single	multiple	single	multiple-stage transformer
Architecture-4	single	multiple	multiple	multiple-stage transformer & voltage multiplication
Architecture-5	multiple-stage	multiple	multiple	multiple-stage inverter & transformer & voltage multiplication
Architecture-6	multiple-stage	multiple	single	multiple-stage inverter & transformer
Architecture-7	multiple-stage	single	multiple	multiple-stage inverter & voltage multiplication
Architecture-8	multiple-stage	single	single	multiple-stage inverter

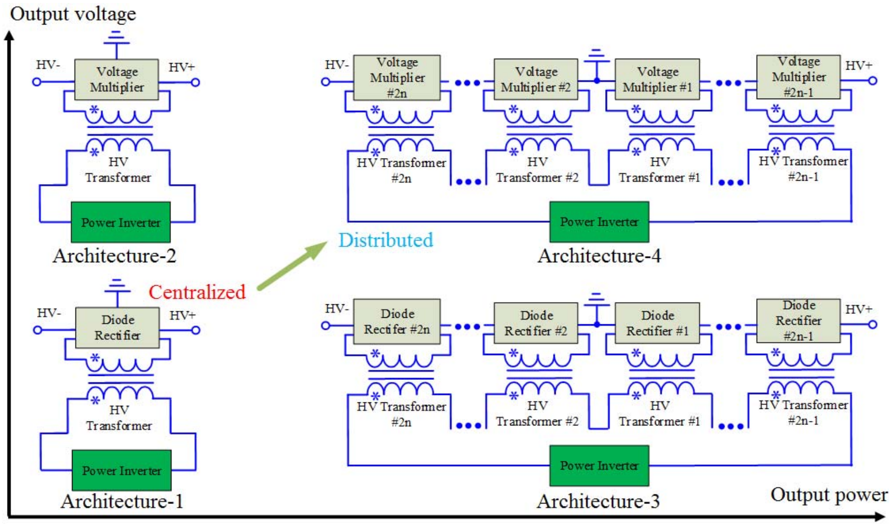


Fig. 2 Overview of HV generation architectures for different output voltage and power levels

considered as single stage type, voltage multiplier is taken considerations as multiple stage type rectification circuits. Above all, there are 8 different high voltage generation architectures according to the level of components modularity. Fig.2 gives an overview of HV power generation architectures with single inverter structure (take single inverter configurations as case study). Based on HV generator architectures classifications, it provides a clear overview of all possible architectures. Each HV generator architecture may fit for one kind of applications. The centralized HV generator with single power building block behaves simple configuration, but suffers from large electric stress for sub-components when the output voltage and power rating gets higher. The power density and efficiency improvement is challenged due to high insulation stress and large parasitic components for HV transformer when the switching frequency is further increased. Furth more, it's not scalable for different output voltage and power rating. The distributed architectures with modular HV transformer, HV rectification, and inverter provides the flexibility of scalability for scalable for different output voltage and power rating. The electric stress for subcomponents can be greatly reduced. The reduced parasitic components enable high switching frequency for size reduction and efficiency improvement. The challenges will be more components amounts, consistence of multiple power building blocks.

III. HIGH VOLTAGE POWER GENERATION ARCHITECTURES PERFORMANCE REQUIREMENTS

The key performance requirements for HV generator are listed below:

- High efficiency
- High power density
- Good dynamic HV pulse quality: fast HV pulse speed
- Good steady state HV pulse quality: small HV ripple
- Low HV insulation stress
- Modularity

The HV generator architectures will impact all the above performances for high output voltage power conversion systems. The evaluations on advantages and disadvantages of

HV generators architecture will be introduced based on the key performance items for HV power generation such as power density, HV pulse speed, HV pulse ripple, energy efficiency and scalability.

(a)Efficiency

The efficiency of HV generator is critical requirement. High efficiency operation will make the power loss and heat reduction. The power density can be also increased with high efficiency operation for HV generator. The efficiency is related to electrical stress of main sub-components of the HV generation system (inverter, transformer, rectification) based on different HV power architecture. The energy efficiency of HV power generation system is also influenced with transformer technology based on magnetic core materials and winding structure, rectification or multiplication technology based on HV diode characteristics, dielectric characteristics of HV capacitor, switching frequency, transformer coupling coefficient, HV insulation technology, high frequency AC dielectric loss and packaging technology.

(b)Power density

High power density will provide compact size, mobility and cost effectiveness for industrial applications. The HV tank which mainly includes HV transformer, HV multiplier, resonators, auxiliary HV circuits, dominates the HV generator weight. The volume distribution portion for HV multiplier and HV transformer can be changed with different HV power generation architecture and different components technology and packaging. The relationship curve between HV generator power density and switching frequency are shown in Fig.3.

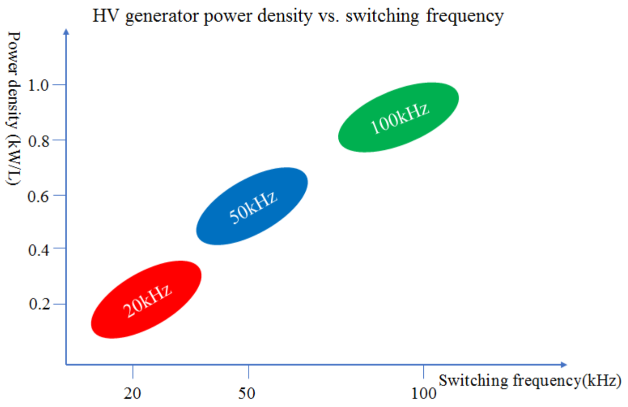


Fig. 3 The relationship curve between HV generator power density and switching frequency

It's can be seen from the curve that the HV generator power density will keep increasing when the switching frequency increases. The high switching frequency will help reduce the size of HV passive components such HV transformer, HV multiplier capacitor and resonators. High switching frequency will also generate large power loss for magnetic core and windings. Furthermore, the high frequency insulation stress needs to be considered for the HV transformer operating at high frequency [7].

(c)HV pulse speed

HV pulse speed is critical to HV generation system performance. The sharp HV pulse with fast speed is requested based on different industrial applications. The HV pulse rise and decay time will be different for different HV generation architectures. HV pulse speed will be impacted by the output capacitance, load resistance, switching frequency and inverter power capability. The output capacitance is most critical points for HV pulse speed.

(d)HV pulse ripple

HV ripple is also important for HV generation system performance such as imaging quality for CT and X-ray machine. The HV pulse ripple will depend on different HV generation architectures.

(e)HV insulation

HV insulation has high impact on the HV generation system volume and weights. Different HV generation architectures will lead to different insulation stress for the subcomponents and packaging for HV generation system.

(f)Modularity

Based on the level of modularity of the main sub-components of the HV generation system (inverter, transformer, rectification), the distributedness of sub-components provide the scalability for HV generation system. The power rating, HV generation and HV insulation capability can be enhanced with the distributedness of sub-components, and maintain the same electrical and insulation stress for sub-components of the HV generation system. The higher power or high output voltage rating can be achieved by the parallel or series combinations of standard sub-components power building blocks. The scalability for HV generation system is important for mass production, and ease manufacturing to save cost and development time.

IV. HIGH VOLTAGE POWER GENERATION ARCHITECTURES PERFORMANCE EVALUATIONS

(a)Evaluation specifications

In order to compare the strengths and weaknesses of each HV generator architectures, these architectures were analyzed in detail using the specifications in Table II as a case study.

TABLE II. THE SPECIFICATIONS OF HV GENERATOR FOR ARCHITECTURES EVALUATION STUDY

Input voltage	400VDC
Output voltage	100kVDC
Output power	10kW

(b)Evaluation assumptions

The following are some assumptions to simplify the HV generator architecture evaluations:

- The analysis and evaluation will focus on the architecture-1 to architecture-4 with single inverter configuration. The HV architecture-5 to architecture-8 are based on multiple inverter topology. The performances of HV generator are mainly determined by the HV transformer and HV rectifications in the HV tank. The single or multiple configurations of inverters has minor impact on the HV generator performance.
- Ferrite magnetic core is considered and planar shape magnetic core is used as much as possible to achieve compact size.
- Fixed current density for transformer windings: 4A/mm^2.
- The capacitance of multiplier is used for same HV pulse ripple at 1% of high output voltage.
- The multiplier stage number is limited to six to avoid very low HV pulse speed.
- The switching frequency investigation range is 100kHz~300kHz.
- The parasitic capacitance value of HV transformer refers the HV transformer prototype parameters measurement in lab.
- The thermal management is not taken considered in the design at current stage.

(c)Evaluation criteria

Table III gives the HV architecture performance evaluation criteria to provide quantitative analysis using 100kV, 10kW power rating a case study based on performance scores for efficiency, power density, HV ripple, HV pulse speed, HV insulation and modularity. The HV architecture performance evaluation criteria are applied for all 4 HV architectures.

- Efficiency: If the efficiency is between 60% to 70%, the ranking score is 1. If the efficiency is higher than 95%, the ranking score is 5.
- Power density: based on the size of key components HV transformer and HV rectifier in HV tank.
- HV ripple: based on peak to peak value of HV ripple.
- HV pulse speed: based on pulse decay time: from 100% to 50%
- HV insulation: based on high frequency HV insulation stress for HV transformer
- Modularity: based on modularity level of HV generator subcomponents.

(d)Evaluation methodology and first-order evaluation flow chart

The HV generation architecture evaluation is based on the above assumptions, specifications and criteria for different out voltage and power rating. Firstly, the switching frequency is chosen at the minimum HV tank power loss for the first order design and evaluation of HV architectures to understand the advantage and challenges. Then according to the requirements of input voltage, output voltage, and output power, the HV transformer magnetic core, windings and HV rectifiers will be calculated based on the first order design. Finally ranking scores calculation and summary based on the first order design results for all 4 HV architectures. The HV architecture evaluation flow chart is illustrated in Fig.4.

TABLE III. HV ARCHITECTURE PERFORMANCE EVALUATION CRITERIA (100KV, 1~10KW)

Score	Efficiency	Power density	HV ripple	HV pulse speed	HV insulation	Modularity
1	60%	5000cm3	3.0%	2.0mS	100% HV output	Single transformer, single rectifier
2	70%	4000cm3	2.5%	1.5mS	50% HV output	Multi-rectifier Single transformer
3	80%	3000cm3	2.0%	1.0mS	10% HV output	Multi-transformer Single rectifier
4	90%	2000cm3	1.5%	0.5mS	5% HV output	Multi-transformer and multi-rectifier
5	95%	1000cm3	1.0%	0.1mS	1% HV output	Multi-transformer and multi-rectifier, multi-inverter

(d)Evaluation methodology and first-order evaluation flow chart

The HV generation architecture evaluation is based on the above assumptions, specifications and criteria for different out voltage and power rating. Firstly, the switching frequency is chosen at the minimum HV tank power loss for the first order design and evaluation of HV architectures to understand the advantage and challenges. Then according to the requirements of input voltage, output voltage, and output power, the HV transformer magnetic core, windings and HV rectifiers will be calculated based on the first order design. Finally ranking scores calculation and summary based on the first order design results for all 4 HV architectures. The HV architecture evaluation flow chart is illustrated in Fig.4.

The total power loss of HV transformer and voltage multiplier in HV tank is a function of frequency. From the relationship curve between HV tank power loss with different switching frequency for 100kV 10kW HV generator is shown in Fig.5, the operation frequency for different HV generation architectures will be different. Switching frequency is determined at the minimum HV tank power loss for each HV generator architectures. The relationship curve of HV tank switching frequency for 100kV 10kW HV generator is shown

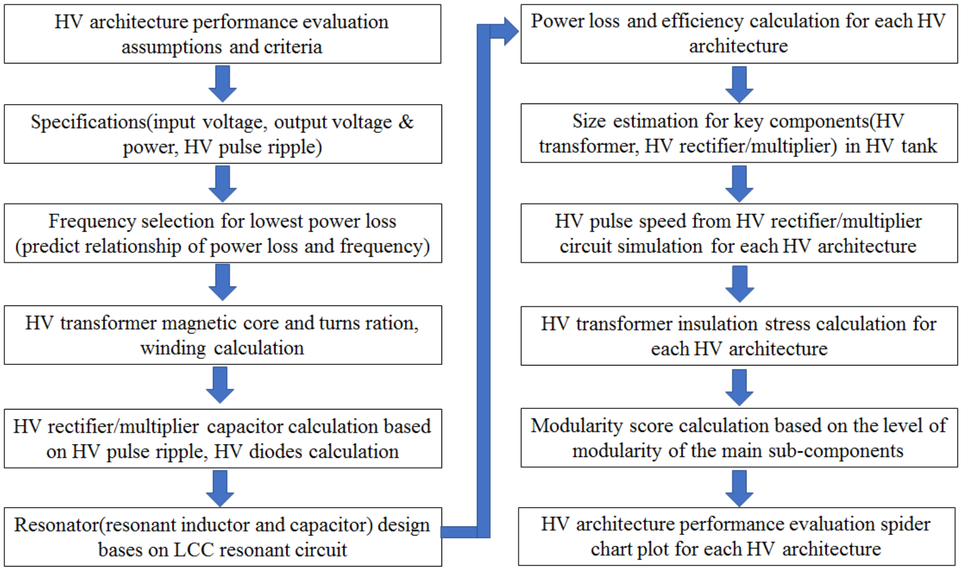


Fig. 4 HV architecture evaluation flow chart

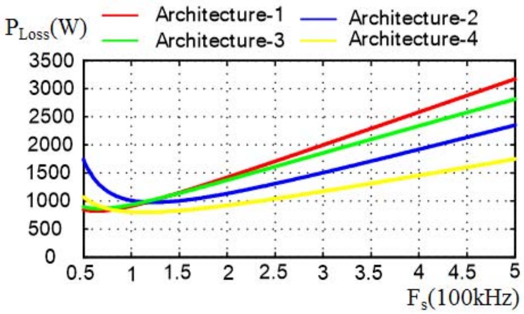
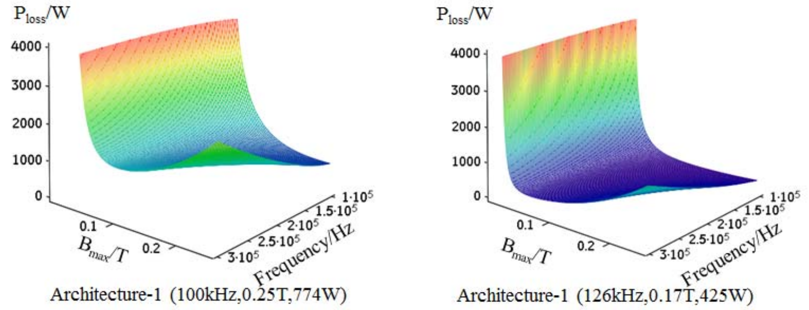
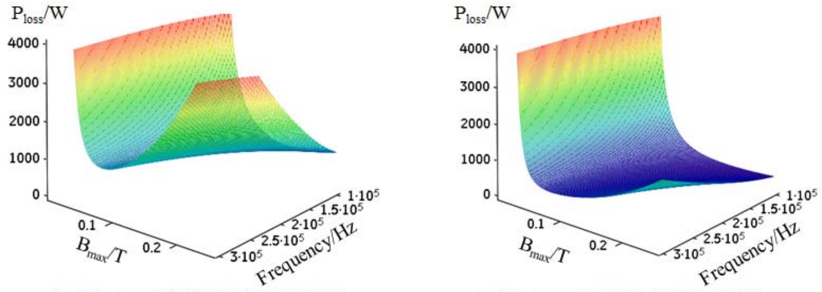


Fig. 5 Relationship curve of HV tank power loss with frequency (100kV/10kW rating HV generator as case study)



Architecture-1 (100kHz,0.25T,774W) Architecture-1 (126kHz,0.17T,425W)



Architecture-3 (100kHz,0.17T,823W) Architecture-4(110kHz,0.25T,422W)

Fig. 6 Relationship curve of HV tank power loss vs. frequency (100kHz ~300kHz) and magnetic flux density (100kV/10kW rating HV generator as case study) in Fig.5, the operation frequency for different HV generation architectures will be different. Switching frequency is determined at the minimum HV tank power loss for each HV generator architectures. The relationship curve of HV tank power loss vs. frequency (100kHz~300kHz) and magnetic flux density for 100kV/10kW rating HV generator is shown in Fig.6.

The switching frequency with lowest HV tank power loss for HV architecture-1 and architecture-3 are 100kHz. While, the optimum operation switching frequency to achieve minimum HV tank power loss for HV generator architecture-2 and architecture-4 are 110kHz and 126kHz respectively. The core loss dominates the total HV tank power loss at low frequency, and the winding loss will increase greatly at high frequency. The lowest HV tank power loss occurs at balanced copper loss and iron loss, as well as multiplier loss. HV generator architecture-4 outperforms other 3 architectures at high frequency above 100kHz. It is the most promising option with high efficiency at high frequency above 100kHz.

(d)Evaluation results

Based on the first order design and calculation, the circuit diagrams for 4 HV generator architectures with single inverter configuration under evaluation are illustrated in Fig.7. According to the HV generator architecture performance evaluation criteria (100kV, 10kW), the HV generator architecture performance evaluation results for 100kV, 10kW rating HV generator are given in Table IV. Fig.8 illustrates the HV generator architecture performance charts for 4 HV generator architectures with single inverter configuration at 100kV, 10kW power rating. HV generator architecture-4 gets the highest ranking core among the 4 HV generator architectures. The ranking score for HV generator architecture-1 is the lowest due to large insulation stress and low modularity level. HV generation architecture-4 overall outperforms other 3 architectures based on HV generation architecture performance chart at 100kV/10kW rating. Architecture-3 suffers the lowest power density among the 4 generator HV architectures. HV generator architecture-1 and architecture-3 with single HV rectification behave fast HV pulse speed. The HV pulse speed for architecture-2 is the slowest. The HV insulation stress for architecture-1 and architecture-3 with single HV rectification are larger than Architecture-2 and Architecture-4 with multiple HV rectification. The efficiency for all 4 architectures is between 90% to 95%. The HV ripple is designed to meet 1% of HV output voltage for all 4 HV generator architectures.

The reason of the big performance score differences for HV pulse speed for 4 HV generator architectures is due to the HV tank capacitance difference. The voltage multiplier capacitance value is determined to meet the HV pulse ripple lower than 1% of HV output voltage.

The peak-to-peak HV pulse ripple of the multi-stage half-wave Cockcroft–Walton voltage multiplier is approximated in [10] if the capacitors throughout all the multiplier stages are equal:

$$\delta Vpp = \frac{n\left(n+1\right)P_O}{2fC_{VM}V_O} \tag{1}$$

where, P_O is the output power, V_O is the output voltage, f is the operation switching frequency, n represents the total stage number of voltage multiplier, C_{VM} is capacitance for the voltage multiplier.

Based on (1), larger voltage multiplier capacitance is required for HV generator architecture-2 with positive and negative 6 stage multipliers compared with HV generator architecture-2 with positive and negative 3 stage multipliers. Furthermore, the operation frequency for HV generator architecture-2 is 110kHz, which is slightly lower than 126kHz for HV generator architecture-4. Larger voltage multiplier capacitance is required for lower operation frequency. As a result, more than 3 times larger capacitance is requested for HV generator architecture-2 to meet the HV pulse ripple target compared with HV generator architecture-4. So, HV generator architecture-2 suffers from the low HV pulse speed.

For diode bridge rectifier based HV generator architecture-1 and architecture-3, the HV pulse speed are faster than HV generator architecture-1 and architecture-3 with multi-stage voltage multiplier to meet same HV pulse ripple requirement.

The big performance score differences for HV insulation come from the HV insulation stress for HV transformer. As shown in Fog.7, the HV insulation stress of transformer for HV generator architecture-1 is the highest, around 100% of rated HV generator output voltage. With the introduction of 3 HV transformer modules, HV insulation stress of the transformer for HV generator architecture-3 can be limited below 50kV. More modular transformers can be adopted to further reduce the transformer HV insulation stress. But it needs to balance the performance of power density and insulation stress. With the help of multistage voltage multiplier, the transformer HV insulation stress of HV generator architecture-2 and architecture-4 has been significantly reduced to below 5% of rated HV generator output voltage.

The performance scores are related to defined criteria for HV generator architecture evaluations. The performance scores can be changed if different criteria are set, or if the design targets are for specific performance items.

HV generator architecture-4 provides the highest modularity level compared with other 3 architectures. The down-selection of HV generator architecture depend on the most critical HV generation system for different industry applications.

HV generator architecture-4 with distributed HV transformer and HV multiplier structure overall outperforms other 3 HV Architectures with lowest electrical and HV insulation stress based on HV generator architecture performance comparisons. HV generator architecture-4 with distributed HV transformer and HV multiplier structure provides the trade-off performance over HV generator architecture-2 with only multiple HV rectifications and architecture-3 with only multiple HV transformers.

HV generation system can be either optimized based on the overall performance or most critical performance item

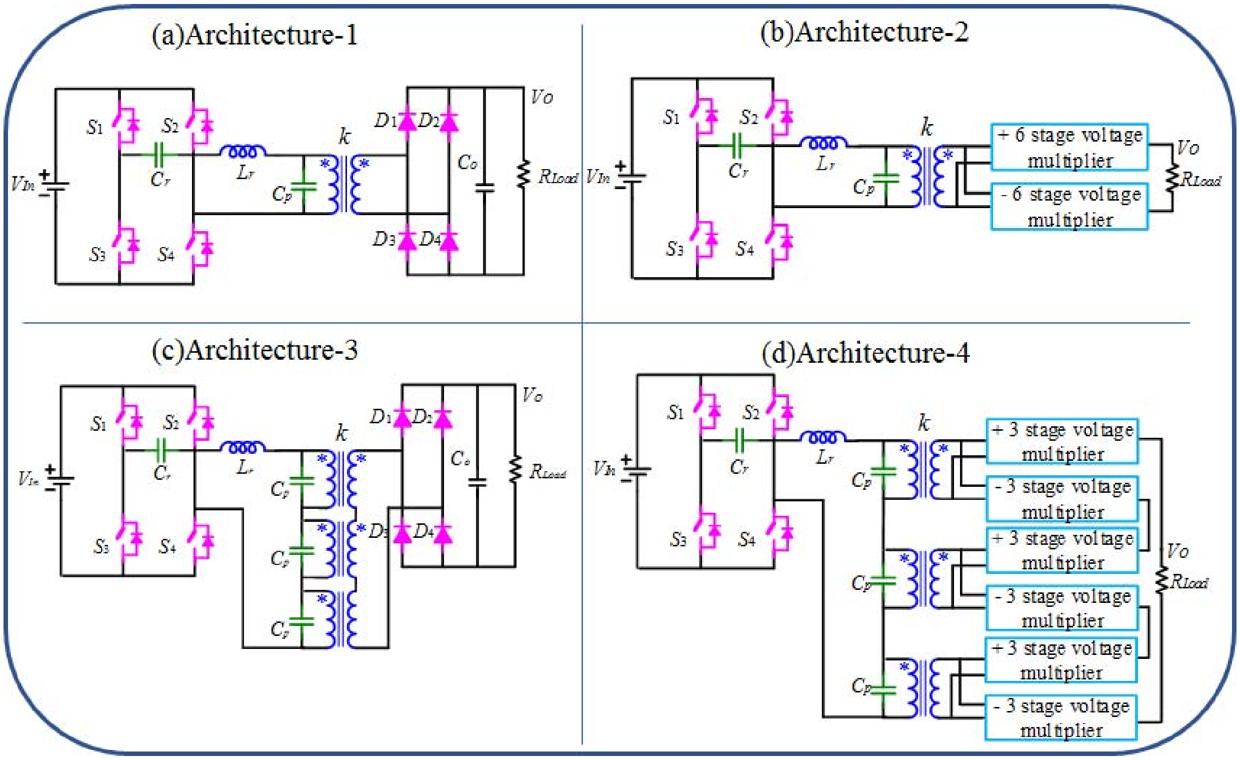


Fig. 7 Circuit diagrams for 4 HV generator architectures under evaluation

Table IV. HV generator architecture performance evaluation results for 100kV, 10kW rating

	Efficiency	Power density	HV ripple	HV pulse speed	HV insulation	Modularity	Total score
Architeture-1	4	4	5	4	1	1	19
Architeture-2	4	5	5	1	4	2	21
Architeture-3	4	3	5	4	2	3	22
Architeture-4	4	5	5	3	4	4	25

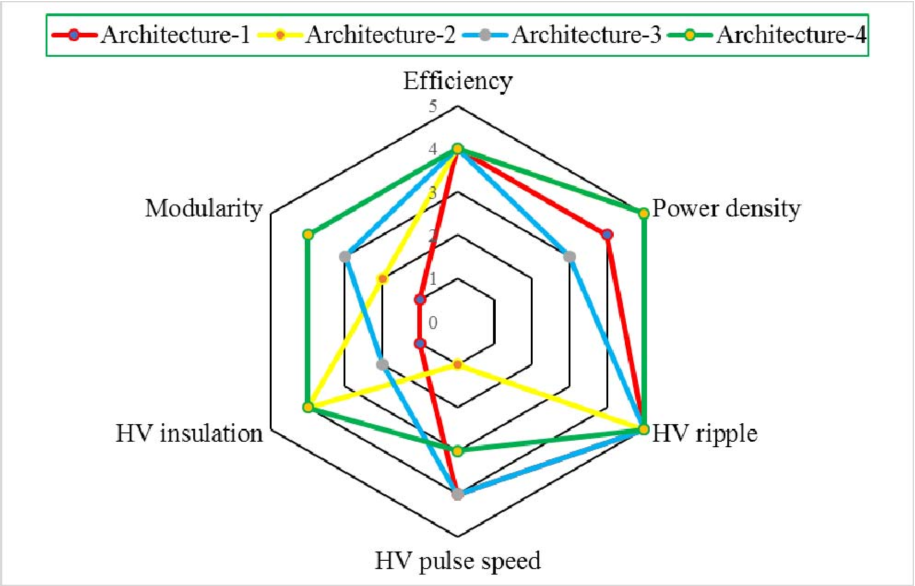


Fig. 8 HV generator architecture performance charts for 100kV, 10kW rating

from the HV generation architecture performance chart. For example, if the HV pulse speed is the most important performance requirement, the HV generation architecture-1 and architecture-4 will be the best choice although the other performance such as power density, HV insulation and modularity is not the best. If the low insulation stress is the most critical performance requirement, HV generator architecture-2 with multi-stage voltage multipliers is one of the promising candidate.

V. CONCLUSIONS AND FUTURE REMARK

In this paper, the systematic methodology to derive, classify HV generator architectures based on modularization level of key sub-components of HV generator are proposed to summarize the existing architectures and explore new possible architecture such as architecture-7 with multiple inverter, single transformer, and multiple rectification structure. The advantages and challenges for each HV generator architecture are discussed. Furthermore, these HV generator architectures are evaluated to understand the performance It provides the guideline for HV generator architectures selection to achieve best performance for different output voltage and power applications.

From the HV generator architecture performance charts, architecture-4 with single inverter, multiple transformer, and multiple rectification structure demonstrates the best overall performance on efficiency, power density, HV ripple, HV pulse speed, HV insulation and modularity for single inverter configuration. Similarly, full distributed Architecture-8 with multiple inverter, multiple transformer, and multiple rectification structure outperforms than other architecture with multiple inverter configuration for medium to high power rating HV power generation applications. In summary, the modular HV tank architecture (multiple transformer, and multiple rectification structure for architecture-4 and Architecture-8) is the most promising candidate to further investigation to achieve good performance.

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