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Equivalent Circuit Model for Modular High Voltage Power Generation Architectures

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***Abstract*—This paper introduces the unified equivalent circuit model for modular high voltage(HV) power generation architectures. The HV generation architectures are introduced considering the modularity of key HV components such as transformers or rectifier circuits firstly. An equivalent resister and capacitor circuit network is adopted to model the HV transformer and multi-stage voltage multiplier circuit for HV generation architectures to simplifies the analysis, design and optimization for HV generation architectures. The expressions of equivalent resister and capacitor network in modular HV generation architectures are deduced. Based on the proposed equivalent circuit model, a 400kHz switching frequency 500W 20kV output HV generator prototype based on modular HV architecture is built to validate the equivalent circuit model. The experimental results of HV generator prototype are given finally.**

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

I. INTRODUCTION

High voltage(HV) power generators are widely used in applications, such as HV capacitor charger, X-ray generation, electrostatic precipitation, and other pulsed power areas [1-3]. Generally, the high frequency HV generator is composed of high frequency DC-AC inverter, resonant tank, HV transformer and high voltage rectifier. There are different HV generator architectures for different output voltage and output power ratings [4]. The HV generation architectures offer more alternatives according to the performance requirements of HV generator system such as efficiency, power density, HV pulse speed, HV ripple, insulation stress and modularity, etc. Simultaneously, more challenges are added in modeling and analysis due to various HV generation architectures.

The first harmonic approximation (FHA) approach by replacing the voltages and currents with the fundamental components of the Fourier transformation to linearize the original circuit is a typical modeling method for resonant converters. The FHA-based steady-state circuit modelling approach which models the HV transformer and the full-bridge rectifier by a resistor and capacitor (RC) network is introduced in [5]. The behavior of the series parallel (LCC) resonant converter with a simple full-bridge diode rectifier is described [5-6]. This simple and extendable RC model is a promising solution to deduce a unified model of HV generation architectures. However, most state-of-the-art steady-state circuit models are investigated only for the full-bridge diode rectifier. The model needs to be further improved for other HV generation architectures with voltage multiplier. The circuit diagram for LCC resonant converter with multi-stage voltage multiplier is illustrated in Fig.1. The accurate analysis of LCC resonant converter with transformer and multi-stage voltage multiplier is rather complex since the equations include unknown time instances at which the output multiplier begins and ceases to conduct. The state equation of a LCC converter with 3-stage full-wave Cockcroft Walton(CW) voltage multiplier is proposed in [7]. However, it cannot represent the complex operation modes of the CW voltage multiplier since the multi-stage voltage multiplier is replaced by the one-stage CW rectifier. The unified equivalent circuit model has not been investigated yet for modular HV generation architecture with voltage multipliers and diode rectifiers. The major contribution of this paper is to develop the unified equivalent circuit model for convenient analysis, design of modular HV generator architectures.

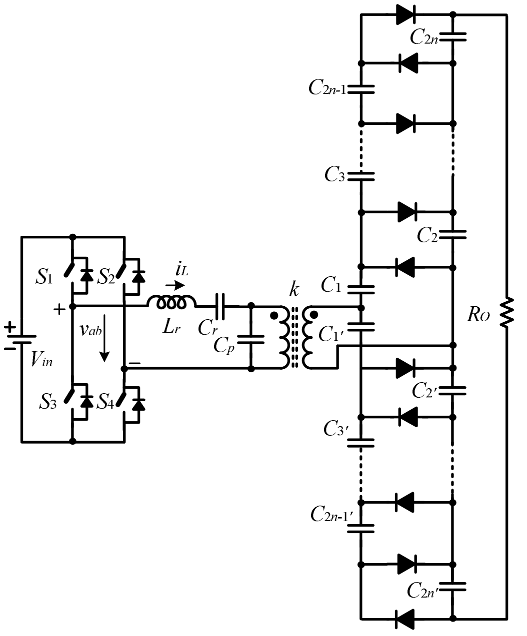

Fig. 1 The diagram of LCC resonant converter with voltage multiplier

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II. HV POWER GENERATION ARCHITECTURES

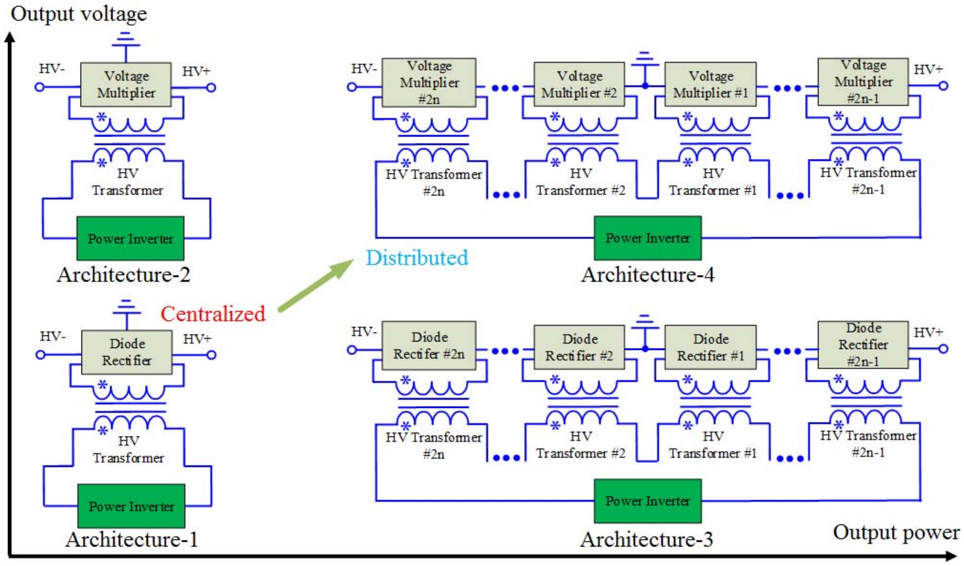

Fig. 2 Overview of HV generation architectures for different output voltage and power levels

Fig.2 illustrates the overview of different of HV generation architectures for different output voltage and power. There are different HV generation architectures according to the level of modularity of the main HV sub-components such as HV transformer and voltage multiplier circuit in HV generation system [3]. The benefits of distributed sub-components of the HV generation system will lead to low electrical and insulation stress on the sub-components, easy for power and high voltage generation scalability.

III. EQUIVALENT CIRCUIT MODEL FOR MODULAR HV POWER GENERATION ARCHITECTURES

The different HV generation architectures can follow common model evolution principle and an equivalent circuit model for steady state model can be derived as described below. Considering four HV architectures, HV transformer followed by capacitive loaded rectifier (diode rectifier or voltage multiplier) is the basic “cell” of a high voltage generator. The steady-state model of this HV structure is derived and then expand it to all architectures. Several assumptions are made below:

A. Switching devices are ideal;
B. Quasi-sinusoidal resonant current of primary side is equivalent by ideal sinusoidal current;
C. Voltage ripple on output capacitors is ignored consider the large dc voltage;

A. Equivalent circuit model of high voltage transformer with single polarity CW voltage multiplier

A mathematical model of LCC resonant converter is proposed in [5], where the HV transformer with a diode rectifier is replaced by RC network, as shown in Fig.2. This RC load models the steady state of converter successfully and is widely adopted. This model can be applied to architecture-1 directly. However, for high voltage transformer loaded by CW voltage multiplier, this model is not suitable due to cascade structure of voltage multiplier. The typical waveform of high voltage transformer with voltage multiplier is shown in Fig.3. The voltage gain of multiplier must be considered in modeling compared to diode rectifier. In diode rectifier, average absolute value of transformer secondary side current equals output current, whereas this is not satisfied in voltage multiplier circuits.

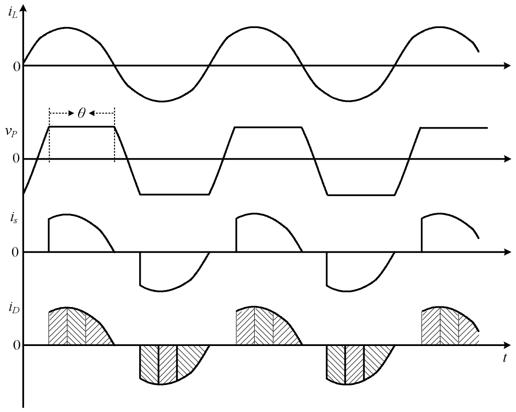

Fig. 2 key waveforms of LCC resonant converter

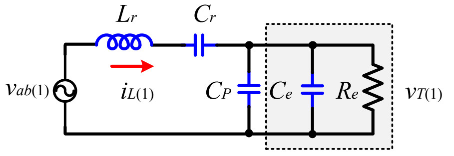

Fig. 3 Equivalent circuit model of LCC resonant converter

The coefficient k_{VM} between transformer's secondary side voltage and output voltage is [3]

$$k_{VM}=\frac{V_O}{V_{\sec}}=\frac{12nf_sC_OR_O}{6f_sC_OR_O+4n^3+3n^2-n} \tag{1}$$

The conduction angle θ of secondary side current is expressed as

$$\theta=2\arctan\sqrt{\frac{nk_{VM}k^2\pi}{2\omega C_PR_O}} \tag{2}$$

Proportional coefficient between peak value of parallel capacitor and fundamental peak value k_{v} is defined by

$$k_v=\frac{V_{C_P(1)\mathrm{m}}}{V_{\sec}} \tag{3}$$

In [4], k_{v} can be approximated by

$$k_v=1+0.27\sin(\frac{\theta}{2}) \tag{4}$$

Furthermore, the phase lag between fundamental components of transformer input current and voltage is approximated by

$$\beta\text{=-}25\sin(\theta)[\mathrm{deg}] \tag{5}$$

Equivalent resistance and capacitance are calculated by

$$R_e=\frac{k_V^2}{2k^2k_{VM}^2}\cdot R_O \tag{6}$$

$$C_e=\frac{\tan|\beta|}{\omega R_e} \tag{7}$$

B. Equivalent circuit model of high voltage transformer with double polarity Cockcroft Walton multiplier

In double polarity CW voltage multiplier, positive half output voltage symmetrically equals negative half output voltage. Output resistor can be divided into two equal resistors connected in series and make no difference from input side of voltage multiplier, as shown in Fig.4. Transformer output current is halved by two polarities. By equivalent transform, HV transformer with double polarity CW multiplier can be transformed to two identical transformers with single polarity CW multiplier connected in parallel. It is noteworthy that value of k_{VM}, C_{p} and R_{o} should be adapted to parameters in equivalent circuit correspondingly. Then value of R_{e} and C_{e} can be calculated by

$$R_e=\frac{R_e^{'}}{2} \tag{8}$$

$$C_e=2C_e^{'} \tag{9}$$

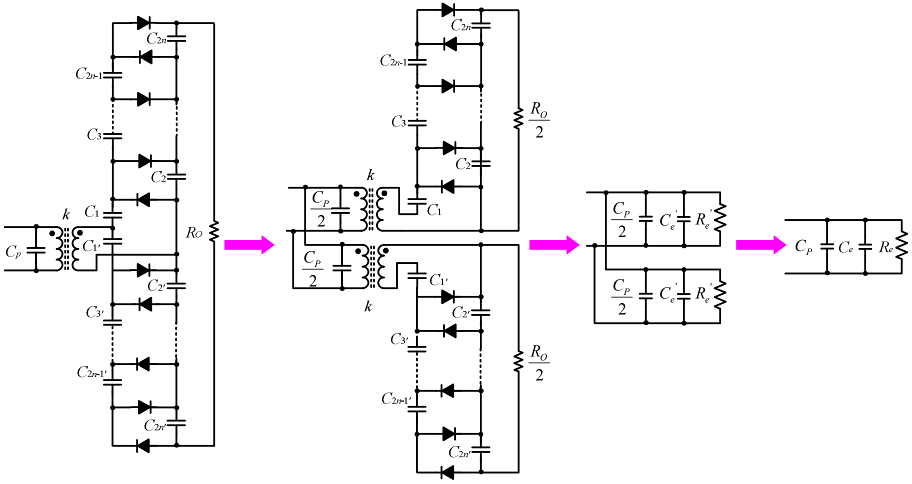

Fig. 4. Equivalent circuit model of HV generation with double polarity voltage multiplier

The basic modeling concept for architecture 1-4 is to convert complicated structures into to the basic cell. To describe these architectures, at least three independent variables are required, that are number of transformers (*m*), stages of voltage multiplier (*n*), polarities (*p*). For HV generation architectures 1-4, value of *m, n, p* is shown in Table I. The output voltage of each voltage multiplier is the same, so output resistor can be equally divided into *m* parts in series. Then each cell can be decoupled from others in circuit. Double polarity voltage multiplier can be split to parallel single polarity voltage multiplier further. Equivalent circuit of every cell has already been deduced in previous chapter. As a result, the modular architecture-4 is subdivided to simple circuits. The parameter *m*, *n*, *p* are three dimensions to describe this circuit. The Equivalent circuit model of HV generation architecture-4 is shown in Fig.5

Table I. Value of *m, n, p* for HV generation architectures 1-4

HV architecture	Number of transformer	Stage of voltage multiplier	Polarity
1	1	1	1
2	1	*n*	*p*
3	*m*	1	1
4	*m*	*n*	*p*

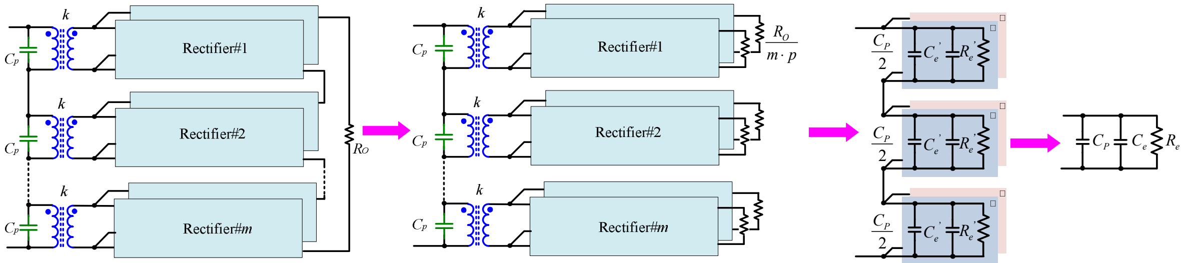

Fig. 5. Equivalent circuit model of HV generation architecture-4

Equivalent capacitance C_e' and resistance R_e' of each sub module can be calculated, output resistor adopted in the equations is

$$R_O^{'}=\frac{R_O}{m \cdot p} \tag{10}$$

The parallel capacitor in the equations is

$$C_P^{'}=\frac{C_P}{p} \tag{11}$$

Total equivalent capacitance and resistance for the equivalent circuit model are calculated by

$$R_e=\frac{m}{p}R_e^{'} \tag{12}$$

$$C_e=\frac{p}{m}C_e^{'} \tag{13}$$

Using the same modeling methodology, steady state model of HV architecture-3 can be easily acquired. For HV architecture-3, transformers are loaded by diode rectifier, number of transformer is enough to describe this architecture. Transformers and diode rectifier are modeled by m basic cells connected in series. In diode rectifier, proportional coefficient between secondary side voltage and output voltage is k_{VM}=1. Stages of voltage multiplier n=1, polarity of voltage multiplier p=1. The value of equivalent RC circuit network can be calculated. Above all, it is evident that model of architecture-4 can be expand to other three architectures by replace m, n, p, k_{VM} accordingly. A unified equivalent circuit model for modular HV power generation architectures is concluded by (14) ~ (17).

$$k_{VM}=\begin{cases}\dfrac{12nf_sC_O(\dfrac{R_O}{m \cdot p})}{6f_sC_O(\dfrac{R_O}{m \cdot p})+4n^3+3n^2-n}, & \text{voltage multiplier}\\ 1, & \text{diode rectifier}\end{cases} \tag{14}$$

$$\theta=2\arctan\sqrt{\frac{mnp^2k_{VM}k^2\pi}{2\omega C_P R_O}} \tag{15}$$

$$R_e=\frac{k_V^2}{2p^2k^2k_{VM}^2}\cdot R_O \tag{16}$$

$$C_e=\frac{\tan|\beta|}{\omega R_e} \tag{17}$$

IV. HARDWARE PROTOTYPE EXPERIMENTAL RESULTS

Based on the above equivalent circuit model for modular high voltage power generation architecture. A 400kHz 500W 20kV output HV generator prototype based on HV architecture-4 with modular HV transformers and voltage multiplier circuits is built in lab to validate the design. The specifications and key parameters of HV generator prototype are given in Table II and Table III respectively. The hardware prototype photo and key experimental waveforms are shown in Fig.6 and Fig.7.

Table II. Specifications of HV generator prototype

Specifications	Value
Input voltage V_{in}	250V
Output Voltage V_o	20kV
Output Power P_o	500W
Switching frequency f_s	400kHz

Table III. Key parameters of HV generator prototype

Specifications	Value
HV transformer number	2
The voltage multiplier stage number	2
Multiplier polarity	2
HV transformer turns ratio	4:45
HV transformer parasitic capacitance reflected to primary	3.5nF
Series resonant inductor	88μH
Series resonant capacitor	2.5nF
Voltage multiplier capacitance	1.5nF
Inverter MOSFET(SiC)	C2M0080120D
Voltage multiplier diode(SiC)	GB01SLT12-214

Fig.7 provides a comparison result between the measured prototype experimental waveform and the equivalent circuit in Fig.5. The purple line is the experimental results of the resonant current, and the blue line is the calculated resonant current in which the HV generation circuit is replaced by the computed equivalent RC circuit: $R_e = 99.1\Omega$, $C_e = 3.58\text{nF}$. The two resonant currents match well with each other, which verifies the validity of the proposed equivalent RC circuit model of the HV generation architectures.

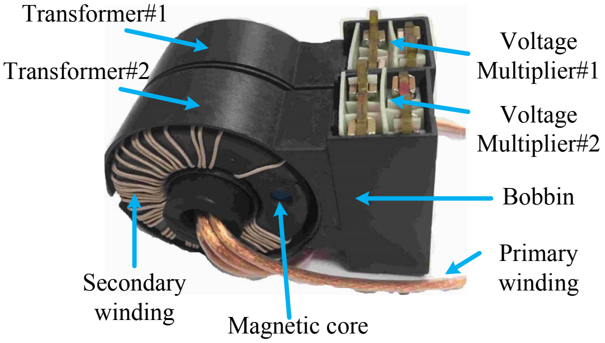

Fig.5 Hardware prototype photo of 400kHz 500W 20kV output HV generator

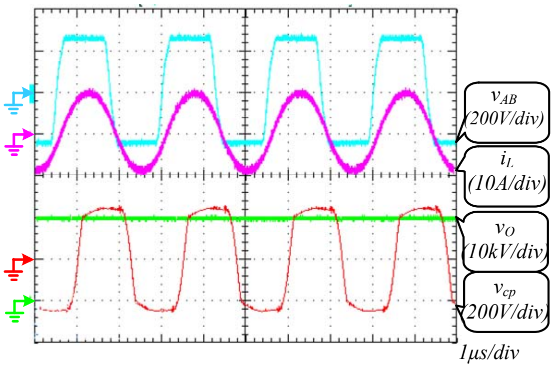

Fig. 6 Experimental waveforms at $P_o = 500\text{W}$, V_o=20kV, f_s=400kHz

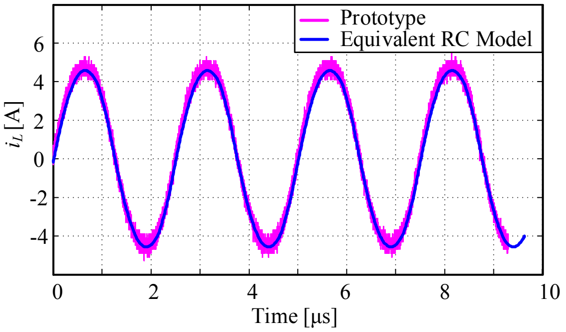

Fig. 7. Resonant current comparison between the experimental and the proposed model

V. Conclusions and future remark

The unifier equivalent circuit model is proposed for HV generation architectures considering the multistage rectifier circuits. It is proved that the RC model is extensible and can be used to all four HV generation architectures. Based on this methodology, an equivalent circuit model is proposed for modular HV generation architectures to achieve convenient circuit design, circuit analysis and HV generator performance optimization. The equivalent circuit model is validated by a 400kHz 500W 20kV output HV generator prototype with HV architecture with modular HV transformer and multi-stage voltage multiplier. Although this paper discusses the circuit model for LCC resonant converter with multi-stage voltage multiplier, the modeling procedure are also validity for other resonant converter topologies.

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