Modeling and simulation of klystron-modulator for linear accelerators in PRTA

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ABSTRACT

Approximately 70% of commercial industries worldwide use electron accelerator technology for various irradiation processes. The advantages of irradiation processes compared to thermal and chemical processes are higher output levels, reduced energy consumption, less environmental pollution, and producing superior product quality and having unique characteristics that cannot be imitated by other methods. Research Center for Accelerator Technology (PRTA), BRIN, Indonesia is developing standing wave LINAC (SWL) for food irradiation applications at S-band frequencies (±2856 MHz), electron energy of 6-18 MeV, and an average beam power of 20 kW. This paper aims to model, simulate, and analyze the klystron modulator in the RF linear accelerator (LINAC). The klystron modulator is the main component of the RF LINAC, which functions to supply klystron power with the order of megawatt peak DC, so that the klystron can amplify the low-level RF signal from the RF driver into a high-power RF signal with a power of 2-6 MW peak. The klystron modulator modeling is carried out based on mathematical modeling, then simulated using LTspice to analyze the system performance of the klystron modulator. The results of the klystron modulator modeling simulation show stable system performance and dynamic response. So that it meets the specifications of the 6-18 MeV SWL LINAC being developed by PRTA-BRIN.

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1. INTRODUCTION

Electron accelerators for industrial purposes have been widely used in recent years. Approximately 70% of electron accelerators worldwide are used for industrial applications [1]. Commercial industries use electron accelerators for a variety of applications [2], namely: polymer processing [3], sterilization of medical products [4], food irradiation [5], and waste processing [6]. Electron beam irradiation becomes popular due to the advantages of the process over thermal and chemical processes [7], including higher output levels [8]-[10], reduced energy consumption [9], lower environmental pollution [10], and the ability to produce superior product quality with unique characteristics that cannot be replicated by other methods [11].

Electron accelerators for irradiation process can have two output modes, namely electron mode and x-ray mode [12]. Electron accelerators can be divided into several categories depending on the source of the electric field used. The first category is electrostatic accelerators, in which the increase in particle energy is achieved through the application of high voltage. Examples include Van de Graaff, cascade, and transformer accelerators [13]. The second category is an induction accelerator, where the electric field is caused by the variation of the magnetic field as a function of time [14]. The third category is radio frequency (RF) accelerator, where particles gain energy from the cavity supplied by high-frequency electromagnetic fields [15], [16]. Among the electron accelerator categories, RF electron linear accelerators (LINACs) can produce high-energy beams exceeding 10 MeV while maintaining a compact size. Since the use of electron beams remains high, especially in Indonesia, and there is a growing need for higher-energy electron beam, Research Center for Accelerator Technology (PRTA), BRIN, Indonesia is developing electron LINAC prototype for research purposes. The LINAC development has begun with the design of a 3 MeV LINAC cavity for radiography applications [17]. A higher-beam current electron LINAC is currently under design, with an energy range of 6–18 MeV and an average beam power of 20 kW, powered by a klystron.

One of the key components of the LINAC that must be designed is the klystron modulator. Its function is to supply the klystron with megawatt-level peak DC power, enabling the klystron to amplify the low-level RF signal from the RF driver into a high-power RF signal with a peak power of 2–6 MW [18], [19]. This paper aims to model, simulate, and analyze the klystron modulator in RF LINAC. A simulation of the klystron modulator has been conducted using PSpice tools [20]. Another study utilized the LTspice tool to model certain parts of their existing LINAC modulator [21]. However, neither of these research works mentions the use of analytical calculations. In this study, the proposed klystron modulator is designed to produce a voltage pulse of 104–125 kV and a current of 64.8–85.2 A (based on klystron specifications), with a pulse duration of 6 µs and a repetition rate of up to 200 Hz. The simulation encompasses all parts of the modulator, from the high-voltage (HV) power supply to the klystron load, using LTspice. Analytical calculations were performed prior to the simulation to determine component parameters, and parameter optimization was carried out during the simulation.

2. RESEARCH METHOD

Figure 1 shows the block diagram of the klystron-modulator in the proposed methodology. All of the parts were pre-calculated and then simulated using LTSpice software individually and in one unified system. The modulator converts AC line power into a series of high-voltage, high-current pulses required by the klystron [22]. Since the modulator is an important component of the LINAC that operates to supply power to the klystron [23], it must be designed carefully, because it will affect the performance and the lifetime of the klystron. In the end, the design must be applicable to drive the klystron specified by Table 1, which is the klystron specification that will be used for the 6–18 MeV LINAC proposed by PRTA BRIN. At least the klystron modulator can produce a voltage pulse of 104–125 kV and a current of 64.8–85.2, with a pulse duration of 6 µs and a repetition rate of up to 200 Hz.

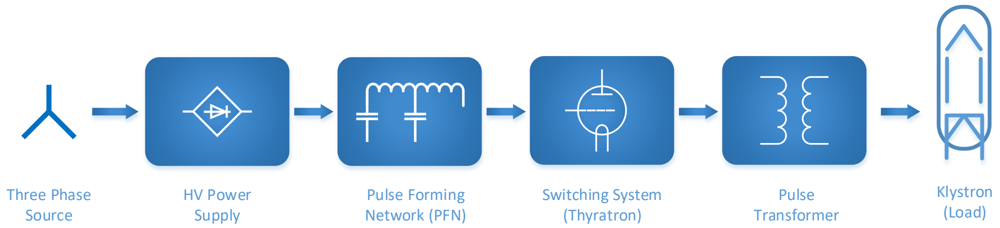

Figure 1. Block diagram of the klystron-modulator

Table 1. The klystron parameters

Parameters	Value
Peak RF output power	6 MW
Peak RF input power	60 W max
Beam voltage	104 - 125 kV
Beam current	64.8 – 85.2 A
Pulse width	10 µs (max)
Duty cycle	0.0026 max

3. MODELING OF KLYSTRON-MODULATOR COMPONENTS

Modulator modeling involves several main components, high voltage power supply (HVPS), pulse forming network (PFN), switching system and pulse transformer. Topology and mathematical modeling play a crucial role in enhancing the design and functionality of this modulator system.

3.1. HV power supply (HVPS)

HV charging power supply is one of the important parts in the modulator to provide high voltage and ensure the modulator has the power needed to produce high voltage pulses during particle acceleration, both electrons and ions [24]. Figure 2. Is a modeling of the HV power supply circuit that functions as a capacitor charger on the pulse forming network (PFN) [25]. The type of rectifier used is a 12 pulse rectifier equipped with a capacitor filter.

The HV power supply was simulated using the schematic diagram Figure 2. The three-phase AC line from the source is rectified by 12-pulse rectifier into HVDC voltage that charges the pulse forming network (PFN) in the next stage. The HVPS must be able to provide several output voltages which are used to regulate the klystron voltage according to the desired RF power. In this case, multi-tap transformers are used in the design. The output voltage value of the HVPS will become the initial voltage of the PFN. Therefore, the voltage requirement for the PFN must be calculated first. The maximum voltage required by klystron is 125 kV (Table 1). The pulse transformer ratio was defined to be 1:11, which is the common ratio for pulse transformer products. Therefore, we get voltage requirement of 11.36 kV at the primary side of the pulse transformer. The 11.36 kV is the pulse voltage output from the PFN, and the charging voltage must be higher than that (more than twice), because the PFN makes pulse by storing the energy in to the capacitors and discharging them through the inductor-resistor load. The combination of this RLC circuit will shape the voltage to become rectangular and the voltage will always below the initial capacitor voltage. The charging voltage of the PFN was found by trial in the LTSpice simulation.

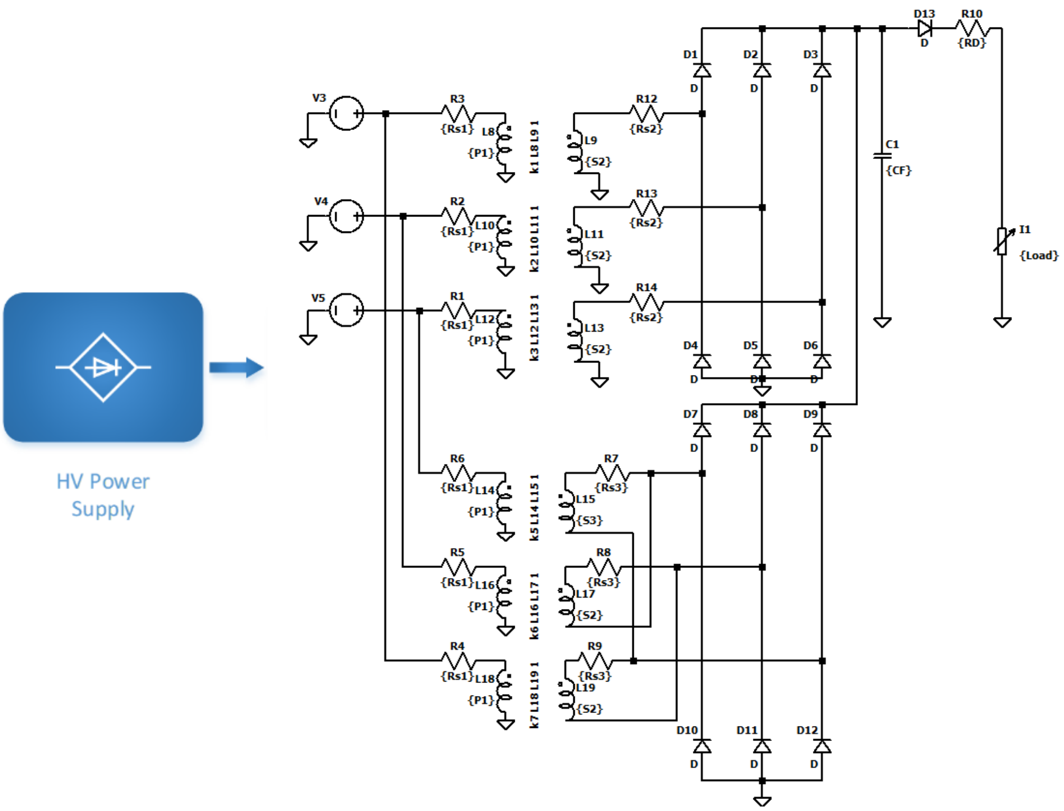

Figure 2. Modeling circuit diagram of the HV power supply

3.2. Pulse forming network (PFN)

Pulse forming network (PFN) functions as a form of electrical pulses needed to drive the LINAC [18]. PFN will collect electrical energy from the HV charging power supply and store it in the form of potential energy [20]. When needed, this energy is released in the form of electrical pulses. The PFN circuit generally consists of a number of inductors and capacitors arranged in parallel so that the discharge pulses from the capacitors are spaced out and produce square or trapezoidal current pulses with relatively flat peaks [26].

The pulse forming network used in this design is the Rayleigh type. Figure 3 shows the schematic diagram of the PFN. The 6 stages PFN was chosen in this design, because we assume that it was the optimum number for 6 us pulse width modulator, because we are experienced that 6 capacitors (high voltage) and 6 inductors will be ideal for the cabinet space, which in this case is 120 cm in length, 100 cm in width, and 200 cm in heigh.

To calculate the initial capacitors and inductors values for the Rayleigh PFN, (1) and (2) were used [27]. The values were then optimized through trial adjustments in the simulation. T is the pulse duration, which is 6 μs; N is the number of stages, which is six stages; and R is the load resistance.

$$C = \frac{T}{NR} \tag{1}$$

$$L = \frac{RT}{N} \tag{2}$$

The load resistance *R* in this case is the klystron. The *R* value can be simply calculated using the ohm's law using data from the specification, but after it was calculated, the value is still at the secondary side of the pulse transformer. Therefore, it needs to be converted into the primary side using (3). After we calculated the *C* and *L* values, the values was then optimized through the simulation.

$$\frac{Primary\ Turns}{Secondary\ Turns} = \sqrt{\frac{Primary\ Impedance}{Secondary\ Impedance}} \tag{3}$$

3.3. Switching system (thyratron)

Thyratron functions as a high voltage switch whose application is used for fast switches such as in radar, laser, and accelerator [28]. The working principle of thyratron is almost the same as thyristor, but the advantage of thyratron compared to other switches is the ability of its switching system to tolerate high voltage and current [29]. Figure 4 shows the modeling of the thyratron structure consisting of an anode, cathode, grid 1 and grid 2 [30]. Grid 1 and grid 2 in real situation are supplied by thyratron trigger circuit. Thyratron in this modeling functions to transfer electrical energy stored in PFN into high current-high voltage electrical power pulses and then forwards the power to the pulse transformer. The thyratron used in this modeling is able to withstand a maximum voltage of 80 kV with a current of 3 kA.

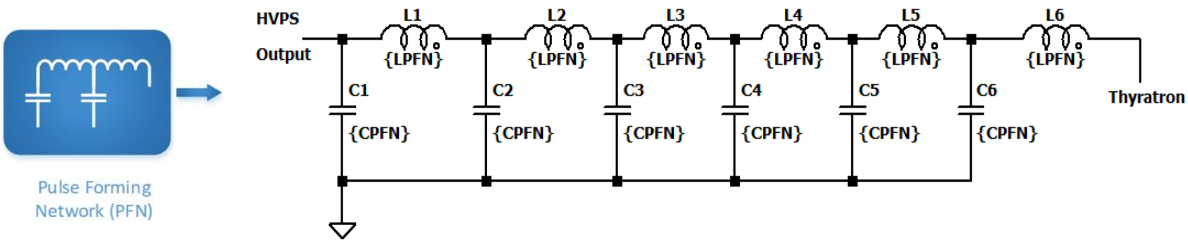

Figure 3. Modeling circuit diagram of the pulse forming network (PFN)

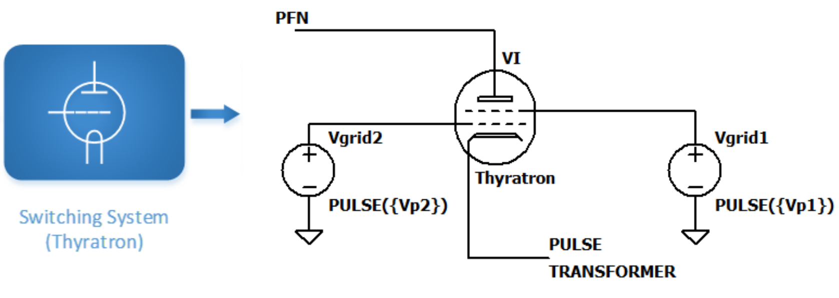

Figure 4. Modeling circuit diagram of the thyratron

3.4. Pulse transformer

The pulse transformer is an important component in the modulator that functions to increase the power pulse voltage from the PFN so that it is in accordance with the needs of the klystron. In addition, the pulse transformer also functions to reduce the amount of ripple so that the output pulse is smoother [31]. Pulse transformers can transfer maximum energy from the PFN to the load efficiently (maximum η) in a certain pulse duration τ [32], when meeting the following conditions:

$$R_L = \sqrt{\frac{L_L}{C_D}} \quad (4)$$

$$\tau = \sqrt{2L_p C_D} \quad (5)$$

$$\eta = \left[1 - \left(\sqrt{\frac{2L_L}{L_P}}\right)\right] X\ 100\ \% \quad (6)$$

where, *Lp* is the primary inductance, *Ls* is the secondary inductance, *LL* is the Leakage inductance, and CD is the winding capacitance which depends on the pulse transformer design [33]. Figure 5 shows the modeling of the pulse transformer, the variables of the pulse transformed was adjusted in the simulation in order to get the right values for the system [34].

3.5. Klystron (load)

Table 1 is the parameter of the klystron used for the 6-18 MeV LINAC in this study. The klystron amplifies the input RF signal into a high-power RF output by modulating the electron beam inside the klystron so that the electron beam will form bunches with certain intervals, when passing through the last cavity of the klystron, this bunch will transfer its kinetic energy to the cavity so that the cavity will produce high power RF waves [35]. Klystrons have the ability to emit accurate, coherent, and high power microwave energy up to several gigahertz [36]. Figure 6 shows a klystron modeling in LTspice simulation. The model was based on the calculation of the V/I characteristics of the klystron, through (7) [37].

$$I = KV^{3/2} \quad (7)$$

Where, *I* is the klystron beam current [38], *V* is the klystron beam voltage. The constant *k* is a function of the geometry of the cathode-anode structure and is called perveance. This model was later used as a load on the modulator.

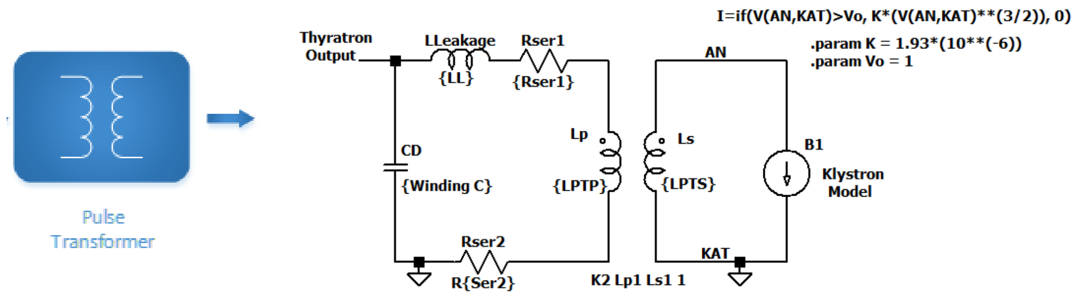

Figure 5. Modeling circuit diagram of the pulse transformer

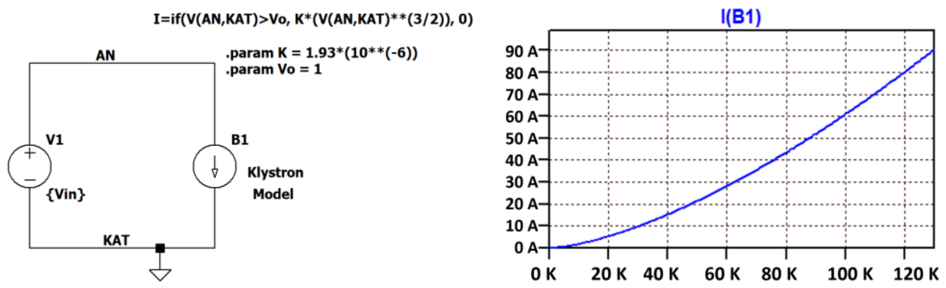

Figure 6. Klystron modeling

3.6. Simulation steps

Figure 7 shows the schematic of overall simulation. At the first, the klystron model was implemented. It needs to be simulated first so that we sure that the *V/I* characteristic of the klystron is correct. After that, we implemented the pulse transformer model. *LL*, *LP*, and *CD* values were calculated and implemented. Next was the implementation of the thyratron model, in this case the thyratron trigger (grid 1 and grid 2) were set to trigger the thyratron every 5 millisecond in order to get 200 pulse per second (repetition rate). The next step was to implement the *C* and *L* values in the PFN model. The six-phase transformer of the HVPS was then initially set to the output voltage of twice of 11.36 kV.

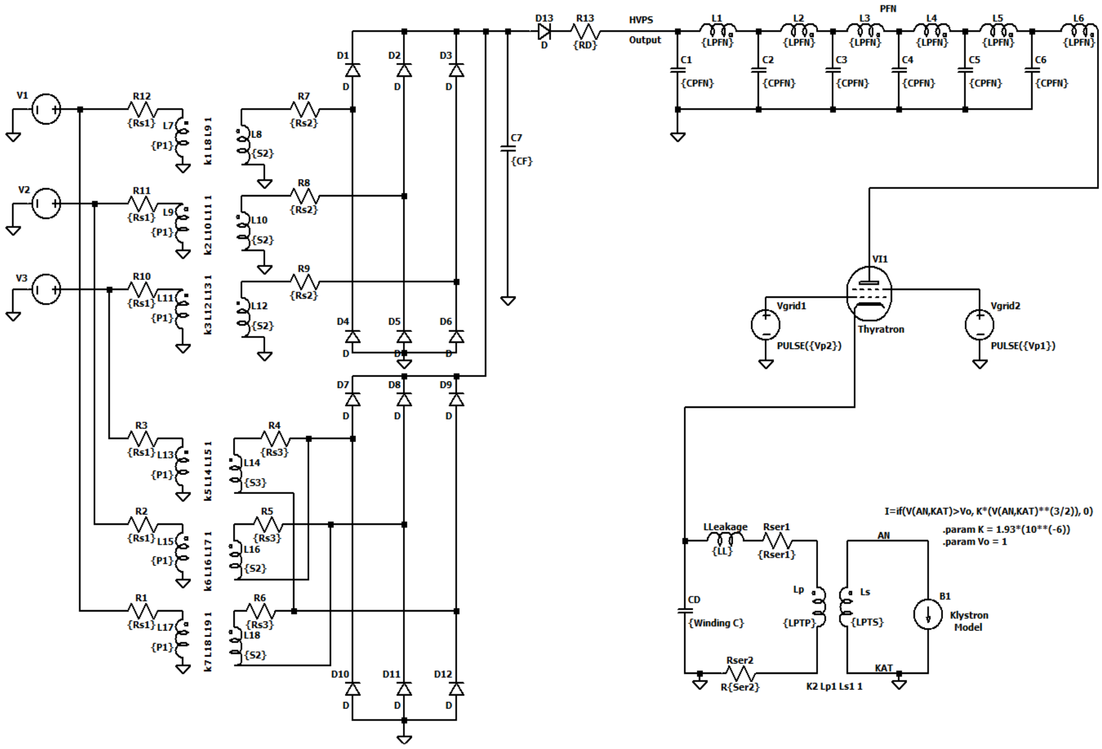

Figure 7. The schematic of overall simulation

4. RESULTS AND DISCUSSION

After simulations were conducted, we got the best result shown in Figures 8(a) and 8(b). Figures 8(a) and 8(b) show the output voltage and current coming out of the pulse transformer and fed to the klystron. From the figures, it can be seen that the voltage and current are in accordance with the klystron specification input, which are 104 - 125 kV and 64.8 - 85.2 A. The quality of the pulse produced has a flatness of 2% and a rise time of <1 µs. The final output results of this pulse transformer show that the designed modulator can be applied to the LINAC system really well where it is able to supply the klystron and is able to vary the klystron RF power by adjusting the modulator output voltage from 104 to 125 kV. This variation in klystron RF power is very necessary for the LINAC feature in determining the desired particle energy mode, which is 6-18 MeV.

To reach the output voltage range of 104 – 125 kV, the HVPS needs to have output of 22 – 27 kV. It means that the six-phase high voltage transformer needs to have multi-taps to reach the range. Therefore, for 380 V 3-phase power source, the ratio of the primary and secondary transformer is 1: 56 – 71. To reach this range, the transformer should have a multitap coil customized by the manufacturer. Figures 9(a) and 9(b) show the simulation results of HV power supply modeling at a maximum voltage of 27 kV. The transformer model used is a 6-phase transformer which supplies a 12-pulse rectifier. A 12-pulse rectifier has many advantages compared to a 6-pulse rectifier, one of the main ones is that it has a low ripple level so that it produces a higher quality output.

The *C* and *L* values of the PFN of the final simulation were 0.04499 µF and 12.12 µH. They were calculated using (1)-(3) with the R value of the klystron is 125 kV divided by 85.2 A. Figures 9(c) and 9(d) show the current waves in the thyratron and capacitors when the thyratron is triggered. The current magnitude varies with a range of -1 kA to 1.4 kA for the input voltage of 27 kV. In this case, the thyratron current is the sum of the currents of the 6 capacitors on the PFN. Figure 9(c) shows that the thyratron current experiences an overshoot at the beginning of the pulse, then an undershoot at the end of the pulse. This overshoot and undershoot will be eliminated by the pulse transformer in the next stage. From the simulation we can get the information that we can use the 30 kV capacitor and also 30 kV thyratron with the current capacity more than 1.5 kA, which are easy to get in the markets.

Figures 9(e) and 9(f) are the input voltage and current on the pulse transformer with variations in PFN input voltage of 22 kV, 24 kV, 26 kV, and 27 kV (HVPS output). From the figure, we can see that overshoot and undershoot are gone due to the response of the pulse transformer. For PFN voltages of 22 to 27 kV, the output produced (vin pulse transformer) is a pulse voltage of 9.8 to 11.5 kV with a duration of 6.2 µS. While the current is 740 A to 940 A. The optimal values of winding capacitor CD and leakage inductance in this simulation are 0.12 µF and 0.3 µH with the inductance *Lp* is 1 mH. The efficiency of the pulse transformer is 97% which is good enough for the system.

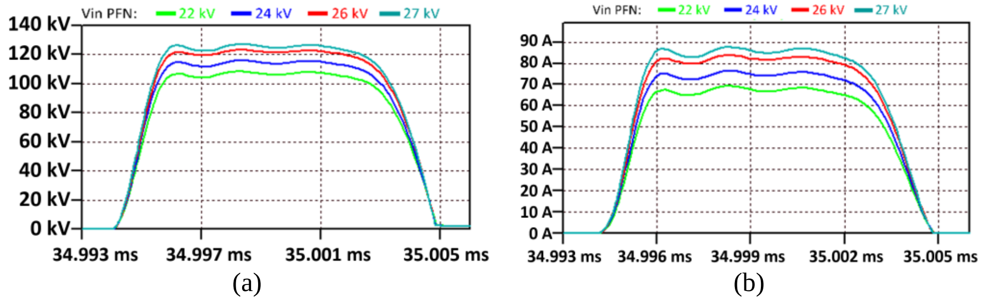

Figure 8. Output pulse of modulator: (a) voltage output pulse and (b) current output pulse

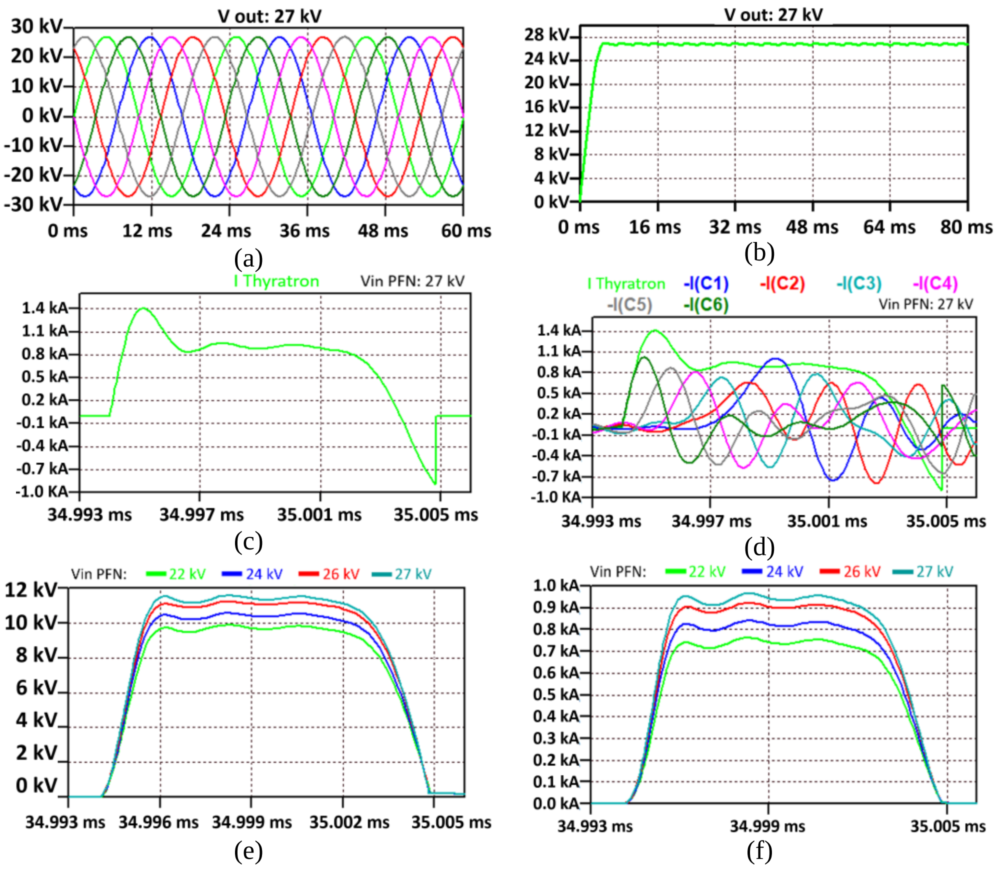

Figure 9. Current and voltage waveform of the simulation: (a) HVPS transformer output waveform, (b) twelve-pulse rectifier output, (c) thyratron current waveform, (d) thyratron current and PFN capacitors current waveform, (e) pulse transformer voltage input, and (f) pulse transformer current input

5. CONCLUSION

This study presents the modeling of a 10.7 MW peak line-type modulator that will be proposed for 6-18 MeV standing wave LINAC as a source of X-rays and electrons for industrial food irradiation applications. The modulator in this study is capable of producing a pulse voltage of 104-125 kV and a current of 64.8-85.2 A, with a pulse width of 6 µs and a repetition rate of 200 pulses per second. The main components consist of an HV power supply capable of producing a voltage of 22-27 kVDC; six stage line type PFN with the capacitors value of 0.04499 µF and the inductor value of 12.12 µH; 30 kV/1.4 kA thyratron; pulse transformer with the ratio of 1:11 and the efficiency of 97%. The quality of the produced pulse has a flatness of 2% and a rise time of <1 µs. The final output results of this modulator indicate that the designed modulator can be applied to the LINAC system really well where it is capable of supplying klystrons for LINAC 6-18 MeV.

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AUTHOR CONTRIBUTIONS STATEMENT

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Dwi Handoko Arthanto	✓	✓	✓	✓	✓	✓			✓	✓	✓			
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [W], upon reasonable request.

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