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PI Controller Implementation on HV Power Supply Generation with Super Lift Luo Converter for X-Ray Machine

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Abstract: Nowadays, the use of a transformer for high voltages in converter circuit reduces the overall operating efficiency due to leakage inductance; core loss and use of transformer also increase the operational cost, installation space and weight. Therefore, the proposed system is implemented with transformer less DC-DC converter to obtain high DC voltage. A positive output super-lift triple-lift Luo converter is proposed in this work to generate high voltage DC power for a medical use X-ray machine. This proposed scheme is introduced in order to achieve rapid transient and dead-beat output voltage responses without any overshoots in addition to output voltage characteristics with low voltage ripple in its steady state within widely specified setting ranges of the high output voltage and output current for the X-ray tube. The simulation results are presented and evaluated using PI controller.

Key words: DC-DC converter · High voltage · X –ray machine · Luo converter · PI controller

INTRODUCTION

DC-DC conversion technique has developed in recent years since it is required to reach a high power density, high-voltage transfer gain and high power efficiency. Double-output DC-DC converters convert the positive input source voltage to positive and negative output voltages. They consist of two conversion paths; one is positive conversion path and the other is a negative conversion path. These mirror symmetrical double-output voltages are especially required in industrial applications and computer periphery circuits such as operational amplifiers, computer periphery power supplies, differential servo motor drives and some symmetrical voltage medical equipment. To regulate the output voltage of DC-DC converters irrespective of load variations and supply disturbances, it is necessary to operate the DC-DC converters as closed loop systems. With pulse-width modulation control, the regulation of output voltage of DC-DC converters is achieved by varying the duty cycle of the electronic switch keeping the frequency of operation constant. These converters, in general, have complex non-linear models with parameter variation problems.

With a great advance of MOS-gate, power semiconductor devices, a variety of DC-DC power converters with a high-frequency transformer link have been widely studied and put into practice so far [1-5]. One of these, a certain particular application of a high-voltage DC power supply suited to drive an X-ray tube in an X-ray power generator has recently attracted particular interest in medical power electronics. The X-ray power generator must have the particular capability to adjust its DC output voltage across the X-ray tube to assure the best quality image for each specified pattern of the body part to be imaged. Higher output voltages are required so as to diagnose more substantial body parts of all types of bones and lower output voltages may be used for diagnosing soft tissues of the organs [6-7].

Thus, it is necessary to control the DC output voltage across the X-ray tube over widely specified voltage setting ranges by using high-power DC-DC converter. However, the practically-specified voltage setting ranges of the DC output voltage (tube voltage) across the X-ray tube and the output current (tube current) flowing through the X-ray tube may range from 20kV to 150kV in the output voltage and from 0.5mA to 1250mA, respectively [8-15].

The excellent dynamic and steady state responses of DC output voltage desired for the high-voltage X-ray power generator in which this resonant power converter using the IGBT modules cannot be sufficiently obtained by the conventional state feedback control procedures based on the classical and modem linear control theories.

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The desired dynamic responses in rising time and no overshoot performance in a transient state as well as reduced voltage ripple in steady state of tube voltage responses provide the best-matched quality of the image and the minimum amount of exposure time for special purpose application as X-ray power generator indispensable for medical use. High precision, as well as fast responses of the DC output voltage of converter or tube voltage, has to be performed by the widely specified voltage setting ranges and variable current setting conditions for X-ray tube drive. In practice, some gain parameters in converter control system used as X-ray power generator must be adequately adjusted by a variety of specific setting load conditions. At present, the system gain parameter adjustment depends on the experience of the skilled operator over a wide load range of output voltage and output current in the hospital as well as needs considerable laborious works [16-22].

In this paper, the discussion is focused on the design of a power supply for an X-ray application for medical purposes. The area of operation of the load and X-ray tube has been represented in Fig. 1. There, it can be observed that both the output voltage and the output power required have a range of 100 kV.

Proposed System Description for X-Ray Power Generator: Fig. 1 shows the block diagram of proposed dc-dc converter for x-ray power generator. The figure displays the bridge rectifier, used to convert the ac voltage to dc voltage and fed to the dc-dc converter. Positive output super lift. Triple-lift luau converter is used as a dc-dc converter, in this proposed system. This luau converter does not consist any large capacitors and switches, the control and operation of this converter are easy because of its structure is very simple in nature.

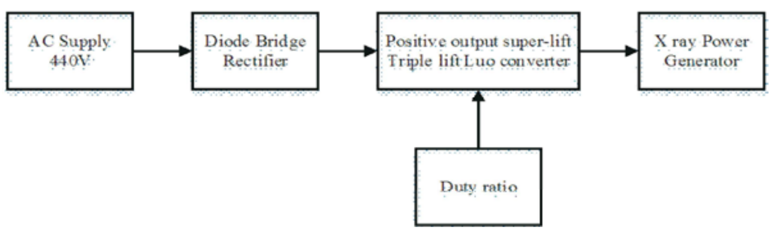
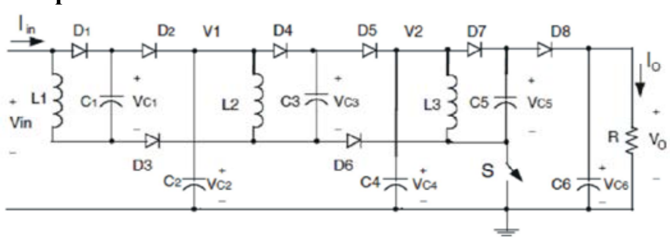
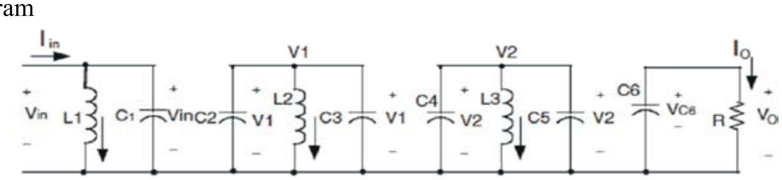


Fig. 1: Block diagram of high voltage generation for X-ray power generator using Luo converter

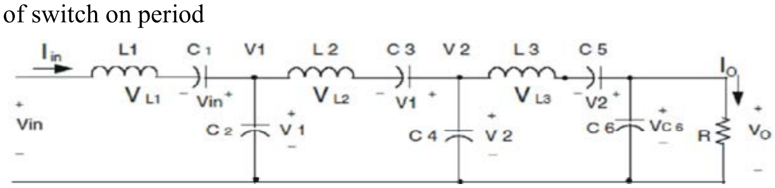
Positive Output Super-Lift Triple-Lift Luo Converter:



(a) Power circuit diagram



(b) Equivalent circuit of switch on period



(c) Equivalent circuit of switch off period

Fig. 2: Positive output super-lift triple-lift Luo converter

Positive output super-lift triple-lift circuit is derived from the re-lift circuit by double adding the parts (L_2-D_3-D_4-D_5-C_3-C_4). Its circuit diagram and equivalent circuits during switch on and off are shown in Fig. 2 [23]. The voltage across capacitor C_1 is charged to VIN. As described before the voltage V_1 across capacitor C_2 is:

$$V_1 = (2–k/1–k)V_{in} \quad (1)$$

Moreover, voltage V2 across the capacitor C_4 is;

$$V_2 = (2–k/1–k)^2V_{in} \quad (2)$$

The voltage across capacitor C_5 is charged to V_2. The current flowing through inductor L_3 increases with voltage V_2 during switch-on period k_T and decreases with voltage $–(V_O – 2V_2)$ during switch-off (1 – k) T. Therefore,

The ripple of the inductor current i_{L2} is;

$$\Delta i_{L3} = \frac{V_2}{L_3}kT = \frac{V_O - 2V_2}{L_3}(1-k)T \quad (3)$$

The Voltage Transfer Gain is;

$$V_O = \frac{2-k}{1-k}V_2 = \left(\frac{2-k}{1-k}\right)^2 V_1 = \left(\frac{2-k}{1-k}\right)^3 V_{in} \quad (4)$$

$$G = \frac{V_o}{V_{in}} = \left(\frac{2-k}{1-k}\right)^3 \quad (5)$$

Analogously,

$$\Delta i_{L1} = \frac{V_{in}}{L_1}kT \quad I_{L1} = \frac{I_{in}}{2-k}$$

$$\Delta i_{L2} = \frac{V_1}{L_2}kT \quad I_{L2} = \frac{2-k}{(1-k)^2}I_o$$

$$\Delta i_{L3} = \frac{V_2}{L_3}kT \quad I_{L3} = \frac{I_o}{1-k}$$

Therefore, the variation ratio of current i_{L1} through inductor L_1 is;

$$\xi_1 = \frac{\Delta i_{L1}/2}{I_{L1}} = \frac{k(2-k)TV_{in}}{2L_1I_{in}} = \frac{k(1-k)^6}{2(2-k)^5}\frac{R}{fL_1} \quad (6)$$

The variation ratio of current i_{L2} through inductor L_2 is;

$$\xi_2 = \frac{\Delta i_{L2}/2}{I_{L2}} = \frac{k(1-k)^2TV_1}{2(2-k)L_2I_o} = \frac{kT(2-k)^4V_o}{2(1-k)^3L_2I_o} = \frac{k(2-k)^4}{2(1-k)^3}\frac{R}{fL_2} \quad (7)$$

The variation ratio of current i_{L3} through inductor L_3 is;

$$\xi_3 = \frac{\Delta i_{L3}/2}{I_{L3}} = \frac{k(1-k)TV_2}{2L_3I_o} = \frac{k(1-k)^2TV_o}{2(2-k)L_2I_o} = \frac{k(1-k)^2}{2(2-k)}\frac{R}{fL_3} \quad (8)$$

Moreover, the variation ratio of output voltage v_o is;

$$\varepsilon = \frac{\Delta v_o/2}{V_O} = \frac{1-k}{2RfC_6} \quad (9)$$

PI Controller Implementation of HV DC-DC Power Generation: Although all the existing techniques for the PI controller parameter tuning perform well, a continuous and an intensive research work is still underway towards system control quality enhancement and performance improvements.

A PI controller is essentially a generic closed loop feedback mechanism. In working principle is that it monitors the error between a measured process variable and the desired set point; from this error, a corrective signal is computed and is eventually feedback to the input side to adjust the process accordingly. The differential equation for the PI controller is as follows,

$$u(t) = K_p e(t) + T_i \int_o^t e_p(t)dt \quad (10)$$

Thus, the PID controller algorithm is described by a weighted sum of the three times functions were the three distinct weights are: KP (Proportional gain) determines the influence of the present error value on the control mechanism, I (integral gain) decides the reaction based on the area under the error time curve up to the present point accounts for the extent of the response to the rate of change of the error with time [24]. PI controller is a most widely used type of controller for industrial applications and exhibits robust performance over a wide range of operating conditions. Proportional (P) and Integral (I) are involved. Fig. 3 shows the basic structure of PI controller. The proportional part is responsible for following the desired set-point while the integral part accounts for the accumulation of past errors. Despite the simplicity, they can be used to solve even a very complex control problem, especially when combined with different functional blocks, filters (compensators or correction blocks), selectors, etc. The structure of PI controller fed super lift Luo converter is shown in Fig. 4.

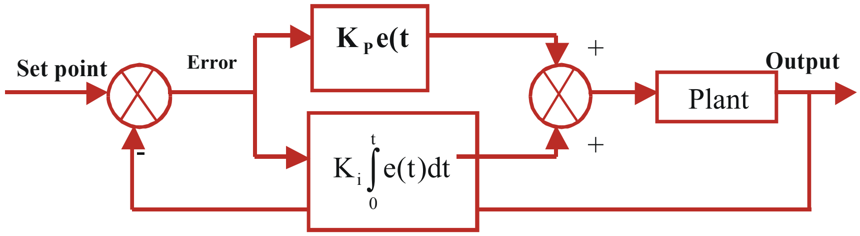


Fig. 3: Structure of PI controller

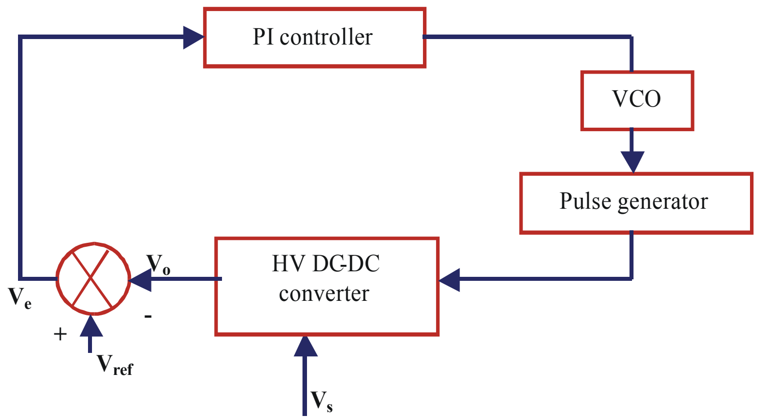


Fig. 4: Block diagram of PI control for HV DC-DC converter

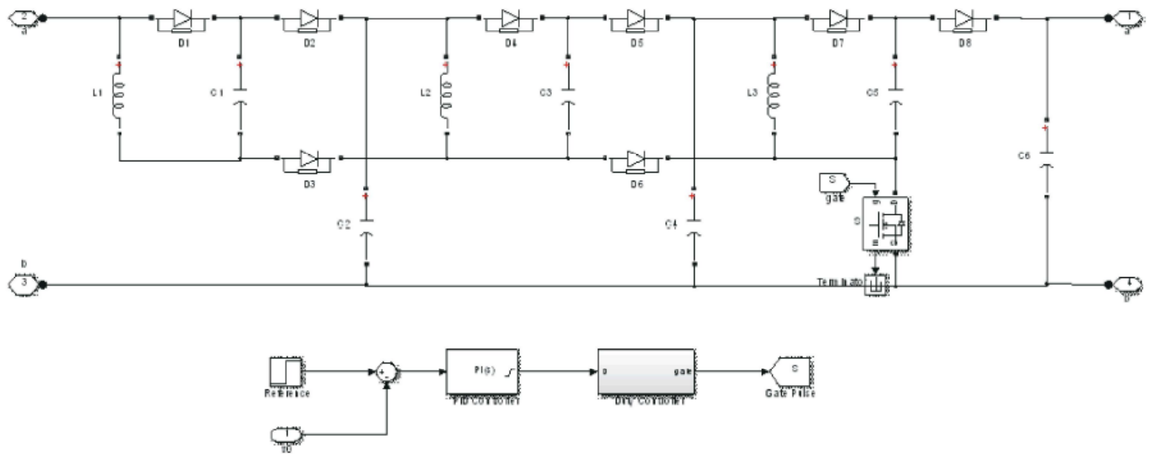
RESULTS AND DISCUSSION

The Simulink representation of PI controller implementation of HV generation involving positive output super-lift Luo converter in shown in Fig. 5. The figure displays the bridge rectifier, used to convert the AC voltage to DC voltage and fed to the DC-DC converter. Positive output super-lift Triple-lift Luo converter is used as a DC-DC converter, in this proposed system. This Luo converter does not consist any large capacitors and switches, the control and operation of this converter are easy because of its structure is very simple in nature. The duty of the Luo converter is varied; simultaneously the output voltage of the converter is also improved. PI controller varies the duty cycle. PI controller fixes the output voltage of the proposed Luo converter 100 KV is obtained for the corresponding duty.

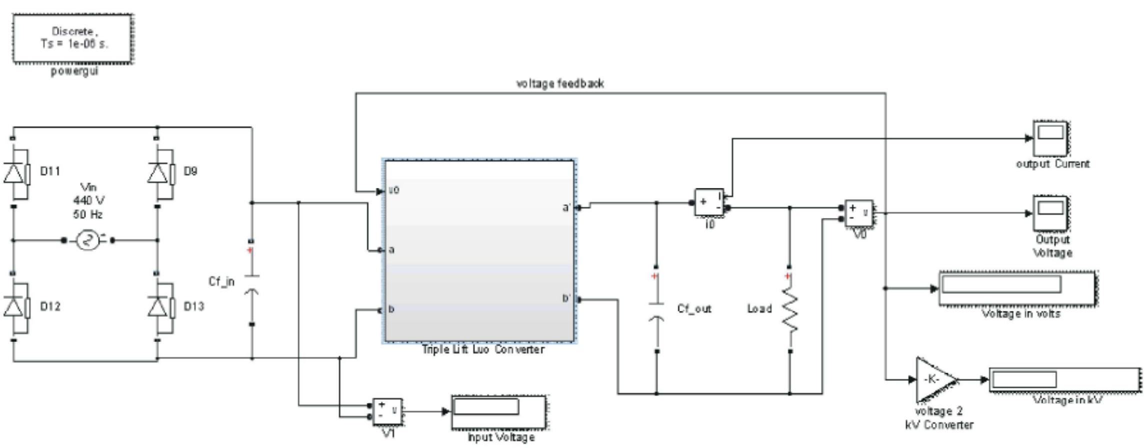
Our objective is to produce a high voltage without the use of a transformer for medical use X-ray power generation. Short circuit protection, coolant, installing space, weight and core loss is the main factors that affect the X-ray power generation system due to the presence of transformer. To eliminate the transformer, to compensate those additional burdens of the X-ray power generator a novel circuit has been implemented to produce high voltage generation.

Figs. 6-10 show the output voltage generated by the proposed Luo converter for the X-ray power generation. The proposed X-ray power generation system needs a 100 KV.

Fig. 6 shows the open loop output voltage produced by Luo converter for X-ray power generation. From the figure 6, it is observed that the open loop response of the converter output voltage is settled at 110kV. Fig. 7 shows the simulated start-up response of voltage and the current waveform. From figure 7, it is observed that the required output voltage of 100KV achieved and the required voltage is settled at 0.028 sec without any shoots. Fig. 8 shows the simulated servo response of voltage and current waveform of proposed HV power generation using super-lift triple-lift Luo converter. From the Figure 8, the response is observed that t=0-0.2 with V=100kV, incremented at t=0.2-0.4, V=120kV with settling time of 0.0195 sec; t=0.4-0.6, V=100kV and decremented at t=0.6-0.8, V=80kV with settling time of 0.0655 sec, t=0.8-1.0, V=100 kV. Fig. 9 shows the simulated regulatory response of voltage and the current waveform. From the Figure 9, the response is observed that t=0.2-0.4, V=+20kV increment with settling time of 0.0635 sec and t=0.6-0.8, V=-20kV decrement with settling time of 0.017 sec. Fig. 10 shows the simulated input transient response of voltage and current waveform (t=0-0.2, V=440V; t=0.2-0.4, V=540V;



(a)



(b)

Fig. 5: (a) Super-lift Luo converter Simulink structure (b) Simulink diagram of Luo converter based HV generation for X-ray using PI controller

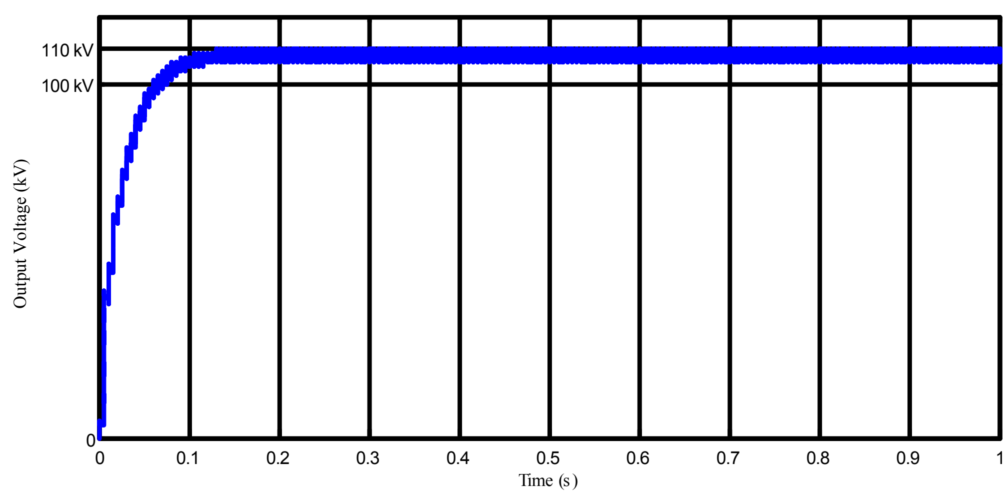


Fig. 6: Shows the open loop output voltage produced by Luo converter for X-ray power generation

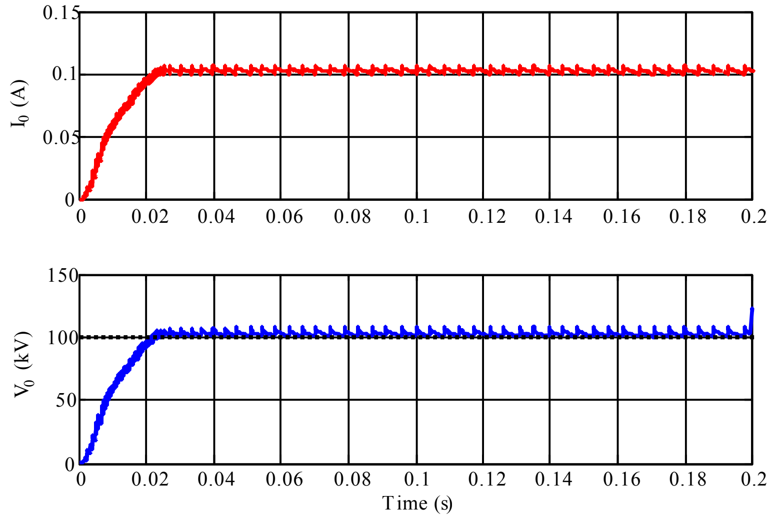


Fig. 7: Simulated start-up response of voltage and current waveform (set voltage =100 kV)

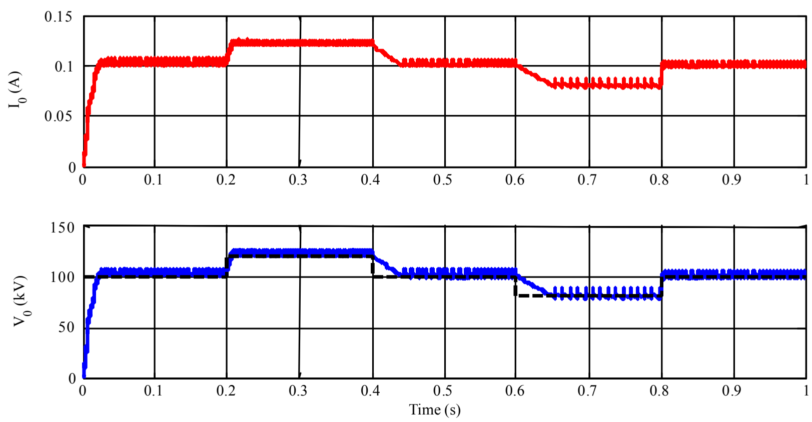


Fig. 8: Simulated servo response of voltage and current waveform (t=0-0.2, V=100kV; t=0.2-0.4, V=120kV; t=0.4-0.6, V=100kV; t=0.6-0.8, V=80kV; t=0.8-1.0, V=100 kV)

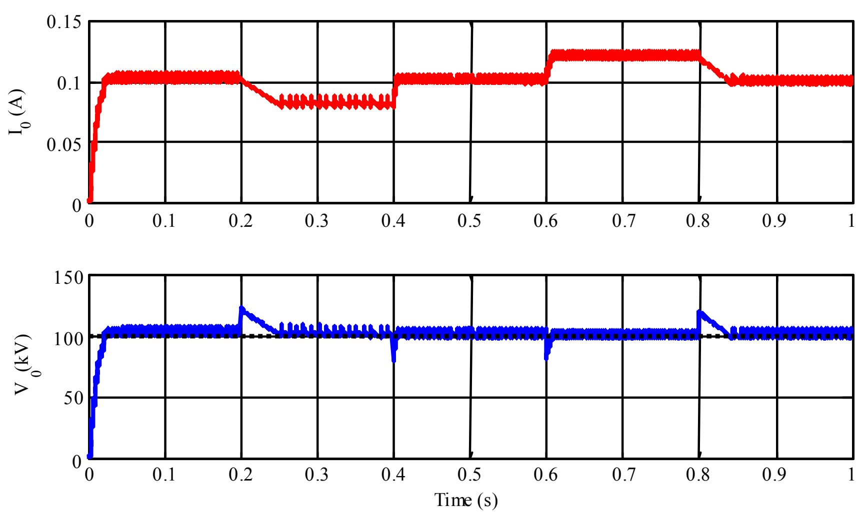


Fig. 9: Simulated regulatory response of voltage and current waveform (t=0.2-0.4, V=+20kV increment; t=0.6-0.8, V=-20kV decrement)

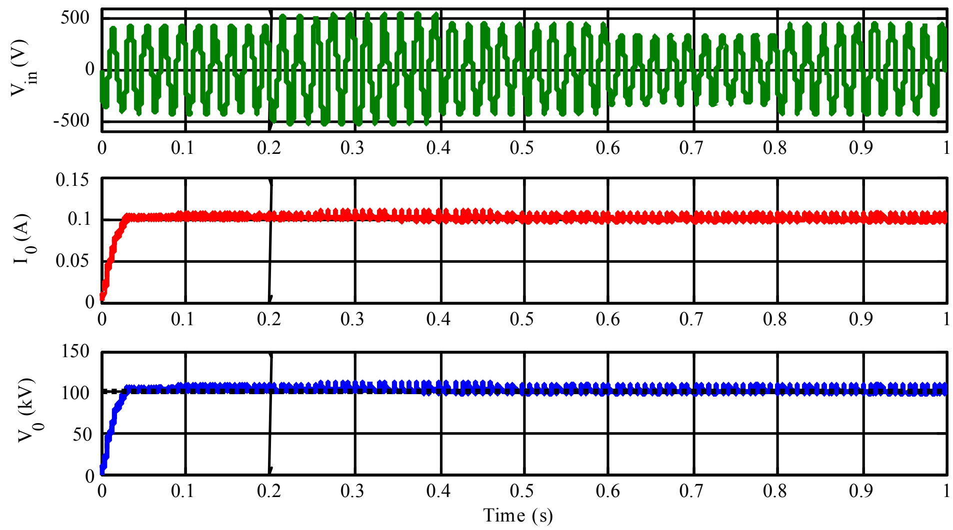


Fig. 10: Simulated input transient response of voltage and current waveform (t=0-0.2, V=440V; t=0.2-0.4, V=540V; t=0.4-0.6, V=440V; t=0.6-0.8, V=340V; t=0.8-1.0, V=440V)

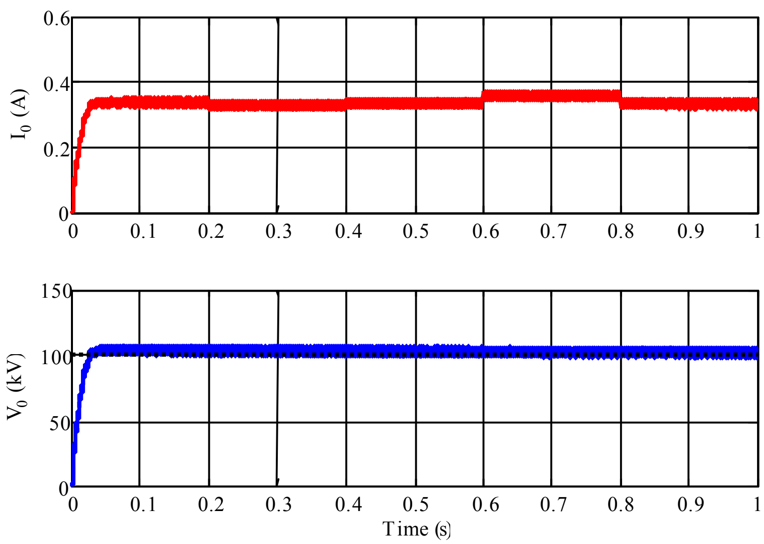


Fig. 11: Simulated load transient response of voltage and current waveform (t=0-0.2, R=1MΩ; t=0.2-0.4, R=1.5MΩ; t=0.4-0.6, R=1MΩ; t=0.6-0.8, R=0.5MΩ; t=0.8-1.0, R=1MΩ)

t=0.4-0.6, V=440V; t=0.6-0.8, V=340V; t=0.8-1.0, V=440V) and Fig. 11 shows the simulated load transient response of voltage and current waveform (t=0-0.2, R=1MΩ; t=0.2-0.4, R=1.5MΩ; t=0.4-0.6, R=1MΩ; t=0.6-0.8, R=0.5MΩ; t=0.8-1.0, R=1MΩ).

CONCLUSION

In this paper, the PI controller implemented positive output super-lift triple-lift Luo converter is presented for the medical use X-ray power generator from a practical viewpoint. It has been discussed how to take disadvantages of the harmful parasitic energy storage circuit elements of the high-voltage high-frequency transformer. The proposed DC-DC converter system is effective for the medical use X-ray power generator from a practical point of view According to the MATLAB/ Simulink simulation results. The open loop operation of the proposed converter is produced 110 kV output voltage, but the x-ray machine required 100kV, this required output voltage of 100kV is achieved by implementation of PI controller. The desired output X-ray tube voltage with a fast rise-time within 0.028sec and without any disturbances. The settling time of the converter response is very fast with the implementation of PI controller. The transformer is eliminated with the use of this proposed converter control.

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