High-Voltage Power Supply for X-Ray Computed Tomography and Time-Delay Compensation of Cockcroft-Walton Circuit

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Abstract. In recent years, an image diagnostic apparatus using X-ray is intensively investigated to reduce the radiation exposures amount. Above all, high-speed control of the high voltage generator to control the X-ray output is a very important issue. A Cockcroft-Walton circuit (CW circuit) is one of the method to generate the high voltage output. However, it has problem of the long time delay in the output response due to the huge capacitive component of the CW circuit. Therefore, it is required to achieve the stable output voltage with a quick transient response, which can be obtained by the time delay compensation technique of the CW circuit. This paper proposes an application of a Smith method to compensate for the time delay of the CW circuit output to reduce the undesirable excessive radiation exposure. AS a result of verification through the computer simulation, it has been confirmed that the overshoot of the output voltage can effectively be suppressed and that the optimal response can be realized without sacrificing the high-speed response. The paper indicates some possibilities of further improvement of the CW circuit output response by introducing the more precise compensation technique to the X-ray computed tomography.

1. Introduction

Declining birth-rate and aging population are advancing all over the world along with development if medical technology and economic development. In addition, number of the patients with diseases caused by aging and lifestyle is increasing.

Image diagnostic apparatus such as X-ray computed tomography (CT) and MRI can capture organ or like in the human body as image without giving trauma so that is indispensable of modern medical care, such as early detection and identification of various diseases. [1]

The X-ray CT system (Figure 1) is composed of scanning gantry for imaging, a bed on which the subject is cajoled, and console operated to perform imaging. Scanning gantry is composed of rotating part and fixed part. The fixed part has interface device with the console. The rotating part has the X-ray tube that generate X-ray, high voltage generator that suppling power to the X-ray tube, optical system for adjusting shape of X-ray and detector that detecting transmitted X-ray.

Figure 1. X-ray Computed Tomography

As the principle of image generation, while rotating the X-ray tube and the detector around the subject, the subject is irradiated with X-ray and transmitted through the subject is detected by the detector. A tomogram is generated by computer that reconstruct for the difference value of the X-ray transmitted through the object.
In recent year, following the Great East Japan Earthquake of 2011, people became interested in health effect of radiation exposure so image diagnostic apparatus using X-ray is required to reduce unnecessary exposure.

2. Principle of X-ray output

The block diagram of the X-ray high voltage device is shown in figure 2 and struct of the X-ray tube is shown in figure 3. Thermionic electrons are emitted by passing electric current from the filament heating circuit to filament in the X-ray tube. The X-ray tube is applied high voltage from High voltage power supply to accelerate thermionic electrons. The accelerated electrons cause to collide with anode target to generate X-ray.
The filament heating circuit controls the number of thermionic electrons (Tube current) and controls amount of X-ray emitted from the X-ray tube. The high voltage power supply gives kinetic energy to thermionic electrons by suppling high voltage to the X-ray tube on the order of kV (Tube voltage). The thermal electrons collide with the anode target and generate X-ray. When generate X-ray, kinetic energy converts into X-ray intensity and transmittance. [2]
Therefore, control of the tube voltage, the tube current, and the irradiation time is important to control X-ray. In addition, the computed tomography system requires good response of output, stability of the tube voltage, reduction of output ripple.

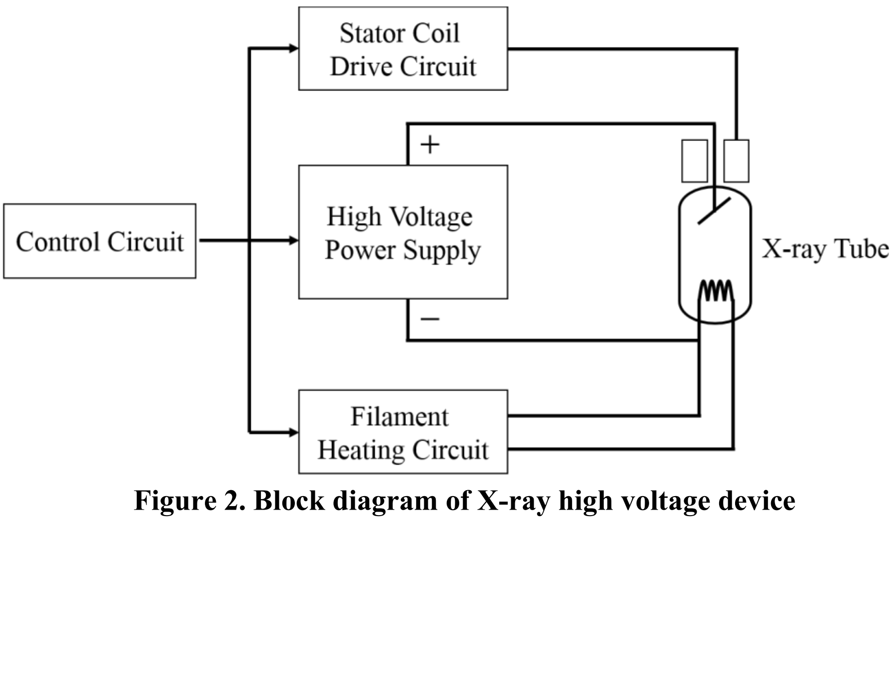


Figure 2. Block diagram of X-ray high voltage device

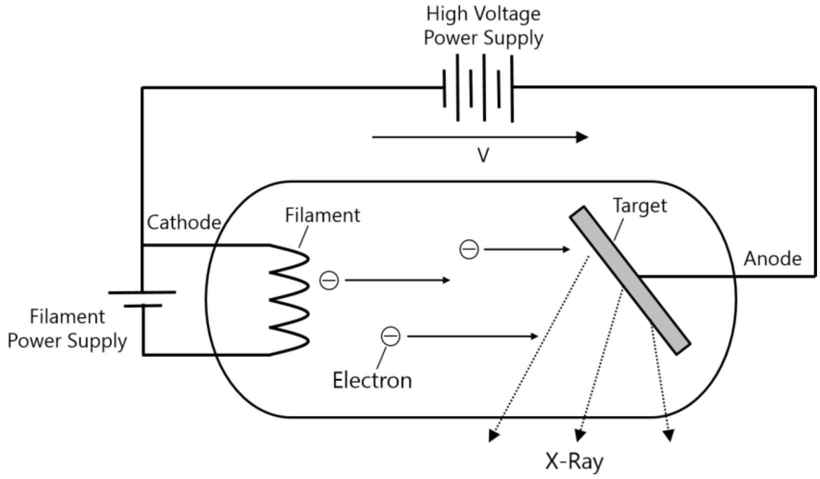


Figure 3. Struct of X-ray tube

3. High voltage power supply

3.1. Conventional circuit

The conventional high voltage circuit is shown in figure 4. The rectification unit uses diodes and two full bridge inverters using IGBT is connected in parallel to the DC bus capacitor. Inverter outputs are isolated and boosted by the transformer, and further boosted by the six-stage full-wave rectification type Cockcroft-Walton (CW circuit). [3] The actual CW circuit is configured by connecting multiple capacitors and diodes in series due to problem of breakdown voltage.

However, the input power factor is poor due to use of diodes in rectification unit. The CW circuit can easily boost high voltage if number of the circuit stages are increased, but number of the elements to be constructed increases and cost becomes higher. In addition, the conventional circuit has problem that transient response time of the output voltage become long by increasing number of the circuit stages. [4]

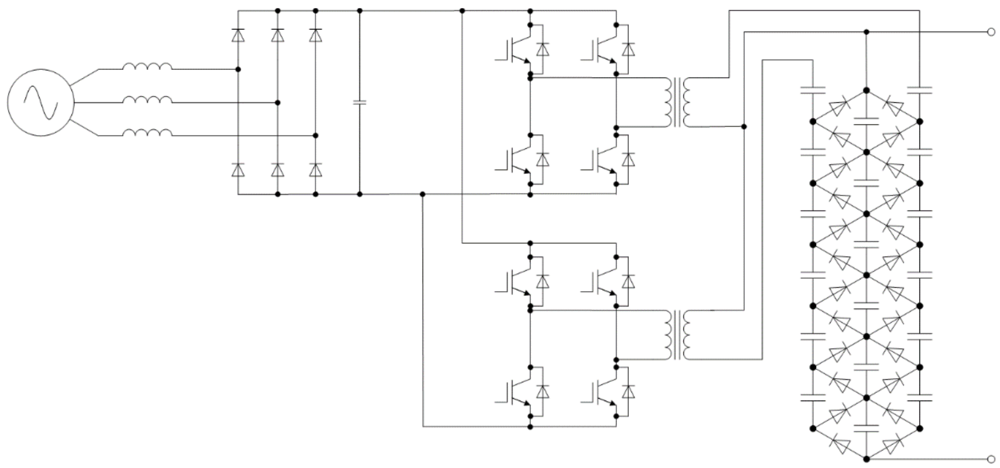


Figure 4. Conventional circuit

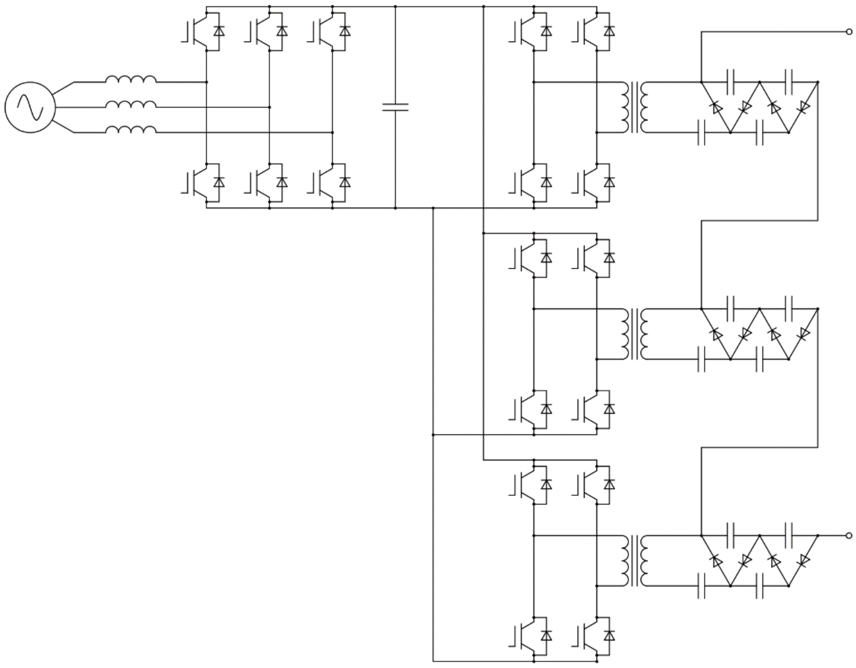


Figure 5. Proposed circuit

3.2. *Proposed circuit*

The proposed circuit is shown in figure 5. The input part is composed by PWM rectifier using switching device to control the DC bus voltage and the input power factor. The inverter part is composed three full bridge inverters are connected in parallel to the DC bus capacitor and reduce energy distribution of each inverter and the output voltage ripple are reduced by interleave operation that pseudo raise operating frequency. The high voltage part is composed by 2 stages of half wave rectification type CW circuits are connected in 3 series and that cause reducing number of the parts. This paper reports on improvement of transient response in CW circuit when Smith method is applied as delay time compensation.

4. Principle of Smith method

The Smith method is compensation method that is applied to systems with a large amount of control the dead time, and prevent excessive operations from occurring during the dead time by feedback correction of manipulated variable a fixed time before command value.

When the consider system as show in figure 6, liner function of the system is shown in equation (1). Here, *X*(s): Command value, *Y*(s): Output, *D*(s): Disturbance, G_c(s): Control function, *P*(s): Smith predictor, G_p(s): System function, *E*(s): Dead time.

$$\mathrm{Y(s)} = \frac{\mathrm{G_c(s)G_p(s)E(s)}}{\mathrm{1+G_c(s)\{G_p(s)E(s)-P(s)\}}}\mathrm{X(s)} + \frac{\mathrm{\{1-G_c(s)P(s)\}G_p(s)E(s)}}{\mathrm{1+G_c(s)\{G_p(s)E(s)-P(s)\}}}\mathrm{D(s)} \tag{1}$$

If the Smith compensator *P*(s) is substitute into equation (1) as equation (2), loop transfer function becomes equation (3).

$$\mathrm{P(s)} = \mathrm{G_p(s)\{E(s)-1\}} \tag{2}$$

$$\mathrm{Y(s)} = \frac{\mathrm{G_c(s)G_p(s)E(s)}}{\mathrm{1+G_c(s)G_p(s)}}\mathrm{X(s)} + \frac{\mathrm{[1-G_c(s)G_p(s)\{E(s)-1\}]G_p(s)E(s)}}{\mathrm{1+G_c(s)G_p(s)}}\mathrm{D(s)} \tag{3}$$

Equation (3) shows that the dead time can be eliminated from denominator of transfer function between input and output.

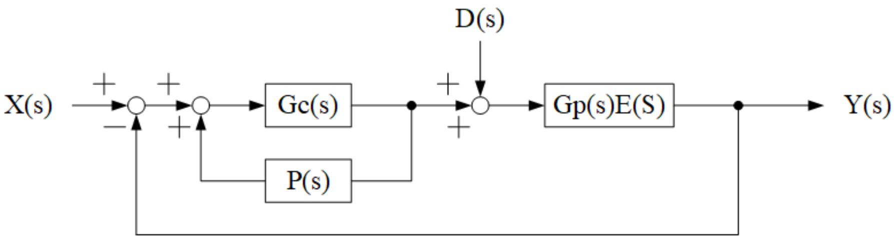


Figure 6. Smith Predictor Control Diagram

5. Dead time and compensation method in CW circuit

In operation of the CW circuit, capacitor is charged from lower stage to upper stage each time polarity of applied voltage is reversed. In case of circuit shown in figure 7, the output voltage is obtained by sum of potential differences of even stages capacitors. Therefore, the output voltage is determined by sum of charges supplied for number of stages of the CW circuit in operation cycle.

Formulate dead time E(s) in equation (4). Here, n: Half number of the CW circuit stages, L_p: Power supply operating cycle.

$$E(s) = \frac{1}{n}(e^{-L_p s} + e^{-2L_p s} + e^{-3L_p s} + \cdots + e^{-nL_p s}) \tag{4}$$

The inverter output voltage that proportional to manipulated variable, so it can be considered as unity gain. When considering the voltage amplification factor K, the system function will be $G_p(s) = K$ and as shown in equation (5).

$$G_p(s)E(s) = 2(e^{-L_p s} + e^{-2L_p s} + e^{-3L_p s} + \cdots + e^{-nL_p s}) \tag{5}$$

The Smith predictor P(s) is shown in equation (6) by substituting each value into equation (2).

$$P(s) = 2\left(e^{-L_p s} + e^{-2L_p s} + e^{-3L_p s} + \cdots + e^{-nL_p s}\right) - K \tag{6}$$

Figure 8 shows the block diagram of the control system in time domain.

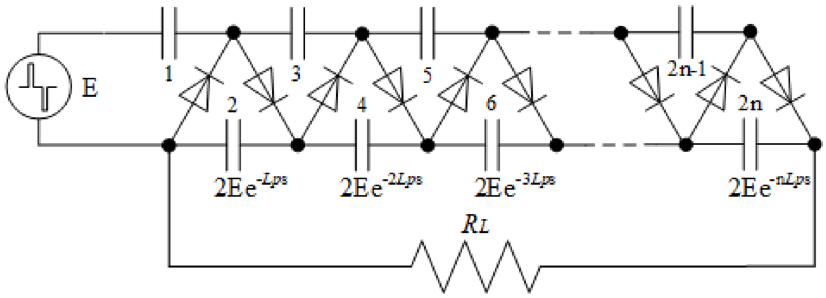


Figure 7. CW circuit output voltage delay

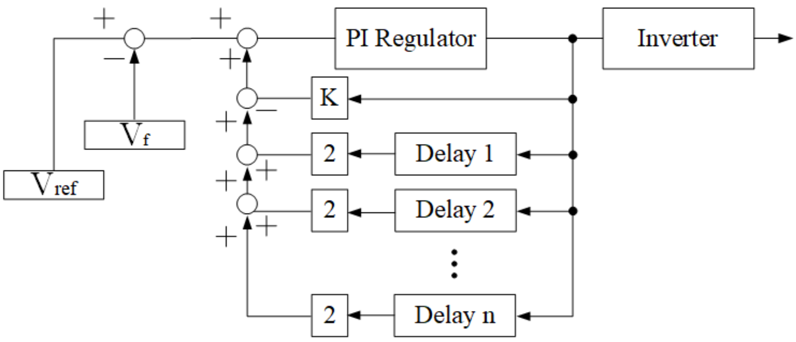


Figure 8. Control diagram with Smith predictor

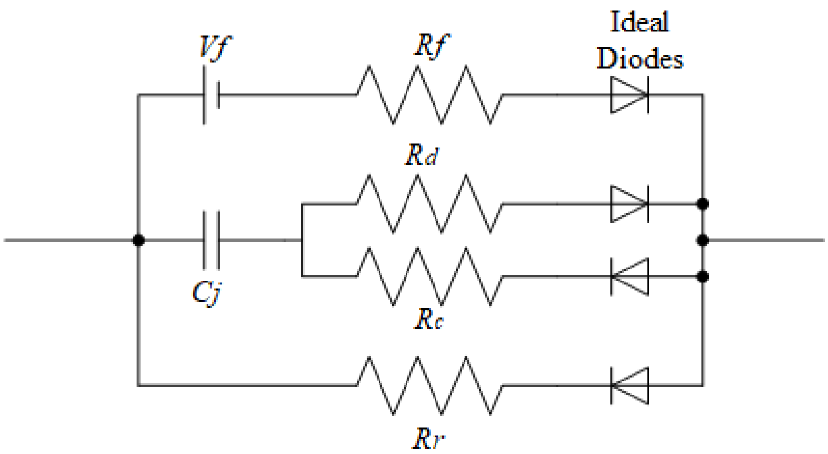


Figure 9. Diode simulation model

6. Simulation

6.1. Diode model

In case of the CW circuit is composed of ideal capacitor and ideal diode, it is difficult to simulate. Because charge and discharge time constant between capacitors become zero. [5] Therefore, in consideration of influence of junction capacitance of diode for output voltage of the CW circuit, the simulation was performed using model that incorporates junction capacitance in ideal diode.
The diode model used for simulation is shown in figure 9. Here, V_f: Forward voltage drop, R_f: Forward resistance, C_j: Junction capacitance, R_d: Discharge resistance, R_c: Charge resistance, R_r: Reverse resistance.

6.2. Simulation results

The simulation was performed on assumption that the 12-stage CW circuit is driven by full bridge inverter like figure 10 using simulation application PSIM. The simulation values are shown in table 1. The load resistance R_L was set that the output current was 600mA. Simulation results are shown in figure.11. (A) is result of applying the conventional Smith method in TD = 0.0008. (B) is result of applying the conventional Smith method in TD = 0.0014. (C) is result of applying the proposed Smith method in TD = 0.00005. TD indicates delay time.
Even if the proposed method is not applied, overshoot can be suppressed by increasing time delay, but the output voltage waveform is distorted because the change of command value becomes discontinuous. On the other hand, when the proposed method is applied, the response can be made close to the first order delay while suppressing overshoot of output voltage waveform. However, even if the proposed method is applied, overshoot remains in output voltage waveform, so it is difficult to realize perfect first-order response.

Table 1. Simulation parameters

Parameter		Value	Parameter		Value
Capacitor	Ccw1~12	100 nF	DC voltage	Vdc	360V
Turn ratio	Np:Ns	1:40	Proportional gain	Kp	0.2
Output voltage command value		120 kV	Integration time constants	Ti	0.0005

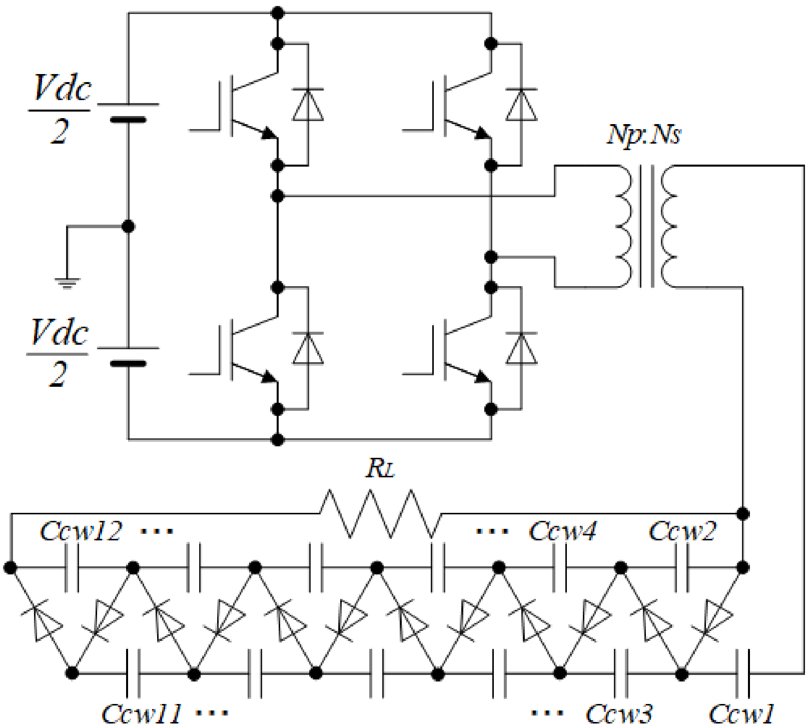
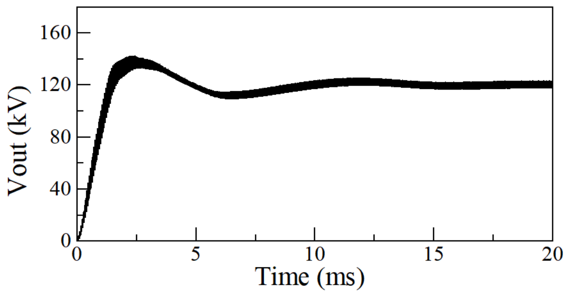
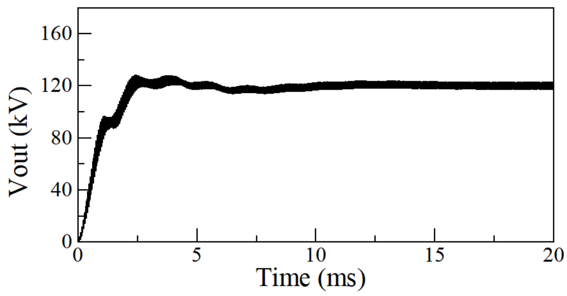


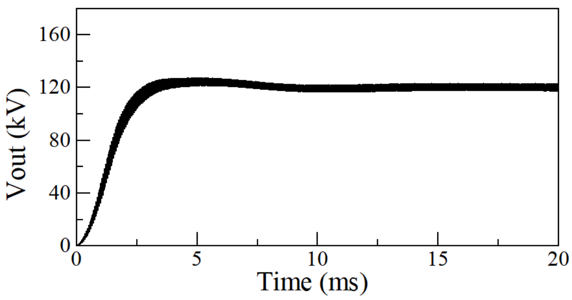
Figure 10. Simulation circuit



(A) Conventional Smith (TD=0.0008)



(B) Conventional Smith (TD=0.0014)



(C) Proposed 6-times Smith (TD=0.00005)

Figure 11. Output voltage waveform

7. Conclusions

In this study, proposed applying the Smith compensation method to the CW circuit and confirmed the effect by simulation. When the time delay element is one, the output voltage waveform is distorted by the output voltage command value changes discontinuously but overshoot of the output voltage waveform can be suppressed and output response can approach primary delay system by increasing time delay element according to number of the stages of CW circuit.

However, overshoot of the output voltage waveform remains with apply the proposed method and perfect primary delay response has not been achieved. In the future, consider more rigorous compensation using the proposed method and we aim to improve output response of output voltage further.

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