Initial Firing Angle Control of Parallel Multi-Pulse Thyristor Dual Converter for Urban Railway Power Substations

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Abstract – This paper presents an optimal initial firing angle control based on the energy consumption and regenerative energy of a parallel multi-pulse thyristor dual converter for urban railway power substations. To prevent short circuiting the thyristor dual converter, a hysteresis band for maintaining a zero-current discontinuous section (ZCDS) is essential during mode changes. During conversion from the ZCDS to forward or reverse mode, the DC trolley voltage can be stabilized by selecting the optimal initial firing angle without an overshoot and slow response. However, the optimal initial firing angle is different depending on the line impedance of each converter. Therefore, the control algorithm for tracking the optimal initial firing angle is proposed to eliminate the overshoot and slow response of DC trolley voltage. Simulations and experiments show that the proposed algorithm yields the fastest DC voltage control performance in the transient state by tracking the optimal firing angle.

Keywords: Thyristor dual converter, Initial firing angle, DC voltage control, Power substations

1. Introduction

Urban railway trains generate a large amount of energy when applying regenerative braking in subway stations. Regenerative energy is currently harvested in two ways in railway power substations: by using storage systems and by feeding energy back to the distribution grid.

Devices for storing regenerative energy can be classified into four categories [1]. First, a battery storage system (BESS) can be installed in parallel with the power substations [2]. This system can reduce the energy consumption by the braking resistor. However, the BESS has disadvantages such as the short battery lifetime, limitations on charge-discharge cycles, and lower efficiency. Second, a superconducting magnetic energy storage system (SMES) performs well in terms of the efficiency (which exceeds 95%), charge and discharge time, long lifetime, and lower maintenance cost [3]. Disadvantages of the SMES include limited production, the high cost of superconducting materials, and the ecological effects of the high-intensity magnetic field [1]. Third, the flywheel energy storage system has been studied [4, 5]. However, in urban railway power substations, this system cannot supply long-term energy storage because it is suitable for a short discharge time and high-power applications. Finally, an ultra-capacitor energy storage system differs from a BESS in that it has very high capacitance. However, it

has disadvantages such as voltage fluctuations, short service life, and low operation reliability for regenerative energy systems.

There are two types of regenerative energy systems for feeding energy back to the distribution grid. In the regenerative inverter system using an insulated-gate bipolar transistor (IGBT), the power factors can be controlled, and the system generates high-quality voltage waveforms. However, it cannot absorb the regenerative energy from several trains on high-traffic railways because IGBT inverters have low power density per volume. The thyristor dual converter has advantages in terms of fast response and high power density per volume compared with the IGBT inverter. Therefore, the thyristor dual converter is still used in many railway power substations.

Fig. 1. Urban railway power substations

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The converter's control scheme has three operating modes depending on the electric energy flow of trains. When a train departs a subway station, it accelerates to its maximum speed and then maintains a constant speed. During this time, the converter operates in forward mode to supply power to the train. When the train slows, the DC voltage at the trolley bus rises because of regenerative energy of regenerative braking. If the DC trolley voltage exceeds its upper limit, the converter operates in reverse mode to feed energy back to the distribution grid. However, a zero-current discontinuous section (ZCDS) is required to prevent short-circuiting of the parallel connected thyristor dual converter. During conversion from the ZCDS to forward/reverse mode, an overshoot and slow response of the DC trolley are generated because of an initial firing angle. To reduce the overshoot and slow response, the initial firing angle was experimentally selected by the fixed constant values [6]-[10]. However, the optimal firing angle varies with the percentage impedance of the traction transformers, AC filter impedance, DC filter impedance, and line impedance.

In this paper, the control algorithm for calculating the optimal initial firing angle is proposed to eliminate the overshoot and slow response of DC trolley voltage. The performance of the proposed control algorithm is verified through various simulations and experiments.

2. Voltage Control of Parallel Multi-Pulse Thyristor Dual Converter

2.1 Nomenclature

V_{dc}	DC trolley voltage, V
V_{ll}'	AC trolley line-to-line voltage, V
V_{ll}	AC trolley line-to-line input voltage, V
V_{ref}	Reference value of DC trolley voltage, V
I_{ref}	Reference value of DC trolley current, V
I_{dc}	DC trolley current, A
$I_{dc\Delta}$	DC trolley current of Δ converter, A
I_{dcY}	DC trolley current of Y converter, A
V_{max}, V_{min}	Upper and lower voltage limits, V
I_{max}, I_{min}	Upper and lower current limits, A
α	Firing angle, °
PI_{out}	Output value of PI controller, p.u.
P_o	Output Power, W.
K_{for}, K_{rev}	Initial PI_{out} of forward/reverse mode
t_0, t_1, t_2, t_3	Response points of V_{dc}
T_1, T_2, T_3	Response section of V_{dc}
K	Incremental PI_{out}
K_p, K_i, K_c	Gain of PI controller, p.u.

2.2 Configuration of thyristor dual converter

Fig. 1 shows the urban railway power substations located at the Hopo commuter subway in Korea. Fig. 2

Fig. 2. Block diagram of parallel multi-pulse dual thyristor converter

Fig. 3. Block diagram of voltage controller with differential current controller

shows a block diagram of a parallel multi-pulse thyristor dual converter.

The average DC voltage is a function of the firing angle α when the converter current is in the continuous section [11, 12]:

$$V_{dc} = \frac{2\sqrt{3}V_{ll}}{\pi} \cos \alpha \quad (1)$$

Where V_{ll} is the line-to-line input voltage. The firing angle for voltage control is obtained as follows:

$$\alpha = \cos^{-1} \left(\frac{\pi V_{dc}}{2\sqrt{3}V_{ll}} \right) = \cos^{-1} (PI_{out}) \quad (2)$$

Fig. 3 shows a block diagram of a voltage controller with a differential current controller. The differential current controller is used to prevent unbalanced current between the Δ and Y thyristor dual converters [7]. The voltage controller calculates the firing angle to ensure the stability of the DC voltage. However, the DC trolley voltage in railway power substations varies with the energy consumption and regenerative energy generated by trains. During mode changes, the response characteristic of the DC trolley voltage varies with the initial firing angle [10]. Therefore, the initial firing angle selection is very important.

Table 1. Relationship of points and sections

Points	Sections	Priority
t_0-t_1	T_1	2
t_1-t_2	T_2	3
t_2-t_3	T_3	1

Fig. 4. Flow chart of conventional control

(a)

(b)

Fig. 5. Response characteristics of V_{dc} according to constant values of initial PI_{out} : (a) Forward mode (b) Reverse mode

2.3 Conventional voltage control

Fig. 4 shows a flow chart of the conventional control

algorithm to control the DC trolley voltage in both forward and reverse modes. After V_{dc} and I_{dc} are measured, V_{dc} is compared with $V_{ref} - V_{min} \leq V_{dc} \leq V_{ref} + V_{max}$, and then I_{dc} is compared with $I_{dc} > I_{max}$, $I_{dc} < I_{min}$. Consequently, there are two possibilities for the operating mode. If $V_{dc} < V_{ref} - V_{min}$ and $I_{dc} > I_{max}$, the forward mode is used. If $V_{dc} > V_{ref} + V_{max}$ and $I_{dc} < I_{min}$, the reverse mode is used. Otherwise, the discontinuous mode is used to prevent short circuiting of the parallel connected dual thyristor converter. When the forward or reverse mode is started, constant values are applied to K_{for} and K_{rev} . These values are experimentally selected because they depend on the percentage impedance of the traction transformers, AC filter impedance, DC filter impedance, and line impedance. Fig. 5 shows response characteristics of V_{DC} according to constant values of initial PI_{out} during conversion from the ZCDS to the forward/reverse mode. In forward mode, when the initial PI_{out} value increases, the V_{DC} has slow response and a large

(a)

(b)

Fig. 6. Flow chart of proposed control algorithms: (a) Proposed voltage control algorithm (b) Optimal initial firing angle tracking algorithm

overshoot. In contrast, in reverse mode, PI_{out} value decreases, the V_{DC} has slow response and a large overshoot. As a result, the optimal initial firing angle may be determined to be between 0.1 and 0.5 in forward mode. In the case of reverse mode, the optimal initial firing angle is between 0.8 and 0.95.

2.4 Proposed voltage control

In the ZCDS, DC trolley voltage is ringing or lowering because thyristor of both converters turn off to prevent short-circuit. When the voltage is less than the V_{min} or exceeds V_{max} , the forward or reverse mode is started. After the mode is started, this paper proposes a control scheme for improving the response characteristics of DC trolley voltage using the optimal initial firing angle tracking algorithm.

Fig. 6 (a) shows a flow chart of the proposed control algorithm. It is the same as the conventional control algorithm until mode selection. K_{for} and K_{rev} are continuously adjusted to optimize the initial firing angle using the equations $K_{for}/K_{rev} += K*1000$, $K_{for}/K_{rev} -= K*1000$, $K_{for}/K_{rev} += K$, and $K_{for}/K_{rev} -= K$.

In Fig. 7, t_0 , t_1 , t_2 , and t_3 are the starting points of the forward/reverse modes, recovery point of V_{max} or V_{min} , recovery point of V_{ref} , and recovery point of V_{ref} after overshoot, respectively. The relationships among t_0 – t_3 and T_1 – T_3 are shown in Table 1. If count values of T_1 , T_2 and T_3 are all reduced, the V_{dc} response is improved. However, the priorities must be selected to improve the V_{dc} response because it is not possible to reduce all the count value of each interval. In the T_3 of forward/reverse mode, if the V_{dc} exceeds the V_{max} or is less than the V_{min} , the parallel multi-pulse dual converter becomes unstable because it can operate reverse/forward mode without ZCDS. Therefore, T_3 was selected as the first priority. T_1 was selected as the second priority to prevent a trip to the load system. Lastly, T_2 was selected as the third priority to compensate for the fast response. Finally, the values of T_{1max} , T_{2max} and T_{3max} were selected as 30, 100 and 10, respectively.

3. Simulation Results

Table 2 compares the actual model and scale model. The scale of the voltage and current is 1/20. The scale model

Table 2. Comparison of actual model and scale model

Items	Actual Model	Scale Model
P_o	4 MW	10 kW
V_{II}'	22,900 V	380 V
V_{II}	1750 V	87.5 V
V_{dc}	1600 V	80 V
V_{max}/V_{min}	1700 V/1500 V	85 V/75 V
I_{dc}	2500 A	125 A
I_{max}/I_{min}	100 A	5 A

can obtain the same response characteristics as the actual model. The load converter operates as a current source control to generate energy consumption and regenerative

Fig. 7. Point selection and count values according to response characteristics of DC trolley voltage in forward/reverse mode: (a) V_{dc} and starting points of t_0 – t_3 (Forward mode, $PI_{out} = 0.5$ p.u.) (b) Count values of T_1 , T_2 , T_3 (Forward mode, $PI_{out} = 0.5$ p.u.) (c) V_{dc} and starting points of t_0 – t_3 (Reverse mode, $PI_{out} = 0.8$ p.u.) (d) Count values of T_1 , T_2 , T_3 (Reverse mode, $PI_{out} = 0.8$ p.u.)

energy. The reference current is a triangular-wave current source. The frequency of the reference current is 1 Hz. The peak-to-peak current amplitude is 250 A.

Fig. 8. Equivalent circuits of differential DC filters: (a) Filter 1 (b) Filter 2

Fig. 9. Response characteristics of DC trolley voltage for filters 1 and 2 (Forward mode: $PI_{out} = 0.5$ p.u., reverse mode: $PI_{out} = 0.8$ p.u.)

Fig. 10. Response characteristics of I_{dc_A} and I_{dc_Y} using conventional control for filters 1 and 2. (Forward mode: $PI_{out} = 0.5$ p.u., reverse mode: $PI_{out} = 0.8$ p.u.) (a) Filter 1 (b) Filter 2

3.1 Comparison of characteristics for different filters

To verify the performance of the proposed algorithm, two types of DC filter are designed assuming differences in the line impedances such as the traction transformers, AC filter, DC filter, and trolley line impedance. The equivalent circuit and parameters of the DC filters are shown Fig. 8.

Fig. 9 shows the response characteristics of the DC trolley voltage for filters 1 and 2. Both filters are applied at the same constant PI_{out} values and PI gain values: forward mode ($PI_{out} = 0.5$ p.u.) and reverse mode ($PI_{out} = 0.8$ p.u.). The PI gain values were chosen as $k_p = 2.0$, $k_i = 0.023$, and $k_c = 0.75$; In forward mode, filter 1 has a larger overshoot than filter 2. In reverse mode, filter 1 has a larger overshoot and slow response than filter 2.

Fig. 10 and Fig. 11 show response characteristics of I_{dc_A} and I_{dc_Y} , and count values of T_1 , T_2 , and T_3 for filters 1 and 2. Due to the count values of T_3 are large both filters 1 and 2, mode change occurs in ZCDS, and then I_{dc_A} and I_{dc_Y} occur large overshoot. In addition, it was confirmed that the optimal initial firing angle is different depending on the line impedance of each converter because of the difference of count values for the filters 1 and 2, as shown Fig. 11. Therefore, the different optimal initial firing angles must be applied to each converter.

3.2 Proposed control algorithm for filters 1 and 2

The simulation is based on a 32-bit fixed-point digital

Fig. 11. Count values of T_1 , T_2 , T_3 using conventional control for filters 1 and 2 (Forward mode: $PI_{out} = 0.5$ p.u., reverse mode: $PI_{out} = 0.8$ p.u.): (a) Filter 1 (b) Filter 2

signal processing (TMS 320F28335). The sampling frequency for measuring V_{dc} and I_{dc} is 10 kHz. The PI control frequency is 10 kHz. The resolution of the PI controller is based on IQ15. Therefore, the minimum value of K can be expressed as

$$K = \frac{p.u}{Q15} = \frac{1}{2^{15}} = 0.00003051757813 \quad (3)$$

The minimum firing angle for the proposed control algorithm is obtained as

(a)

(b)

Fig. 12. Response characteristics comparison using proposed control for filters 1 and 2: (a) Filter 1 (b) Filter 2

$$\alpha = \cos^{-1}(K) = 0.001748528428^\circ \quad (4)$$

Fig. 12 shows the response characteristics comparison for filters 1 and 2 using the proposed control. When the proposed algorithm is started, it will tracking the optimal initial firing angle. Consequently, the count values of T_1 , T_2 and T_3 were all reduced.

Table 3 shows the initial firing angles selected using the proposed control algorithm. When the optimal firing angles has been tracking, Table 4 shows the count values of T_1 , T_2 and T_3 using the proposed control for filters 1 and 2. Compared with the count values of Fig. 11, each count value satisfy within the T_{1max} , T_{2max} and T_{3max} .

Fig. 13 shows the DC trolley voltage response comparison of two converters using the proposed control with different filters. Except for the difference in the amplitude of the DC trolley voltage caused by the frequency response of each filter, each converter has substantially the same response.

Fig. 14 shows the response characteristics of I_{dcA} and I_{dcY} using proposed control for filters 1 and 2. Compared with Fig. 10, the mode change does not occur in ZCDS and the large overshoot of the current does not appear.

Table 3. Simulation results of optimal initial firing angles selected using the proposed control algorithm for filters 1 and 2

Type	Forward mode		Reverse mode	
	PI_{out}	α	PI_{out}	α
Filter 1	0.3267	70.93°	0.9257	22.22°
Filter 2	0.3624	68.75°	0.9032	25.42°

Table 4. Simulation results of count values of T_1 , T_2 and T_3 using the proposed control algorithm for filters 1 and 2

Items	Filter 1	Filter 2
T_{1_REV}	16	18
T_{2_REV}	80	26
T_{3_REV}	9	3
T_{1_FOR}	21	21
T_{2_FOR}	45	48
T_{3_FOR}	9	6

Fig. 13. Voltage response comparison of two converters using the proposed control with different filters

Fig. 14. Response characteristics of $I_{dc_Δ}$ and I_{dc_Y} for filters 1 and 2 using proposed control. (a) Filter 1 (b) Filter 2

Fig. 15. Experimental setup

4. Experimental Results

The experimental setup is shown in Fig. 15. To verify the performance of the proposed algorithm, the converters 1 and 2 are connected filters 1 and 2 in parallel, respectively. To consider the operating conditions of trains, the load converter was used as the current source in the simulation, as shown Fig. 16 and Fig. 17.

Fig. 16 (a) and (b) show the conventional control response with filters 1 and 2. The conventional control was applied to the constant PI_{out} values in the simulation: forward mode ($PI_{out} = 0.8$ p.u.) and reverse mode ($PI_{out} =$

Table 5. Experimental results of optimal initial firing angles selected using the proposed control algorithm for filters 1 and 2

Type	Forward mode		Reverse mode	
	PI_{out}	α	PI_{out}	α
Filter 1	0.3288	70.80°	0.9312	21.38°
Filter 2	0.3712	68.21	0.9131	24.06°

Fig. 16. Experimental waveforms under conventional control: forward mode ($PI_{out}=0.5$ p.u.) and reverse mode ($PI_{out} = 0.8$ p.u.): (a) Conventional control with filter 1 (b) Conventional control with filter 2

0.5 p.u.). Both filter 1 and filter 2 exhibit the slow response and overshoots. In the case of the current, the mode change occurs in ZCDS, and then $I_{dc_Δ}$ and I_{dc_Y} occur large overshoot.

Table 5 shows the initial firing angles selected using the proposed control algorithm. When the optimal firing angles has been tracking, Table 6 shows the count values of T_1 , T_2 and T_3 using the proposed control for filters 1 and 2.

After the proposed control is applied, the voltage response is faster than that of the conventional control and

Table 6. Experimental results of count values of T_1 , T_2 and T_3 using the proposed control algorithm for filters 1 and 2

Items	Filter 1	Filter 2
T_1 REV	19	21
T_2 REV	95	28
T_3 REV	7	5
T_1 FOR	25	23
T_2 FOR	48	55
T_3 FOR	10	7

(a)

(b)

Fig. 17. Experimental waveforms under conventional control and proposed control (a) Conventional control with filter 1: forward mode ($PI_{out} = 0.3288$ p.u.) and reverse mode ($PI_{out} = 0.9312$ p.u.) (b) Conventional control with filter 2: forward mode ($PI_{out} = 0.3712$ p.u.) and reverse mode ($PI_{out} = 0.9131$ p.u.)

there are no indications of the large overshoot and slow response, as shown in Fig. 17. In addition, the mode change does not occur in ZCDS and the large overshoot of the current does not appear. The values are a little larger than that of the simulation one. However, these results are acceptable.

5. Conclusion

In a parallel multi-pulse thyristor dual converter for urban railway power substations, the stability of the DC trolley voltage varies according to the initial firing angle. In the conventional control algorithm, the initial firing angles are experimentally selected as the constant values. However, the optimal firing angle varies with various impedances. In this paper, optimal initial firing angle control was proposed for maintaining a stable DC trolley voltage. The slow response and overshoot of the DC trolley voltage are eliminated by optimal initial firing angle control in the parallel multi-pulse thyristor dual converter. The designed control algorithm was verified through simulations and experiments.

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