Seamless Star-Delta Winding Changeover Circuit for AC Generators

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***Abstract*— This paper proposes a circuit, which can change the winding connection of a generator from the star connection mode to the delta connection mode by changing the circuit operation. In the conventional method, the outage time exits during the dead-time of two magnet contactors. Therefore, the generator current cannot maintain its continuity. Moreover, the surge voltage occurs in the terminal of the generator. In order to achieve the seamless winding changeover, this paper proposes a new circuit, which consists of a PWM rectifier, a diode bridge rectifier and three additional switches. From the simulation results, the transition from the star connection mode to the delta connection mode, and the continuous generator current during the transition time are confirmed. In addition, it is confirmed that the current THD can reduce by supplying the reactive current with the generator of the delta connection mode. When the generator has percent reactance of 30%, the current THD is improved from 19% to 3%.**

Keywords-component; Permanent magnet synchronous generator (PMSG); Winding changeover ;Hybrid bridge rectifier circuit

I. INTRODUCTION

In recent years, the permanent magnet synchronous machines have attracted many attentions in the engine generator, the wind turbine system, or the micro-hydro power plants and more applications due to its high efficiency. In these applications, the permanent magnet machines are driven at wide speed range [1]. If the back electromotive force (EMF) is designed to be higher in order to achieve high efficiency at low speed range, it is necessary to apply field weakening control to the PWM rectifier at high speed range. It causes the increases of the copper loss because the d-axis current increases at high speed range. In contrast, if the back EMF is designed so that field weakening control is not required at high speed range, efficiency at low speed range becomes low. Therefore, it is difficult to achieve high efficiency at wide speed range.

Stator winding changeover methods have been proposed in order to solve this problem [2-5]. In past works, the star-delta winding changeover methods using magnetic contactors have been widely studied and used [6-7]. However, the dead-time between two magnetic contactors is necessary in order to prevent the short circuit of the generator during the transition. Moreover, dead-time causes the outage time and an instantaneous voltage drop of the DC output voltage. Therefore, a large capacity electrolytic capacitor is necessary. It is difficult to reduce the total volume because magnetic contactors are also large.

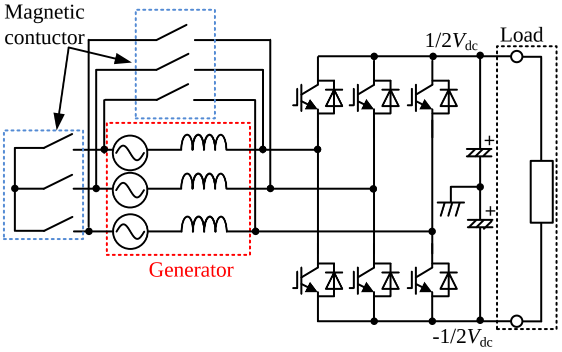
On the other hand, a seamless changeover method which changes the windings connection from the star connection to the delta connection by the mode transition without the outage time is presented [8-9]. However, this circuit consists of the two PWM rectifiers and two additional switches, which uses for mode transition, i.e. many of switching devices are required [10]. Therefore, the system becomes expensive.

This paper proposes a winding changeover circuit, which is specialized to the generator operation. The number of the switches in the proposed circuit is reduced by applying the open-winding half controlled converter topology [11-12]. This paper is organized as follows; first, the fundamental operation of the proposed circuit is described; second, the comparison between the proposed circuit and the conventional method which uses two magnetic contactors are conducted; finally, the increase of the generator current corresponding to the synchronous reactance is evaluated by the simulation.

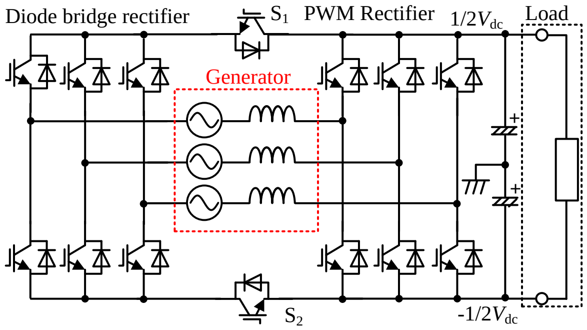
II. OPERATION MODE OF PROPOSE CIRCUIT

A. Conventional method

Fig. 1 shows the conventional star-delta changeover circuit. The method as shown in Fig. 1(a) changes the stator winding connection of the generator from the star connection to the delta connection using two magnetic contactors. This method has been widely studied and used due to its simplicity. However, in order to prevent the short circuit of the generator, the outage time is necessary during the mode transition. It causes an instantaneous voltage drop of the DC output voltage. On the other hand, a generator inductance can be used as boost inductor of the PWM rectifier. The star-delta winding changeover circuit by changing the operation mode as shown in Fig. 1(b) achieves a seamless transient. The seamless transient leads to the star-delta changeover which maintains the continuity of the generator current without the outage time. However, this circuit consists of many switches.



(a) Conventional method using two magnetic contactors.



(b) Conventional method by changing operation mode [8].

Fig.1 Conventional star-delta connection winding changeover circuits, which use generator reactance as boost inductor.

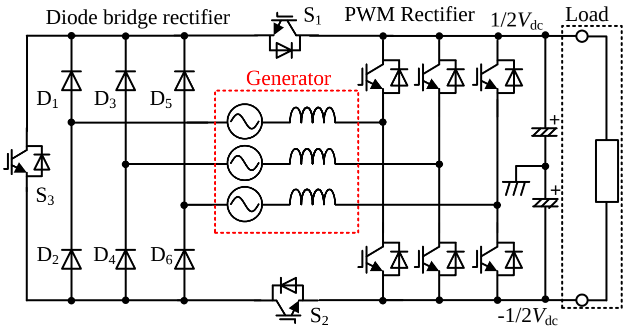
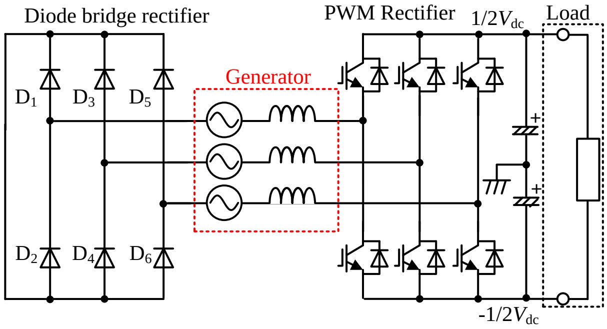


Fig.2. Proposed star-delta connection winding changeover circuit, which uses generator reactance as boost inductor.

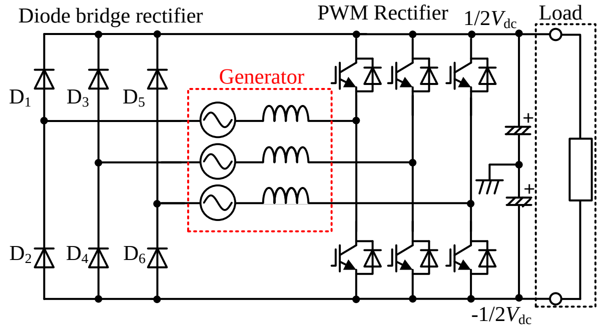
B. *Proposed circuit*

Fig.2 shows the proposed generator circuit which consists of a PWM rectifier, a diode bridge rectifier and three additional switches. The additional switches are used to change the operation mode. This circuit also achieves the seamless winding changeover. Furthermore, this circuit reduces the number of the switches compared to conventional circuit shown in Fig.1 (b). The operation of proposed circuit is described as bellow.

Fig. 3 (a) shows the equivalent circuit of the star connection mode. In the star connection mode, switch S$_3$ are turned on and creates a neutral point in conjunction with diode rectifier. The DC output voltage is obtained by the operation of the boost type PWM rectifier. Note that, switches S$_1$ and S$_2$ should be turned off to avoid the short circuit between the neutral point and the DC bus. The output voltage of the generator is the line-line voltage of the back EMF, when the star connection mode.



(a) Star-connection mode which generator has a neutral point.



(b) Delta-connection mode which consists of three hybrid bridge rectifier circuit.

Fig.3. Equivalent circuits of proposed circuit configuration.

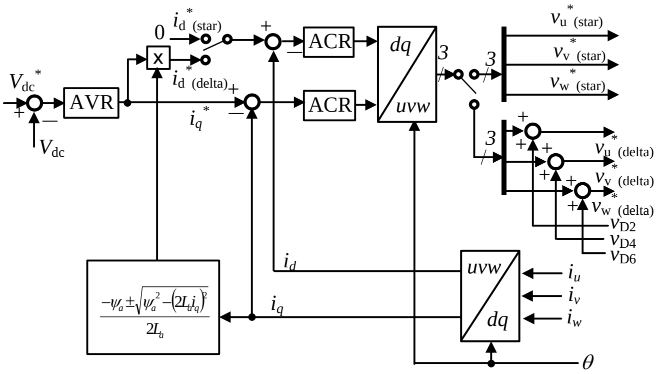


Fig.4. Control block diagram of proposed circuit.

Fig. 3 (b) shows the equivalent circuit of the delta connection mode. The DC bus of the diode bridge rectifier and the PWM rectifier are connected by turning on the switches S$_1$ and S$_2$. Note that, switch S$_3$ has to be turned off. In case of the delta connection mode, the circuit is equivalent to three single phase hybrid bridge rectifiers in parallel as shown in Fig.3 (b). Thus, output voltage of generator is the phase voltage of back EMF.

III. CONTROL METHOD OF PROPOSED CIRCUIT

Fig. 4 shows the control block diagram of the proposed circuit. A control system consists of the automatic current regulator (ACR) and automatic voltage regulator (AVR) based on a rotational d-q frame. The ACR and AVR are implemented to control the generator current and the DC output voltage, respectively. A field-oriented control assigns the magnet flux of the generator, i.e. back EMF is assigned into the q-axis. Therefore, the d-axis current means the reactive current and the q-axis current means the active current respectively. The AVR decides the q-axis current shown in Fig.4 In the star connection mode, i_d^* should be zero to increase the power factor. However, in the delta connection mode, the d-axis current command i_d^* should not be zero since the current of the generator have so much harmonic distortion that the circuit cannot drive. The d-axis current with generator is required.

Fig. 5 and 6 show the circuit configuration of the single phase hybrid bridge rectifier and the terminal voltages of the single phase hybrid bridge rectifier, respectively. If the back EMF is the sinusoidal waveform, a phase voltage of the diode rectifier v_d is the reversed rectangular waveform. Then, the phase voltage of the PWM rectifier v_u is the sum of the terminal voltage of the phase voltage of the diode rectifier v_d, the back EMF of the generator v_s, and the inductor voltage as shown in 5 and 6. It is understood that the phase voltage of the PWM rectifier is non-linear. However, the voltage command of the PWM rectifier v_u^* is the sinusoidal waveform. Although the voltage command of PWM rectifier has to be compensated by the phase voltage of the diode rectifier v_d as shown in Fig. 4.

Fig.7 shows the vector diagram of the general hybrid bridge rectifier circuit and the delta connection mode of the proposed circuit. The input current of the hybrid bridge rectifier circuit i_g is generally controlled to obtain unity power factor from the view point of the input voltage of the hybrid bridge rectifier circuit v_s. However, the input current i_g has to be controlled to obtain unity power factor from the view point of the terminal voltage of the generator v_g due to a large generator reactance. A phase difference exists between the terminal voltage of the generator and back EMF of the generator owing to the voltage drop of the synchronous reactance as shown in Fig. 7. The d-axis current i_d when the delta connection mode is have to fulfill $i_d/i_q=v_d/v_q$. Although, the d-axis current command i_d^* has to be provided as following [11].

$$i_d^* = \frac{-\psi_a \pm \sqrt{\psi_a^2 - \left(2L_a i_q\right)^2}}{2L_a} \tag{1}$$

where, Ψ_a is the flux linkage produced by permanent magnet. From (1) and q-axis current i_q, the generator current on the delta connection mode can be calculated. It is similar to d-axis current with field weakening control, the command i_d^* shown in (2).

$$i_d^* = \frac{-\psi_a \pm \sqrt{V_{OM}/\omega^2 - \left(L_a i_q\right)^2}}{L_a} \tag{2}$$

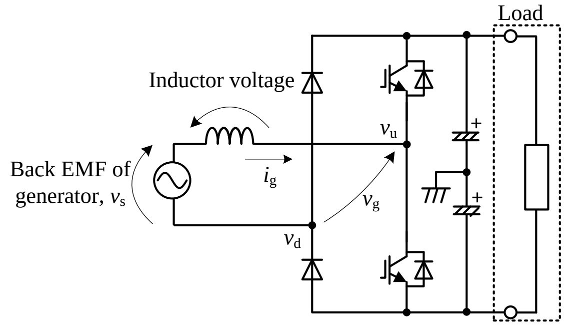
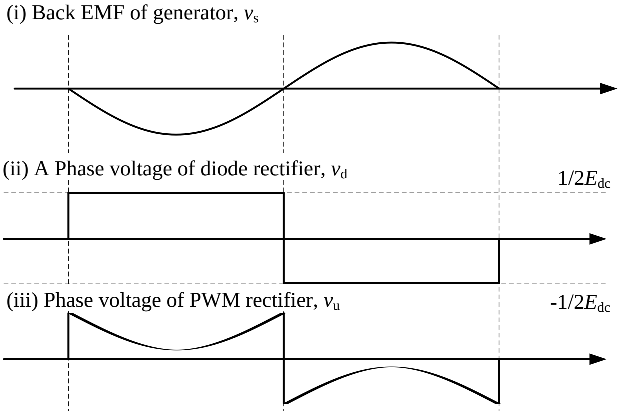


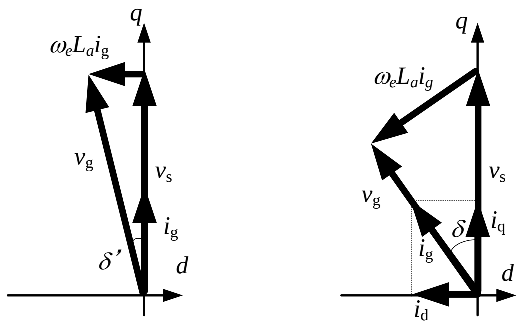
Fig. 5 Single phase hybrid bridge rectifier circuit


(i) Back EMF of generator, v_s

(ii) A Phase voltage of diode rectifier, v_d

(iii) Phase voltage of PWM rectifier, v_u

Fig. 6 Voltages of single phase hybrid bridge rectifier circuit.



(a) General hybrid bridge rectifier circuit

(b) Proposed circuit

Fig.7. Comparison of vector diagrams of hybrid bridge rectifier circuit.

where, ω and V_{OM} are electric angler frequency and the rated value of terminal voltage of the rectifier, respectively.

IV. COMPARISON RESULT OF PROPOSED SYTEM AND CONVENTIONAL SYTEM

A. *Simulation condition*

Table 1 shows the simulation parameters. The carrier frequency of the PWM rectifier is 15 kHz and the natural angular frequency of the ACR and AVR are set to 4000 rad/s, 400 rad/s respectively. The dead-time between the magnetic contactors is 2 milliseconds and the dead time between the additional switches of the delta connection mode (S_1, S_2) and the additional switch of the star connection mode (S_3) is 2 μs. It is considered that the cylindrical machine is applied with proposed circuit. A synchronous inductance is 1 mH (6.28% on the percent reactance). The comparison between the conventional circuit and the proposed one is described as bellow.

B. *Steady state characteristics*

Fig 8 and 9 show the simulation results of the conventional circuit and the proposed circuit respectively. The simulation results are divided into following sectors (i) is the star connection mode (ii) is the delta connection mode. The stator windings are changed from the star connection mode to the delta connection mode at 0.6 s. As results, the output voltage of the generator is changed from 173 V (line-line voltage) to 100 V (phase voltage) with the stator winding configuration as shown in Fig 8 and 9. Nevertheless the input voltage is changed, the output voltage remains 350 V i.e. it indicates that the output AVR works correctly. The operation of the winding changeover action is confirmed. In the proposed circuit, the line current is equals to the phase current in the both connection modes since the delta connection mode differs from general delta connection. Hence, in this paper the phase current is discussed in spite of the delta connection mode. The electric power and the amplitude of the generator current remain at constant in spite of the changing of the back EMF. Moreover, the generator current is controlled to achieve unity power factor from the view point of the back EMF on the conventional circuit. On the other hand, the generator current is controlled to achieve unity power factor in phase from the view point of the terminal voltage of the generator in the proposed circuit.

C. *Transient chractoristics*

In the conventional circuit, the outage time exits during the dead time of magnetic contactors. Therefore, the DC output voltage is dropped by 18 V (5%) as shown in Fig 7. At the end of the outage time, the generator current exceeds 12 A owing to the voltage drop. The outage time is caused by the disappearance of the current paths while the transient. Therefore, in order to reduce the influence of the voltage drop, a large capacity electrolytic capacitor is required. In contrast, the propose circuit can achieve seamless transient as shown in Fig. 8. During the transient state, the generator current is supplied by the freewheeling diodes of S_1 and S_2. However, the generator current increases the reactive current as shown in (2).

D. *Comparison results with field weakening control*

Fig. 10 shows the comparison results of d-axis current of the generator. With proposed circuit, the field weakening control is not required due to the terminal voltage becomes 0.577 times by mode transition. The d-axis current of proposed circuit, which uses to reduce the current THD is calculated by (1). On the other hand, with field weakening control, the terminal voltage becomes constant by supplying the negative the d-axis current calculated by (2). In the condition, q-axis current decrease with increasing of the rotational speed due to the output voltage of the circuit is set to constant value (350 V). At the field weakening region, the d-axis current of field weakening control increases against the increasing of the rotational speed. In contrast, with proposed circuit, d-axis current is decrease with the rotational speed. However, less

Table 1. Simulation parameters.

Inductance of generator, L_a	1 mH
Synchronous Reactance, $\%X_a$	6.28%
Back EMF of Generator, V_{ac}	100 V_{peak}
Frequency of Back EMF, f_{emf}	100 Hz
Carrier Frequency, f_{sw}	15 kHz
Output Voltage, V_{out}	350 V
Response angler frequency of ACR	4000 rad/sec
Response angler frequency of AVR	400 rad/sec

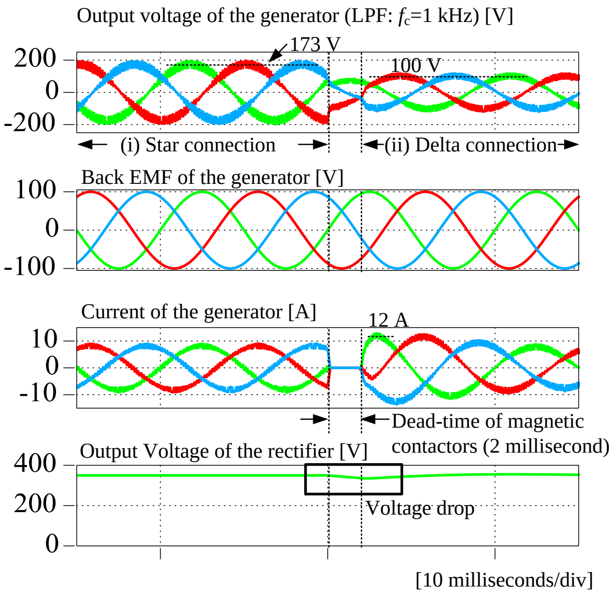


Fig.8. Simulation result of winding changeover using magnetic contactors.

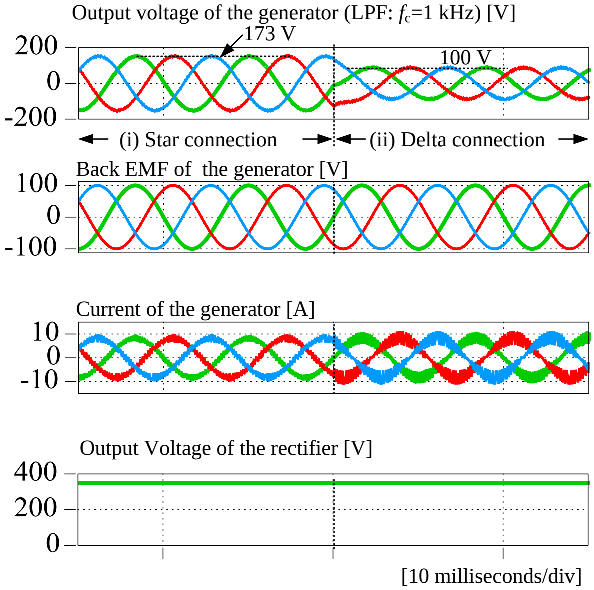


Fig.9. Simulation result of winding changeover using proposed circuit.

than field weakening region, d-axis current of proposed circuit exceeds which of field weakening control. Although with proposed circuit, the star connection mode is used, less than field weakening region. It can become $i_d = 0$. Above those, it is possible to reduce the d-axis current in whole operating region by winding changeover, except for around transition point. It shows that proposed circuit has an advantage in a view point of cupper loss of the generator at high speed range as shown in Fig. 10. The rated voltage is set to 160 V_{peak} per phase.

E. Effect of the synchronous reactance

Fig.11 shows the comparison results of Total Harmonic Distortion (THD) in the generator current. The generator current THD is compared when $i_d = 0$ and when supplying the reactive current. The generator, which has the percent reactance of the synchronous reactance $\%X_a$, is used. In this condition, $\%X_a$ was changed from 3% to 40%. The generator current THD is yielded on simulation and it contains 40th order harmonics of the electric frequency of 100 Hz. When $i_d = 0$, THD of the generator current increases in proportion to squared $\%X_a$ as shown in Fig. 11. Thus, when the generator has 30% of the percent reactance, THD of the generator current reach 19%. Owing to the increase in THD of the generator current, increase of generator loss, noise and torque ripple is unavoidable. It is possible to reduce THD of the generator current by supplying the reactive current to the generator. In the generator has 30% reactance, THD of the generator current are reduced from 19% to 3%.

Fig. 12 shows the comparison results about the RMS value of the generator current. The generator current RMS value is also compared when $i_d = 0$ and when supplying the reactive current with the high percent reactance $\%X_a$ characteristics. The RMS value of generator current is measured at two conditions; (i) rated torque, (ii) 50% torque. The torque is proportional with the value of the active current i_q. Note that, the rotational speed and the active power are also constant. Thus, when $i_d = 0$, the generator current is constant for $\%X_a$. In the generator has 30% of the reactance, the generator current on the delta connection mode increases 5% compared with that of the star connection mode as shown in Fig. 12. The simulation results are in good agreement with the calculated values in the low $\%X_a$ area. On the other hand, in the high $\%X_a$ area, the error becomes bigger. The error is caused by the increases of the distortion components.

V. EXPERIMENTAL RESULT

This chapter evaluates the fundamental operation of the proposed circuit when the star connection mode by experiment.

Fig. 13 shows the experimental result of the proposed circuit when the star connection mode. In this experiment, the grid voltage and inductors, which have a percent reactance of 8.97% (in case of rated frequency is 50 Hz) are used instead of the generator. Similarly, the DC output is connected to the power supply, which maintains an output voltage of 350 V. In this experiment, the ACR based on d-q flame is only implemented. The electrical angle θ, which is used for the d-q transformation is calculated by grid voltage. As shown in Fig. 13, the input current and the phase voltage of the PWM rectifier are sinusoidal. The proposed system achieves unity power factor. As a result, fundamental operation of the star connection mode is confirmed.

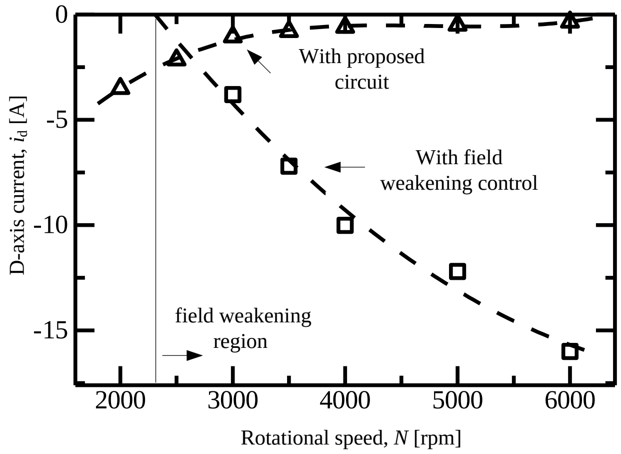


Fig.10. the comparison results of d-axis current of the generator with the proposed circuit and the field weakening control.

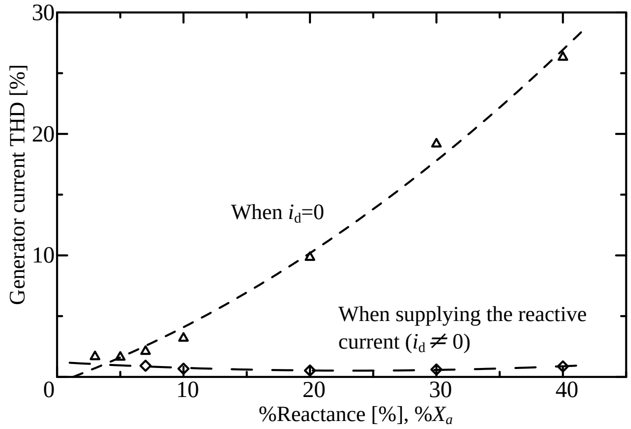


Fig.11. Generator current THD versus synchronous reactance of the generator changes from 3% to 40% of the percent reactance.

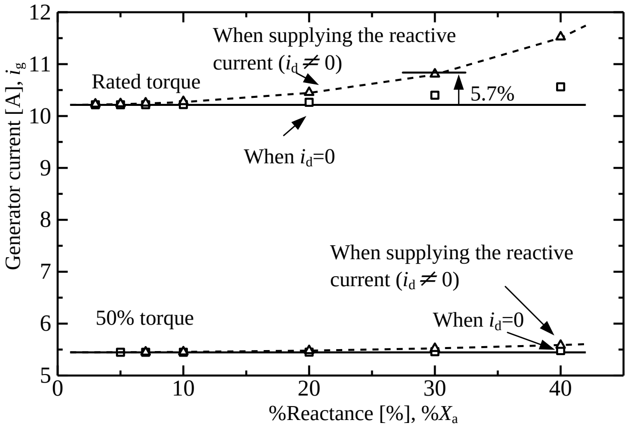


Fig.12. Comparison results of RMS value of generator current characteristics when the synchronous reactance of the generator changes from 3% to 40%.

VI. CONCLUSION

This paper presented a seamless winding changeover circuit from the star connection mode to the delta connection mode of generator stator windings. In this circuit, the output voltage of the generator changes in the case of each mode; (i) in the star connection mode, it becomes the output of which is defined as line-line voltage, (ii) in the delta connection mode, the output of which is defined as phase voltage. From the simulation results, the output voltage of the generator is changed from 173 V to 100 V with the stator windings configuration. Furthermore, the changeover with the seamless generator current is also confirmed. From the comparison with the field weakening control, it is possible to reduce the d-axis current by winding changeover nonetheless d-axis current required to reduce the current THD. The current THD is reduced from 19% to 3% by supplying the reactive current with the generator of delta connection mode when the generator with 30% of the percent reactance. In spite of the increase of the reactive current, the generator current increase to 5.7% in comparison with the star connection mode. In future works, (i) the study of the proposed circuit when it is applied to salient-pole generator, (ii) proposed circuit will be tested by experiments.

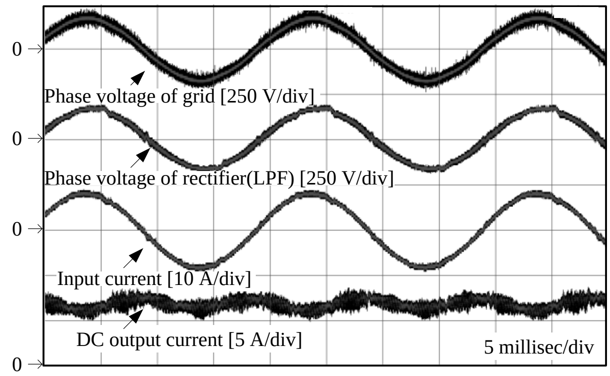


Fig.13. Experimental result of the proposed circuit when the star connection mode.

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