EVTeC 2023
6th International Electric Vehicle Technology Conference 2023
20231029

Development of the power control unit for the new hybrid system

- Action of the system loss minimization -

Yoshihiro Shamoto [1)] Hiroyuki Oyanagi [2)] Ryoji Sato [3)] Ryoji Hironaka[4)]

1) TOYOTA MOTOR CORPORATION., Toyota, Aichi, Japan
Email: yoshihiro_shamoto@mail.toyota.co.jp
2) TOYOTA MOTOR CORPORATION., Toyota, Aichi, Japan
Email: hiroyuki_oyanagi@mail.toyota.co.jp
3) TOYOTA MOTOR CORPORATION., Toyota, Aichi, Japan
E-mail: ryoji_sato@mail.toyota.co.jp
4) TOYOTA MOTOR CORPORATION., Toyota, Aichi, Japan
Email: ryoji_hironaka@mail.toyota.co.jp

ABSTRACT: Toyota Motor Corporation has developed a new hybrid electric vehicle (HEV) equipped with a new generation hybrid system. In 5th generation, we put efforts into power control unit (PCU) development which can realize reduced loss, downsized volume, and increased power. Moreover, as for control technique, we developed a new voltage pulse pattern in motor control which can improve fuel efficiency. In this paper, we will explain how to realize it and what the effect is.

KEY WORDS: EV and HV system, power control unit, electric power conversion, voltage pulse pattern in motor control

1. INTRODUCTION

The concerns about global warming and resource depletion are growing recently. Also, the movements to reduce CO2 emissions and to ensure energy security are becoming actively throughout the world. From this kind of circumstance, we are required to develop globally the vehicle with lower CO2 under tight regulation. In order to solve this issue, Toyota has developed and popularized hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), and fuel cell vehicles (FCV) with high fuel efficiency. Since the 1st HEV development in 1997, we contribute to expand electric vehicle worldwide by keeping on improving fuel efficiency and increasing the variety of vehicle type as time goes by. Moreover, we put efforts into power control unit (PCU) development which can realize reduced loss, downsized volume, and increased power.

We developed a new motor control technique for the 5th generation hybrid system. A new motor control makes it possible to control the motor stably without boosting system voltage in the area where previously the voltage has been boosted to protect parts. Therefore, a new motor control is able to improve the fuel efficiency.

In this paper, we introduce how to realize it for the 5th generation hybrid system.

2. Purpose of development

2.1. Issue on previous control method

THS II is the system which combined boost voltage control with rectangle control in order to raise the motor output power. (Fig.1)

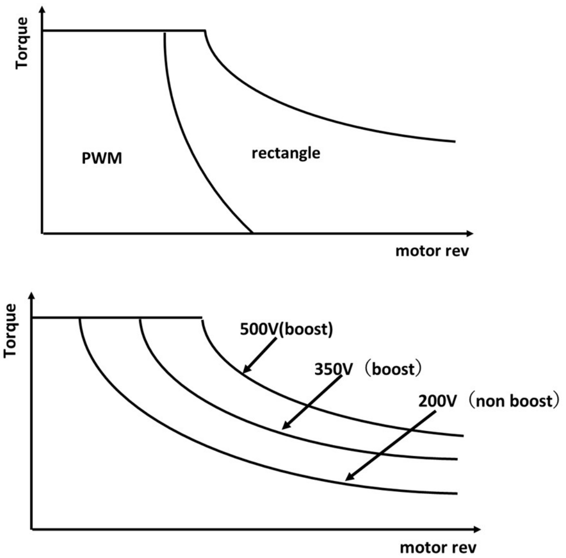


Fig1　Rectangular control and boost control

As for rectangular control, it emits the 6th harmonic electrical power oscillation (hereafter referred to as 6th harmonic oscillation) based on the frequency of motor current. On the other hand, as for

PWM control, the 6th harmonic oscillation is considerably less than rectangular control. (Fig. 2)

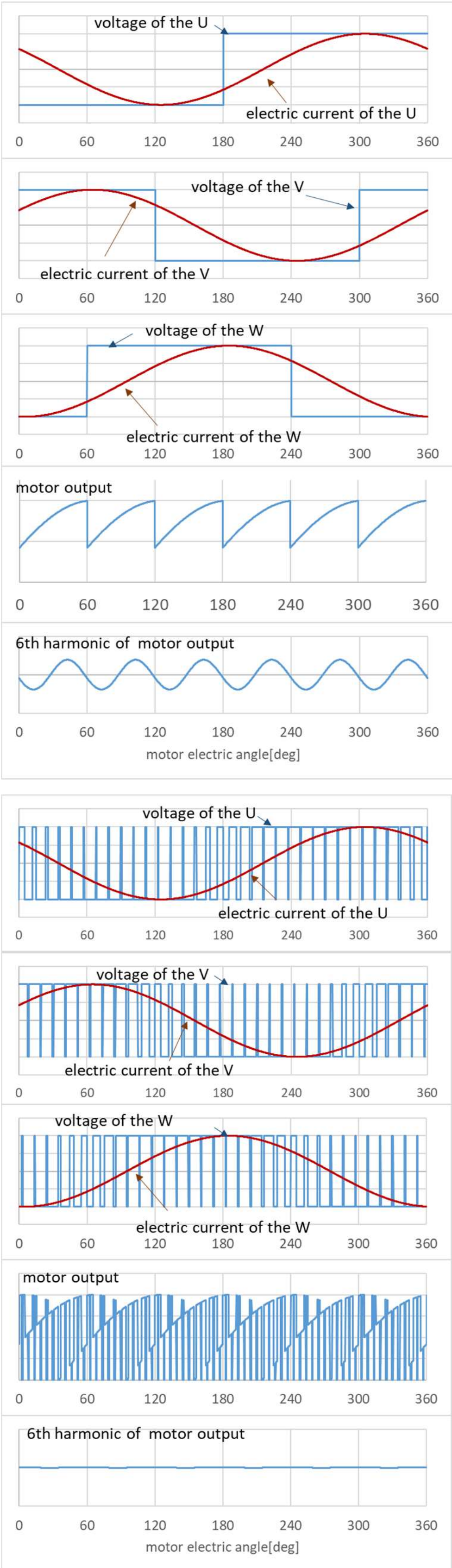
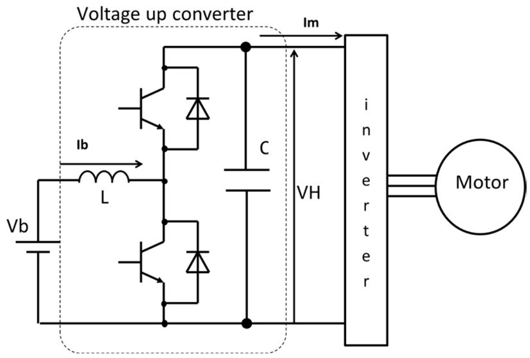


Fig2 Comparison of 6th harmonic oscillation regarding rectangular control and PWM control

Regarding boost voltage converter, as it is generally known, LC resonance occurs if the harmonic of electrical power oscillation come close to the LC resonance frequency when the boost converter is not activated. (Fig. 3)



$$Electric\ resonance\ frequency = \frac{1}{2\pi\sqrt{LC}}$$

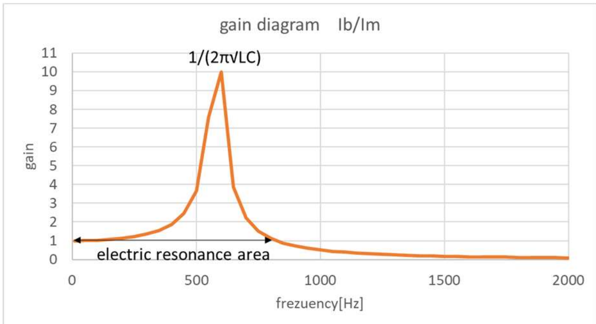


Fig3 LC resonance when not boosted

Accordingly, in case the boost converter is not activated when the motor is operated by rectangular control, LC resonance occurs if the 6th harmonic oscillation come close to the LC resonance frequency. If the LC resonance occurs, there are some issues like overvoltage and degradation because the voltage and current will significantly be fluctuated. Previously, in case the LC resonance is caused by rectangular control, motor control mode is switched from rectangular control to PWM control to avoid it because PWM control has less 6th harmonic oscillation than the one rectangular control has. (Fig. 4)

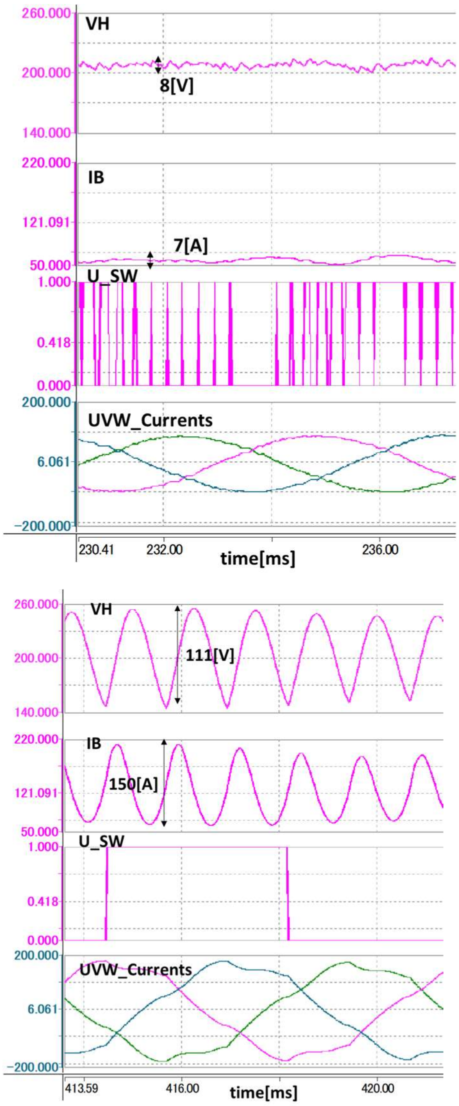


Fig4　LC resonance avoidance by PWM control

On the other hand, it is necessary to boost voltage in order to switch over to PWM control when the motor operating point is in the area of rectangular control. (Fig. 5)

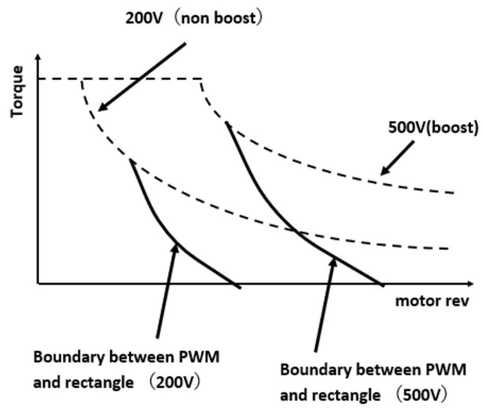


Fig5　Change of rectangular control boundary when not boosted or boosted

As mentioned above, the 6th harmonic depends on motor current frequency. Hence, it is needed to boost converter output voltage in order to avoid LC resonance if the motor operating point is in the range of LC resonance. (Fig. 6)

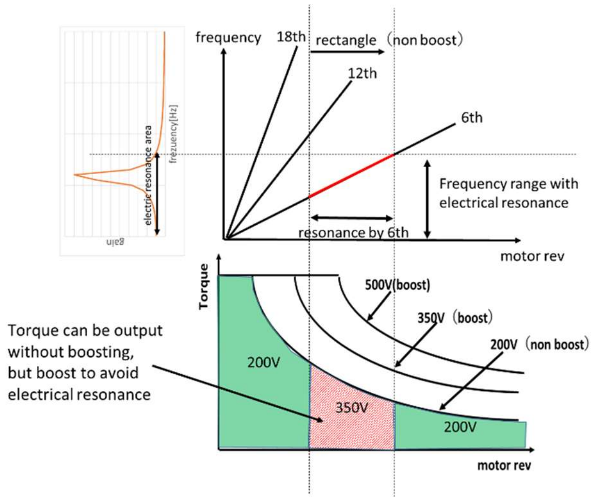


Fig6 LC resonance avoidance by boosting voltage

Regarding electrical losses, it is positive impact on electrical losses if the motor is operated by rectangular control without boosting voltage compared to PWM control with boosting voltage. (Fig. 7)

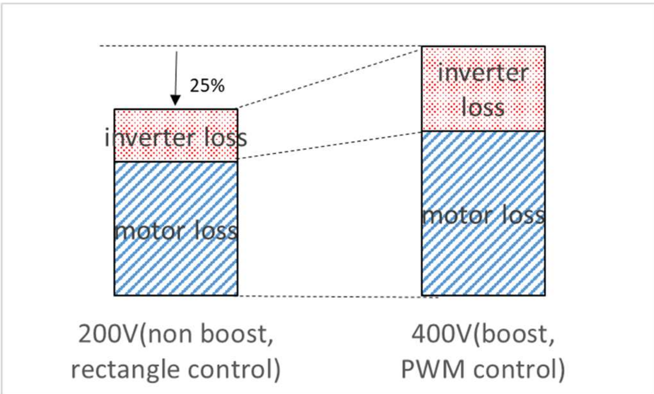


Fig7 Difference between boosting and not boosting in losses

In addition, concerned operating area is under 30kph vehicle speed which is commonly used when driving. Consequently, there is negative impact on fuel efficiency if the voltage has been unnecessarily boosted. Besides, the downsized and higher powered PCU is required recently to enhance vehicle marketability. Therefore, it is necessary to reduce the volume of reactor and capacitor.

Although, if the volume of reactor and capacitor is downsized, the LC resonance frequency spreads across a wide range compared to 4th generation. (Fig. 8)

Thus, it is needed to widen the boosting voltage area to avoid LC resonance. Additionally, concerned area is not only 6th harmonic but also 12th harmonic oscillation due to extensive LC resonance area on 5th generation. (Fig.9)

For this reason, the negative impact on fuel efficiency can no longer be ignored in recent times.

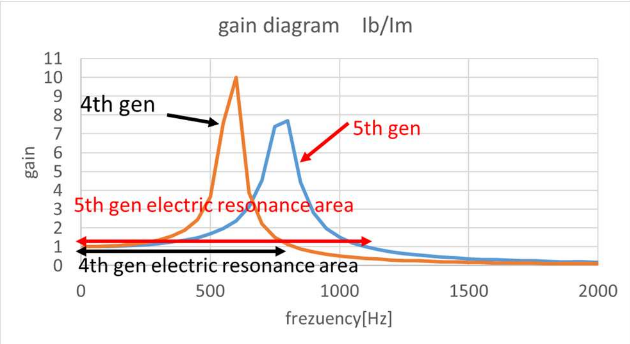


Fig8 LC resonance expansion to higher frequency caused by downsized reactor and capacitor

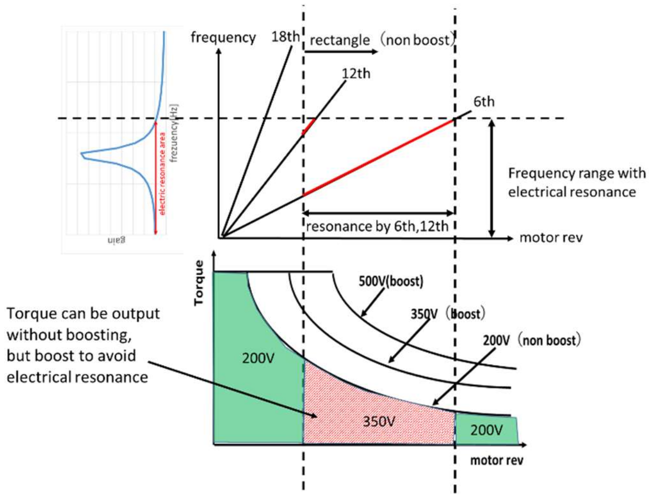


Fig9 Expansion of boost range with widened LC resonance area

In order to solve this issue, we developed new motor control method which can suppress 6th and 12th harmonic oscillation without boosting voltage.

Moreover, the motor controllability is the same level as previous rectangular control.

3. Technical overview

3.1 How to suppress 6th and 12th harmonic（SH-5 pulse）

This paper shows how to suppress 6th harmonic oscillation from rectangular control. Here, we focus attention on the 6th harmonic oscillation included in rectangular wave. At first, the pulse is added to centering on the peak point of 6th harmonic power oscillation wave. By adding this pulse, 6th harmonic oscillation is suppressed. The following contents describe it in detail.

① Calculate 6th hormonic of motor power when operated by rectangular control（Fig10）

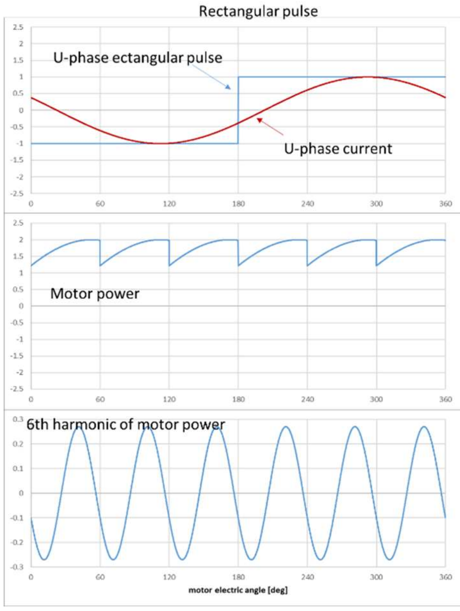


Fig10 The 6th harmonic of the rectangular pulse

② Put additional pulse to suppress 6th harmonic

Next, we put a pulse centering on the peak point of 6th harmonic. This pulse generates inverted 6th harmonic wave against 6th harmonic originally caused by rectangular control.

In order to adjust the amplitude of inverted wave to be the same as original 6th harmonic wave, the width of additional pulse has to be adjusted. (Fig. 11)

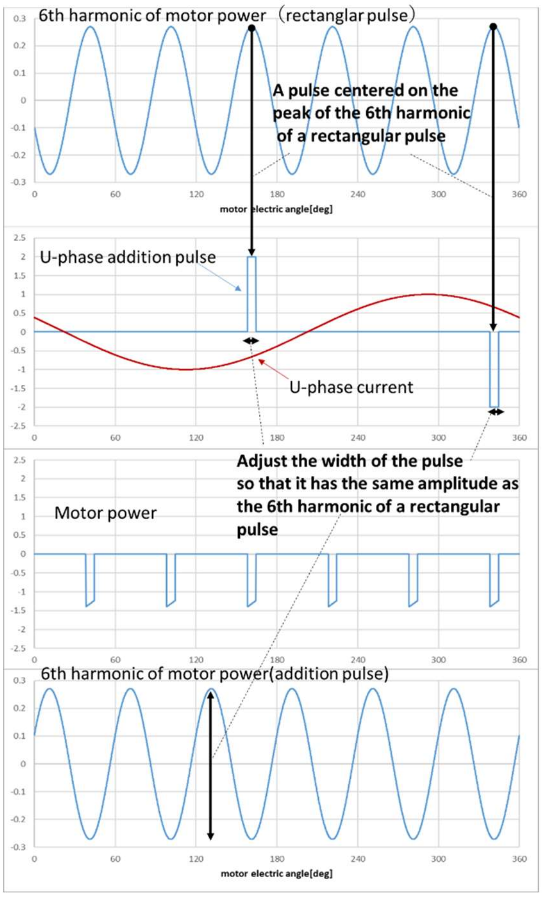


Fig11 How to make an additional pulse to suppress 6^{th} harmonic

③ Synthesize rectangular pulse and additional pulse（Fig12）

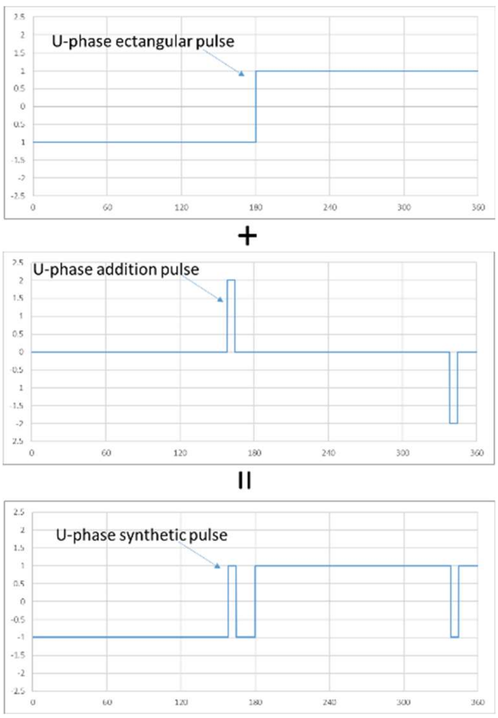


Fig12 How to make a synthesized pulse

By synthesizing these pulses, 6^{th} harmonic is deleted because these 6^{th} harmonics are canceled out each other. (Fig.13)

Then, the pulse that can cancel 6^{th} harmonic has been completed.

Hereafter referred to as SH-3pulse（suppresses Sixth Harmonic by 3pulse）.

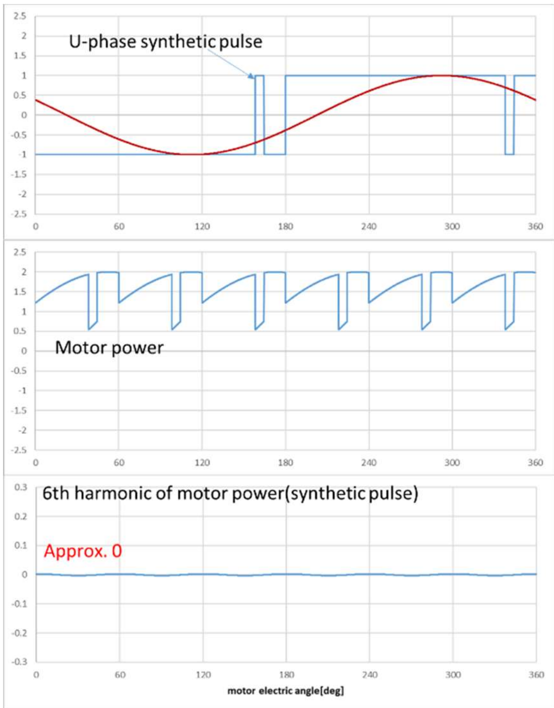


Fig13 6^{th} harmonic of a synthesized pulse(SH-3pulse)

Secondly, we describe how to suppress 6^{th} and 12^{th} harmonic oscillation continuing the additional pulse mentioned above.

The synthesized pulse mentioned before has 12^{th} harmonic. Similar to the case of 6^{th} harmonic elimination, we put a pulse near centering on the peak point of 12^{th} harmonic. (Fig. 14)

Finally, the new pulse pattern which can suppress 6th and 12th harmonic oscillation has been accomplished. (Fig15)

Hereafter referred to as SH-5pulse.（suppresses Sixth Harmonic by 5pulse）

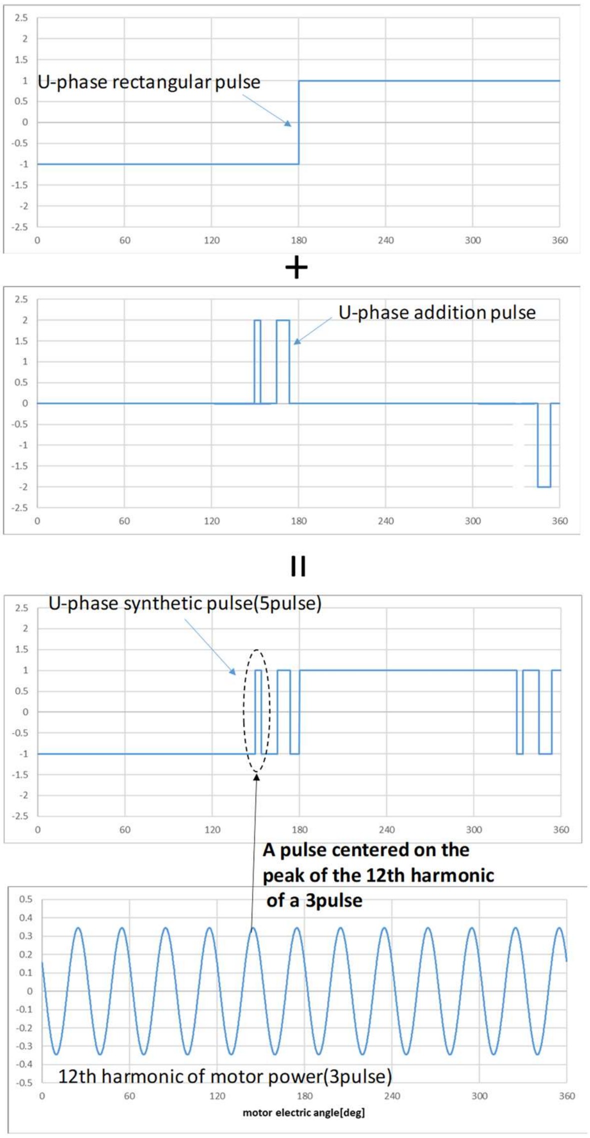


Fig14 How to make an SH-5pulse

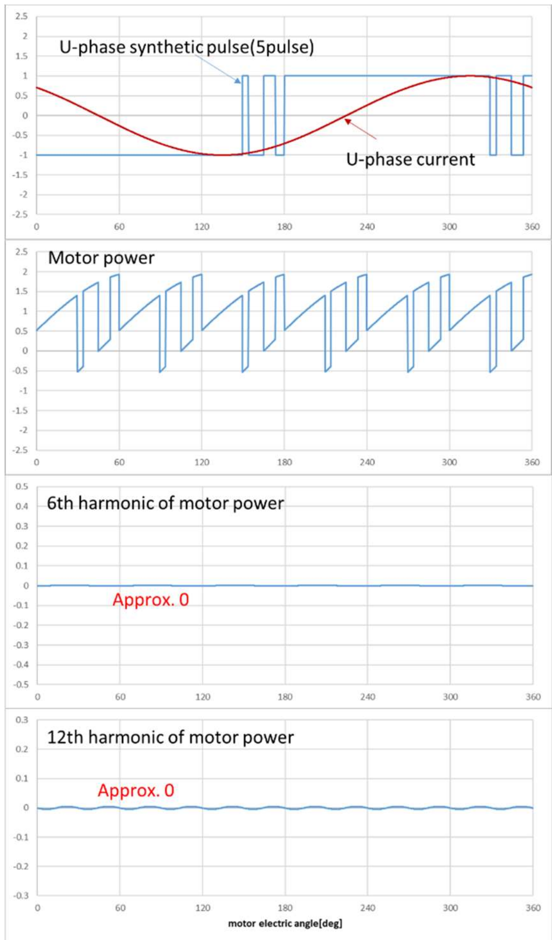


Fig15 6th and 12th harmonic suppression pulses (SH-5pulse)

By adopting SH-5 pulse, electrical system loss has been improved because there is no need to boost voltage in order to avoid LC resonance caused by 6th and 12th harmonic oscillation. (Fig.16,17)

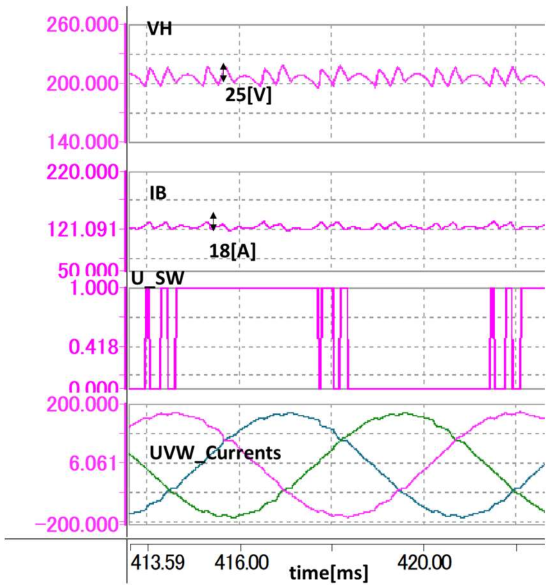


Fig16 Resonance avoidance by adopting SH-5pulse

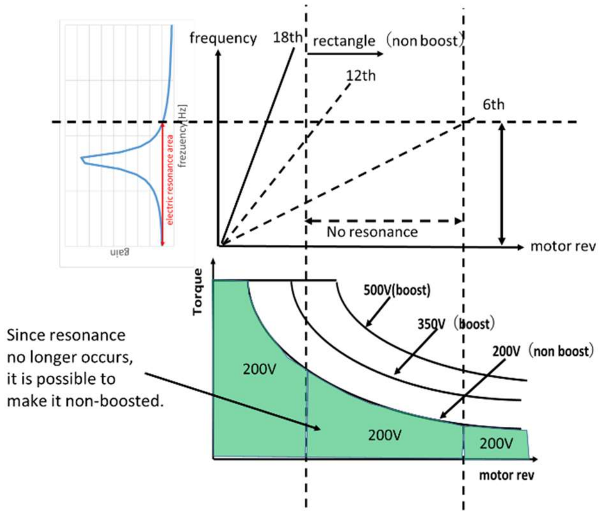


Fig17 Non boost area expansion by adopting SH-5pulse control

We have accomplished balancing downsized reactor and capacitor and electrical loss minimization. (Fig.18)

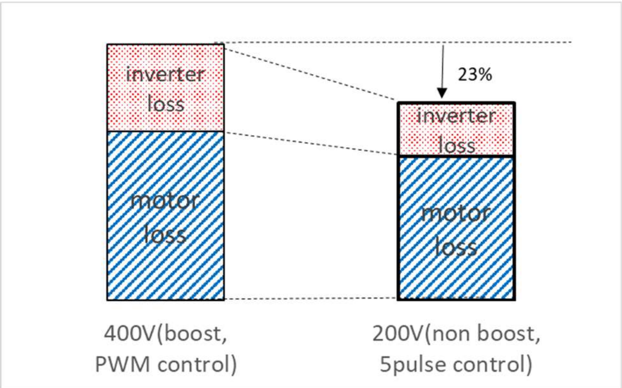


Fig18 Change in losses due to SH-5pulse implementation

3.2 Issue on applying SH-5pulse to HEV

3.2.1 Corresponding with transition of operating point

In usual situation when driving, the motor operating point changes moment by moment. For this reason, SH-5pulse have to keep the ability to suppress LC resonance when the motor operating point is constantly changing. As for SH-5pulse, we determined optimum pulse position by taking into consideration about 6th harmonic oscillation. However, the optimum pulse position changes continuously depending on the power factor of motor. Thus, it is needed to consider the effect of power factor transition when applying SH-5pulse to vehicle running. (Fig. 19, 20)

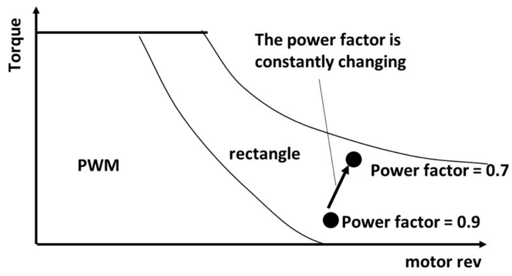


Fig19 Power factor transition by changing motor operating point

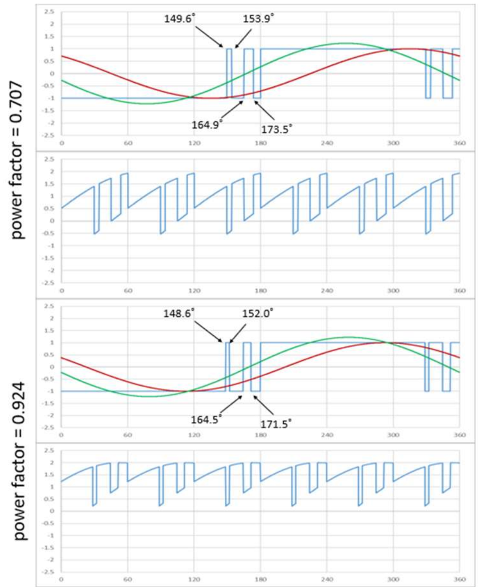


Fig20 Pulse shape change due to power factor

Hence, it is necessary to maintain the performance which can suppress LC resonance if the operating point is changed.

To handle this issue on SH-5pulse, the power factor is constantly calculated by the information of motor's voltage and current.

As a result, the optimum pulse position has been reflected by using the present power factor information. (Fig.21)

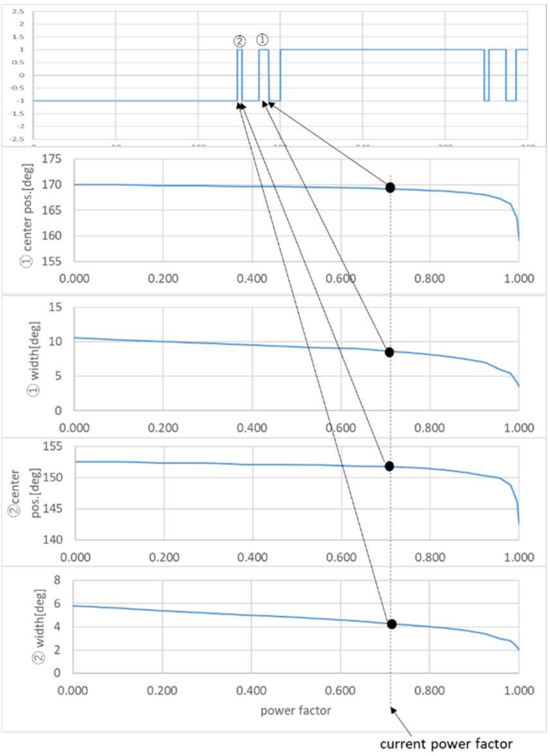


Fig21 Real-time calculation of pulse shape

The measures make it possible to use SH-5pulse as expected, not being influenced by the transition of power factor. Regarding 5th generation hybrid system, we have realized loss minimization and better performance in fuel efficiency than before by using SH-5pulse. (Fig. 22)

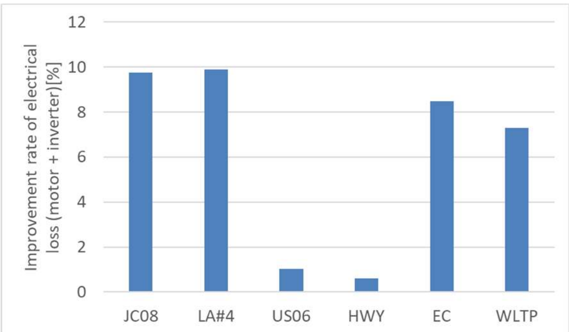


Fig. 22 Improvement rate of electrical loss by using SH-5pulse

4. CONCLUSION

We developed a new voltage pulse pattern in 5th generation hybrid system. It allows us to choose optimum converter voltage and to realize high efficiency in motor drive system. SH-5pulse motor control contributes to extend the running mileage of electrical vehicle.

ACKNOWLEDGMENT

I thank Hironaka, Sato, Oyanagi, Yasuda who had instruction heartily on making this article. In addition, I thank all of Motor Drive System Development Dept. where I get much knowledge and suggestions through an everyday discussion and made up for deeply.

REFERENCES

(1) Yuji Aono "Development of Power Control Unit for a newly developed Hybrid Electric System", JSAE Congress (Autumn).