A Novel Calculation Method on the Current Information of Vector Inverter for Interior Permanent Magnet Synchronous Motor for Electric Vehicle

Ki-Chan Kim
Dept. of Electrical Engineering, Hanbat National University
Daejeon, 305-716, SOUTH KOREA
kckim@hanbat.ac.kr

***Abstract*— In the paper, a novel calculation method on the d-axis and q-axis currents of a vector inverter for an interior permanent magnet synchronous motor is proposed by using finite element method. For a vehicle application, the current information should be calculated effectively within the driving range while satisfying limitation value of battery voltage. Moreover, the parameters related to current and voltage information have nonlinear characteristics because of high power density of traction motor. Finite element method is used in order to calculate exact solution. The proposed method only uses load angle curves of traction motor according to specified current values and can search the driving currents information effectively including field weakening region as well as constant torque region of the vector inverter.**

***Index Terms*— interior permanent magnet synchronous motor, current information for vector inverter, electric vehicle, field weakening control.**

I. Introduction

Traction motors for fuel cell and battery electric vehicles should be designed and controlled with high power density within entire driving range as well as with high torque density at low speed range. For these reasons, traction motors such as an interior permanent magnet synchronous motor (IPMSM) are usually designed to have saliency in their rotor in order to maximize output torque, including reluctance torque and magnetic torque [1], [2]. They are also controlled using maximum torque per ampere (MTPA) control method by a vector inverter at low speed range. For a high output power throughout the entire speed range, traction motors should be controlled with an inverter with the use of field weakening control method after the base speed at which the input voltage is limited by battery voltage [3].

In a vector inverter for synchronous motor, the sinusoidal currents at each three phase windings should be controlled in order for torque control which is necessary for electric vehicle operation. However, the voltages which are inputted to a vector inverter for the appropriate currents should be below the battery or fuel cell voltage range within entire driving range. However, it is difficult to calculate the exact current information of a vector inverter such as current amplitude and current angle because of nonlinear design parameters due to magnetic saturation in a core [4][5]. Especially, the magnetic saturation effect is very critical to motor performance when the motor is operated with field weakening control.

In the paper, the effective calculating method on the current information is proposed by analyzing load angle curves according to specified current values using finite element method (FEM) which can consider the magnetic nonlinearity of IPMSM. The voltages which make calculated current information within an operation range should be below battery or fuel cell voltage range.

II. Calculation Methods for Current Information

In general, the IPMSM for electric vehicles is controlled with maximum power control mode, which can be separated into maximum torque per ampere (MTPA) mode at constant torque region and field weakening control mode at constant power region, as shown in Fig. 1. The parameters such as voltage, current, torque and linkage flux at each region differ from each other. Therefore, the calculation method on current information (current amplitude and current angle) for vector inverter is also proposed in separate regions.

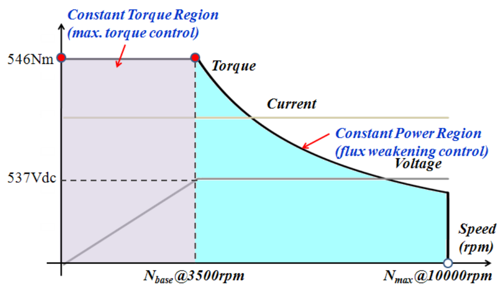

Fig. 1. Torque, voltage, and current characteristic of the IPMSM according to speed as an application of electric vehicle.

1) *Current Information at Constant Torque Region*

First, the load angle curves according to the phase currents with current interval 50A can be analyzed by using FEM as shown in Fig. 2. The current angle of maximum torque at each load angle curve is increased in accordance with current amplitude due to reluctance torque. MTPA control method at constant torque region means efficient torque generation method with minimum current. For example, the torque 61.5Nm can be derived with current 50A and about current angle 10° by MTPA controller. Although, the terminal voltage is also increased according to motor speed, it maintains under battery voltage value in a constant torque region. Therefore, the current information with same torque within constant torque region has the same value of current amplitude and current angle regardless of motor speed [6].

Fig. 3 shows the operation points on which current information should be calculated within constant torque region and flowchart of calculation method for current information at constant torque region. Motor speed is divided into intervals of 500rpm and motor torque is divided into intervals of 40Nm in the operation region.

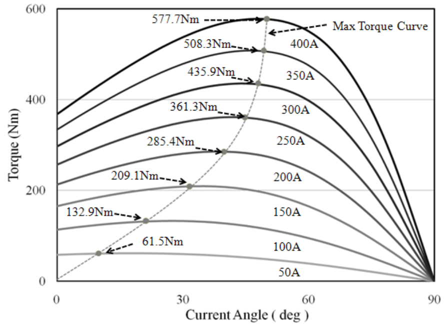

Fig 2. Load angle curves according to currents and MTPA curve.

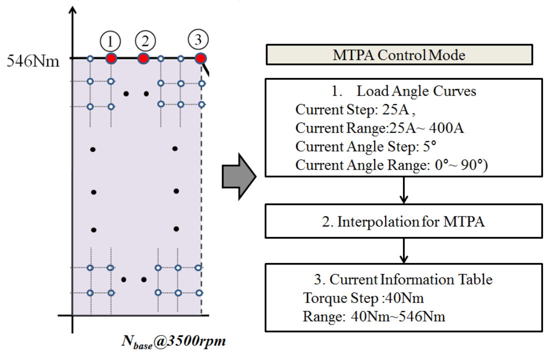

Fig 3. Max torque per ampere control at constant torque region

2) Current Information at Constant Power Region

Induced voltage between stator winding terminals keeps increasing according to motor speed. If it is over battery voltage, it should be decreased by using field weakening control which adjusts current angle appropriately in order to decrease linkage flux. However, the core in the vicinity of the air-gap is saturated magnetically. It is difficult to calculate exact current information satisfying operation voltage below battery voltage. Moreover, it is also necessary to operate IPMSM with maximum voltage because of small current causing high efficiency.

Fig. 4 shows the calculating process of current information with field weakening control mode. For example, in case of operation of torque 240Nm and two kinds of motor speed, 5500rpm and 6000rpm, the current information should be changed with motor speed because of voltage limitation. In Fig. 4, there are five points with torque 240Nm at each load angle curve, which have different current amplitude and current angle. With this current information at these points, the input voltage for the motor can be analyzed by FEM which is changed with motor speed. Finally, the current information can be derived by comparing and interpolating analyzed input voltage with battery voltage. The input voltage of motor should not exceed battery voltage level 380Vrms which is converted from DC to AC.

Fig. 5 shows the operation points on which current information should be calculated within constant power region and flowchart of calculation method for current information with field weakening control mode. Motor speed is also divided into intervals of 500rpm and motor torque is divided into intervals of 40Nm in the operation region. Table III shows the analyzed voltage by FEM with different condition on current and motor speed in Fig. 4.

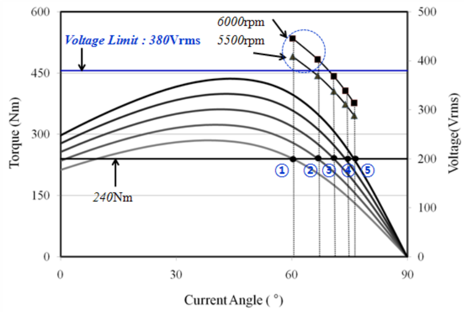

Fig. 4. Current Information for torque 240Nm by interpolating of load angle curves. (Field weakening control mode at constant power region)

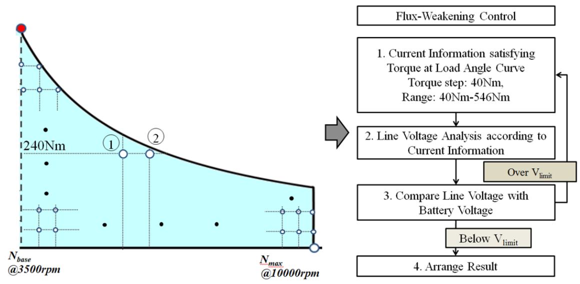

Fig. 5. Field weakening control at constant power region

III. Conclusion

Calculation method on the current information of vector inverter is proposed by using FEM which can analyze magnetic saturation effect in a core. The current amplitude and current angle are analyzed and calculated by separating driving region into constant torque region and constant power region. By using this current information, the IPMSM for electric vehicle can be controlled with appropriate torque considering magnetic saturation in a motor.

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