ADVANCED DRIVING SYSTEM OF THE THREE-PHASE DC MOTOR

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Abstract: The presented article briefly outlines a field-oriented control algorithm used to drive a permanent magnet three-phase DC motor with efficiency maximization and its modification to reduce overall computational complexity. This enables the utilization of the algorithm in computer constrained devices, for example in a self-balancing vehicle, which the algorithm and electronics were previously designed for.

Keywords: BLDC motor, PMSM motor, field-oriented control, Park transformation, Clarke transformation, look-up table.

1 INTRODUCTION

The discovery of the alternating current initiated following widespread usage of three-phase motors, known for almost no need of any maintenance. In these days they can be found in the industrial sector on the one hand, but on the other hand they are also becoming more and more popular in consumer electronics, where they act as a replacement of traditional brushed motors. Some examples of this case represent blenders, vacuum cleaners, white goods and other household appliances. Three-phase motors can be found also in transportation vehicles, including electric bikes, electric cars, trains, trams, etc. Especially in vehicles that carry accumulators as a source of energy along with them, it is essential to convert this energy into suitable voltages to drive each phase of the motor and reduce any power loses to maximize overall efficiency and range.

This article focuses on the solution of energy maximization which will be used as a part of the self-balancing vehicle [1].

2 ROOT OF THE PROBLEM

The previous solution of driving the permanent magnet motor in the self-balancing vehicle was based on a six-step commutation. It means that according to the rotor position sensed with Hall sensors, each phase was connected to the positive or negative pole of a power supply. The speed of the rotation was controlled by a pulse-width modulation duty. This method is simple and easy to implement, but its inefficiency rises with the rotational speed. The reason of this is the inductance of the stator winding, which causes a lag of the current, as a force-creating element, behind the driving voltage. The situation is shown in figure 1. The left side of the figure belongs to a simplified sketch of the rotor. The maximum force and efficiency could be obtained by pushing the magnet with an electromagnetic force perpendicular to the magnet longitudinal axis. In that case, the quadrature component, marked with letter Q, will be the highest, and the direct component, marked with letter D, will be eliminated.

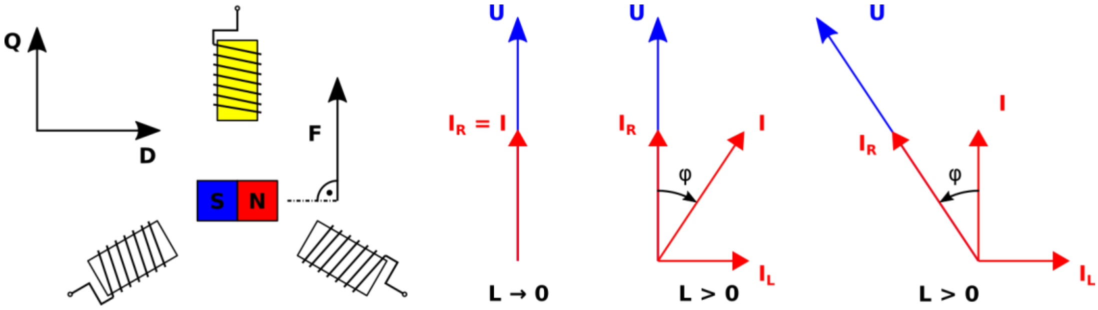

Figure 1: The impact of the winding inductance while driving the motor

The right side of the figure shows three situations. The first one assumes only the resistance of winding and no inductance, which implies that the voltage and current vector share the same orientation. However, the situation in practice is much more like the second part, where the current vector lags behind the voltage vector, due to the previously mentioned and not negligible inductance. It is necessary to move the voltage vector ahead of the direction of the rotation to compensate this effect, which increases the impact of Q component, cancels impact of D component and maximizes the motor efficiency and performance.

3 GENERAL SOLUTION

The traditional solution to this problem is an implementation of a so-called field-oriented control, shown in figure 2. The currents flowing through each phase are measured and converted from a three-component representation into two components of a complex plane by using Edith Clarke's transformation. However, both of these complex plane components named I_α and I_β always change in accordance with the rotor position. Robert Park's transformation is used to simplify subsequent mathematical calculations and to synchronize both components to the current rotor angle, resulting in creation of two almost static current components I_d and I_q. These are fed into PI controllers, to minimize I_d and keep I_q in the compliance with an external requirement.

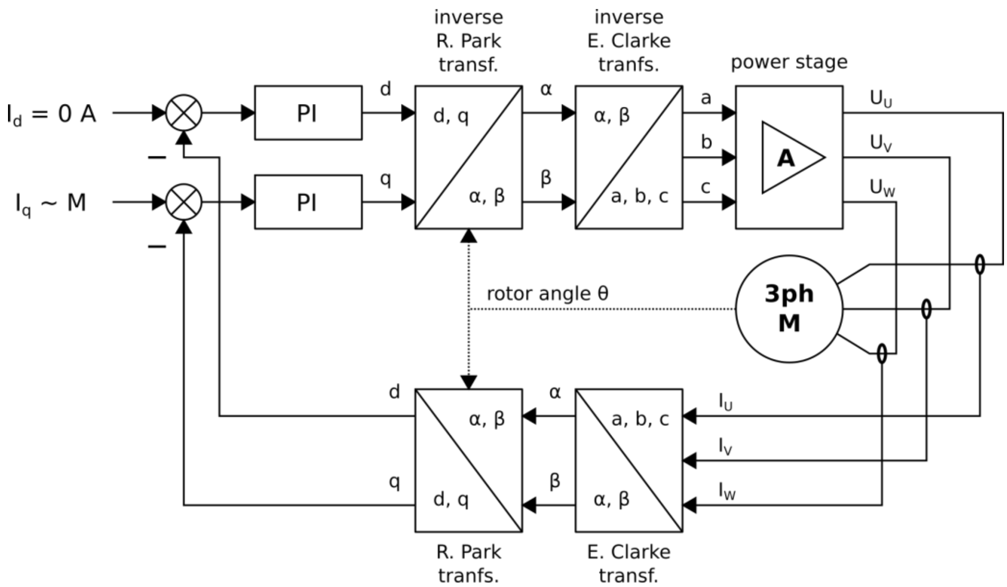

Figure 2: Field-oriented control scheme

The next part of the control scheme consists of inverse transformations. Robert Park's inverse transformation changes PI controllers outputs in terms of voltages U_d and U_q to the right value, depending on the position of the rotor. Edith Clarke's inverse transformation creates three components again to drive each phase. The main disadvantage of this solution is its computational complexity and the fact that the maximal voltage each phase can be driven with is 87 % of the nominal power supply voltage. An advanced driving method should be employed to utilize the full magnitude of power supply voltage, for example Space Vector Pulse-Width Modulation (SVPWM), the third harmonic injection or the use of saddle-shaped profiles, resembling letter M, stored in the look-up table in microcontroller programme memory, as described in [2].

4 THE SOLUTION

The stored driving waveforms and the inspiration taken from [3] serve as the main basis of the solution shown in figure 3. The initial part of the control scheme is the same as in the previous example. The phase currents are measured and gradually transformed into I_d and I_q components. They act as a feedback to PI controllers simultaneously with current commands. The D part needs to be eliminated and Q part should be set accordingly to the output of a balancing algorithm, described in author's previous article [1]. The principle of the balancing algorithm will not be analysed here, but for the purpose of the control algorithm it is essential to mention that it uses the arctan function to estimate the position of the driver from the data provided by the integrated accelerometer. The same function can be used to determine the angle of the voltage vector, given by U_d and U_q components, and to advance the current position, given by the rotor angle, in the look-up table containing suitable driving waveforms. These waveforms are subsequently multiplied by a modulus of the voltage vector and in the form of a pulse-width modulation duty amplified in a power stage.

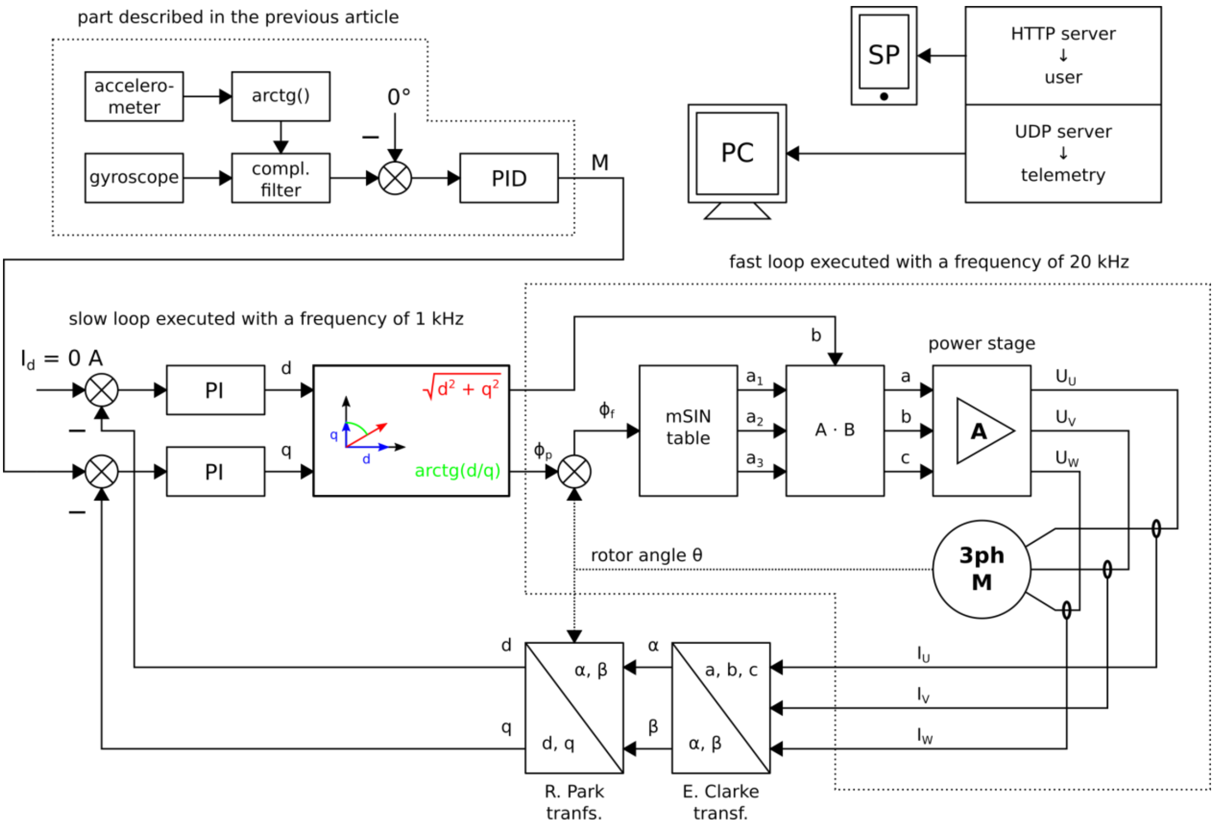

Figure 3: Modified field-oriented control scheme

There is no need to do backward transformations with the solution described above and whole control algorithm can be divided into two separate loops with a different speed of execution. The slow loop calculates all necessary quantities, while the fast one only reads the data from the look-up table and scales them as necessary. There is also a possibility to see selected waveforms and set algorithm coefficients in real time through PC application and to communicate with a smartphone, for example in order to check the battery voltage.

5 ELECTRONIC DESIGN

The key part of the whole electronics, which is shown in figure 4, is the 32-bit Cortex-M3 microcontroller STM32F103C8T6, clocked with a frequency of 32 MHz, performing all calculations described above and providing the communication with external peripherals. These include the three-axis accelerometer and gyroscope LSM6DS3 in a package and the UART to Wi-Fi bridge ESP-01 containing the integrated circuit ESP8266. The power stage consists of three half-bridges, each one containing two N-MOS transistors YJG85G06A and a driver IRS21867. The current sensing in all three phases is done by three Hall effect based sensors ACS712 with a sensing range ± 30 A. The power supply stage contains a buck converter AOZ1282CI and a pair of AMS1117 voltage regulators. The three-phase BLDC motor with the voltage and power rating 24 V and 500 W respectively stays the same from the previous version of the self-balancing vehicle, as well as the six-cell lithium-polymer accumulator with a capacity of 12 Ah.

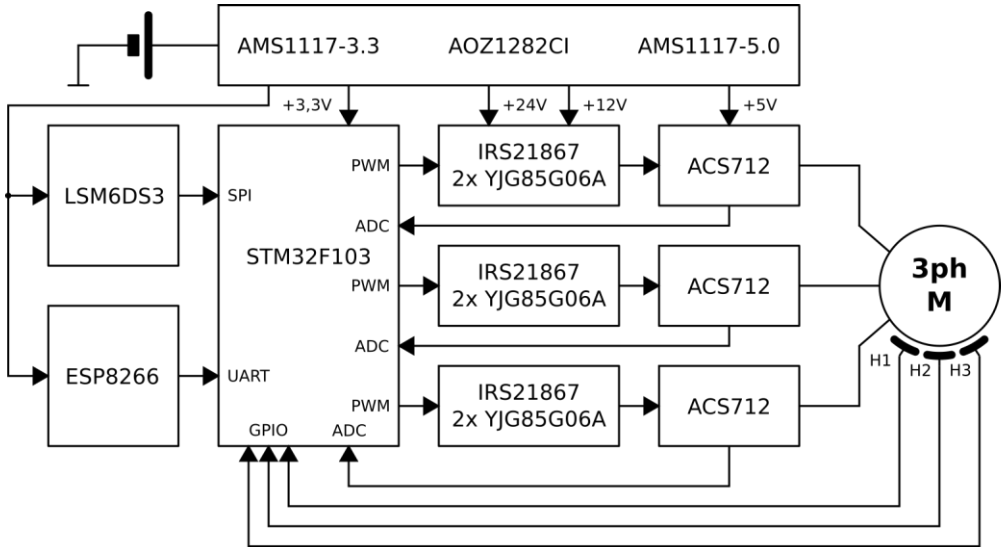

Figure 4: Block scheme of the electronics

6 CONCLUSION

The main purpose of this article is to describe a fast, simple and in term of computational complexity modest implementation of a field-oriented control algorithm used in order to maximize the efficiency of a three-phase BLDC motor. The reason for this was the integration of the algorithm in the self-balancing vehicle, where a part of the computational power already belongs to estimate the rider's position. Another reason can be the utilization in similar personal electric vehicles with low-cost and low-power microcontrollers.

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