Switched reluctance motor drive control algorithms with single line position feedback signal usage and custom phase locked loop microcontroller implementation

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There was presented a frequency multiplication of a single, binary rotor position feedback signal implementation in the article. This technique was necessary to achieve wide-speed control range and improved dynamics. In the beginning a basics of the switched reluctance motors construction were described as the control system challenges were. A nature of the reduced up to one position feedback signal interface line was shown as the reference for phase locked loop system. The problem of low resolution and asymmetrical shape of the mechanical position sensor was described with its solving by embedded system optimized SPLL loop usage. There were appropriate theory dependencies introduced for phase locked loop system as confirming experimental results were shown. In the summary, conclusions were made and the further research steps were proposed. Additionally, custom made drive system for switched reluctance motor and the motor as the control object itself were introduced.

1. Introduction

1.1. Goals and motivation

Switched Reluctance Motor (SRM) is the oldest type of electric motor used in practice. Its historical importance base on its construction simplicity. One of the most important feature of SR motor is its monolithic structure. There are no coils, cages or magnets in the rotor. This special feature makes possible to achieve very high speeds without dangerous of destruction caused by high round-move based mechanical forces. There are known some devices (also in home appliances), where speeds of 100 000 [rpm] are nominal ones [1]. Furthermore, the same feature changes into high reliability. It is very important to make fault-tolerant all the drive and not only the motor. That is why overall system complexity (especially mechanical elements) is reducing by – for example – elimination of mechanical position sensors. On the other hand, mechanical simplification require more sophisticated control algorithms and bigger control system structures [2]. Problems of optimal control in sensorless drives are being analyzing in many past and current researches, but – unfortunately – because of its sophistication often happens it could not be implemented in practice. That is why finding new methods of sensored, based on cheap and simple (but very imprecision) mechanical sensors

control algorithms is necessary and that will be the main concern of the article.

One of this methods tried to use reduced, binary position feedback signal with low resolution in control system of the SRM. The reduction base on lowering interface signal lines number form standard N (where N is equal to number of motor phases) to one. Specific of this signal makes the phase synchronization and commutation process control much more complicated, but possible. Presented article continuing topics discussed in [3] and tries to focus on solving problems mentioned above.

1.2. Switched reluctance motor and its control basics

There is an important fact in the switched reluctance motor operational theory basics that there are no open-loop control systems use in practice because of its instability and poor dynamics.

Figure 1 shows general mechanic characteristic ($T_e = f(\omega)$) of the SRM in wide-speed operation range. It is possible to see three different operational speed ranges: with constant torque, constant power and falling power. Those ranges are connected with torque generation rules [1]. The next drawing (Fig. 2) presents the most important values (in the motor basics of movement) depending from rotor angle. The source of the electromagnetic torque is changing induction L of the motor phase caused by moving rotors tooth in relation to stator pole. That change is guaranteed by motor mechanical construction.

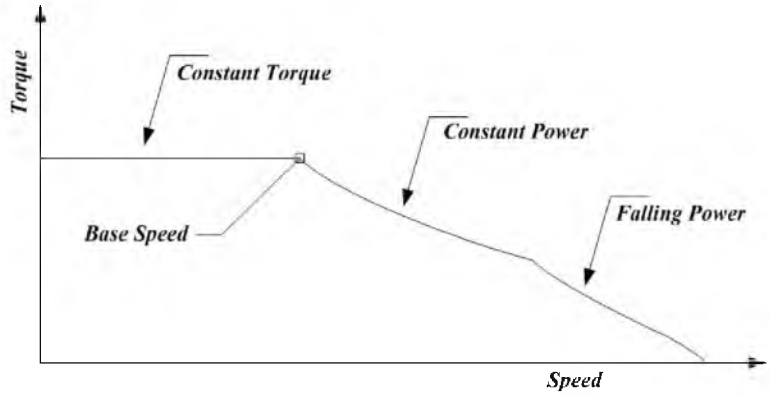

Fig. 1. General SRM mechanical characteristic – three different speed regions

SRM operates in wide-range speeds, but this is possible to achieve only when some special requirements are met by control system. As can be observed on Fig. 1, in the first range (constant torque), when the speed increase constant phase current must be hold by phase voltage rise. In the second range (constant power) nominal speed is crossed over and the electromagnetic force (EMF) reaches the

power supply voltage. This is why changing conduction angles and the phase excitation point are the last freedom level that can be use for speed increase from this point. At the third speed range (falling power) – still increasing phase excitation cause timely generating electromagnetic torque with opposite direction to the speed. At some speed point, average torque falls to zero and further operation is not possible. When applying to described control schema it is clear that the precision rotor position information would be the main requirement [4].

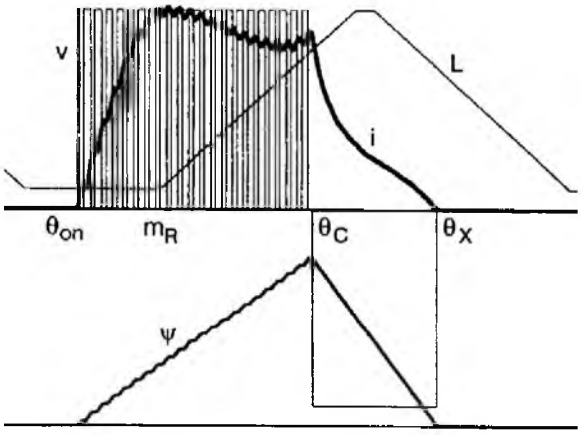

Fig. 2. Voltage controlled phase excitation process

1.3. Custom made laboratory motor drive system

The main concern about custom laboratory stand construction project was to get: high level security, stability and low overall building costs as the drive for general home-appliance purposes.

General structure of the drive system was presented on Fig. 3. The drive project was an effect of compromised level of logic, galvanic and geometrical isolation of modules with sources of electromagnetic interferences (EMI) from sensitive on EMI ones. As could be seen on the corresponding drawing there was achieved full separation of the high voltage part (Fig. 3 – *HV*) from low voltage one (*LV*).

The system core is new, well accessed on the market and cheap, thirty two bits microcontroller based on STM32F107 family with ARM Cortex-M3 inside. Its main advantage is very high energy efficiency coefficient as a relation of computing power to power dissipation. All the drive system consist of several modules as: switched mode power supply for control unit – *PWR*, power factor correction – *PFC*, power bridge in asymmetrical topology chosen from several ones based on the article [5] – *INV*, central unit – CPU, and the galvanic separation board – *ISO*. The motor as the control object was unit from Maytag washing machine, 250 [W], three phase, 12/8 topology. The prototype drive construction details could be found in [6].

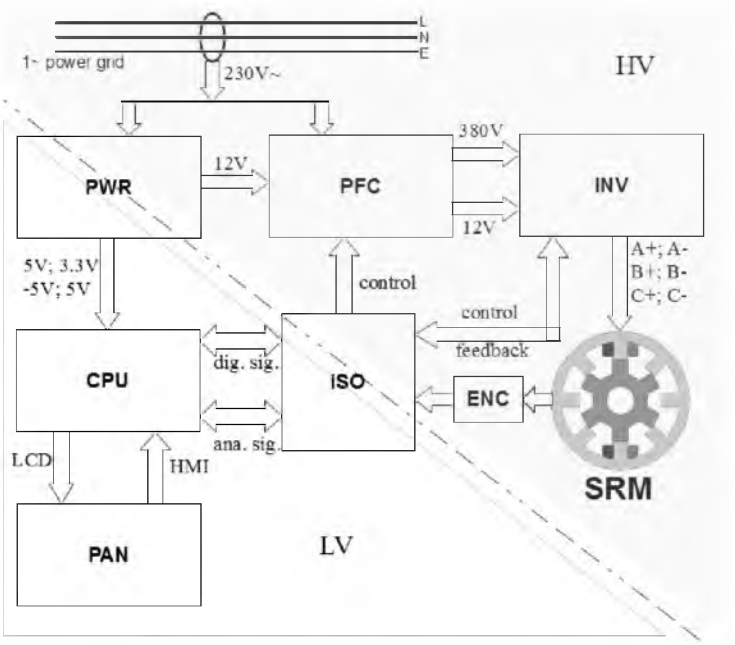

Fig. 3. Structure of the dedicated SRM drive

2. Control algorithms

2.1. Position feedback signal shape

Figure 4 shows feedback signal shape. N (N corresponding to phase count) lines interface was replaced there by binary coded signal by its level and duration time. Finally, four alphabet letters was taken into account (A, B, C, D – see Fig. 4) that shows in cycles of 12-elements.

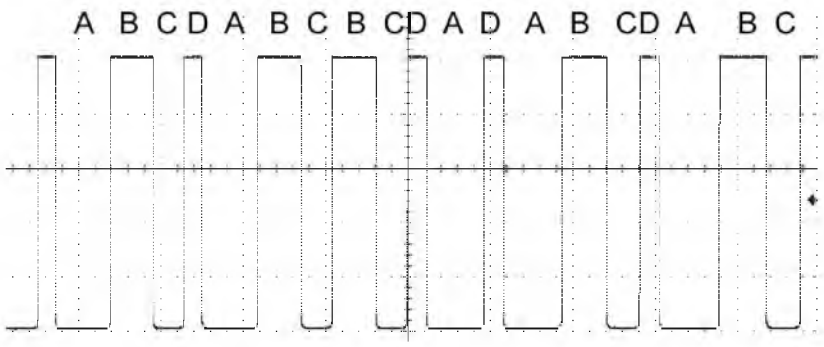

Fig. 4. Position feedback signal shape at constant speed

Theoretically the alphabet was complex enough to detect the phase synchronization point. It was very important because described before N lines interface binary combination naturally gives the synchronization point (as the point where the rotor position defines reluctance change that generates optimal torque with exact stator motor phase number, in some way called rotor-to-stator synchronization). Analysis, signal feedback detection and decoding algorithms as the implementation in embedded system were described in details in the other article [3].

1.2. Phase Locked Loop

Solve for the feedback signal asymmetric nature and its low resolution was found in original implementation of PLL (*Phase Locked Loop*). Theory analysis of PLLs, its features and practical usage examples was introduced in [7].

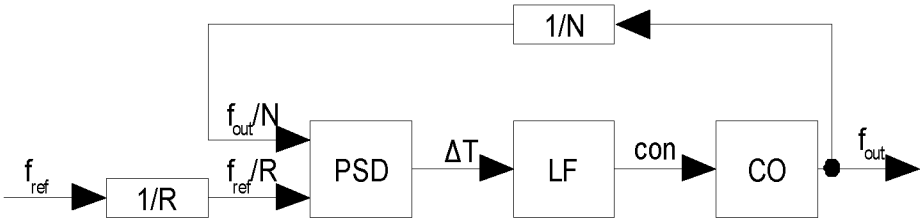

Fig. 5. General PLL structure

Figure 5 presents general PLL structure. Its main concern is multiplication of the reference signal frequency as precisely as possible. The PSD block (*Phase Shift Detector*) computing phase shift between reference signal and the generated one. The value of the shift is filtered in LF block later to change in CO (*Controlled Oscillator*) block into signal with proportional frequency. The analogy to the automatic control system is not coexistent there. When the CO block would change with control object, for example SR motor with rotor position sensor, as the result there would be given speed control system [8]. In the proposed solution, the loop was used only as frequency multiplier of the reference signal. Very similar solution was described in [4], but presented system has four binary lines of the feedback system to use, which were not available in mechanical reduced, laboratory tested system. Additionally it could be said that proposed in [4] solution becomes to DPLL (*Digital PLL*) class, fully hardware and digitally realized.

The method presented in the article would be classified as SPLL (*Software PLL*), fully implemented in one microcontroller (uC) as the all control algorithms were. The SPLL system must be optimized to dedicated embedded system to ensure minimal CPU core usage. Optimization process for SMT23F1 uC unit will be discussed in next paragraphs.

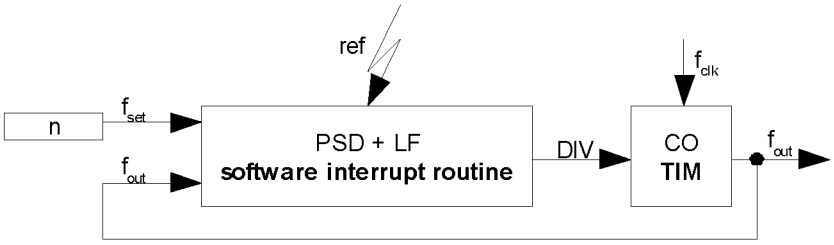

Fig. 6. Dedicated microcontroller PLL structure

There was an idea of the optimization and implementation in embedded system presented in Fig. 6 based on general model from Fig. 5. As the start point there was the presumption made that controlled oscillator role would be taken by built-in STM32F1 system timer (*TIM*) clocked by constant frequency 72 [MHz] with programmable division block (*DIV*) and the register *CNT*. Between the next reference signals with frequency (f_{ref}) proportional to the rotor speed there were synchronized with f_{ref} impulses counting from zero to the set count – n (which was multiplication factor in fact). Achieved in this method *CNT* value was estimated angle position to direct use in control algorithm. The problem was to get an appropriate *DIV* value for actual drive work parameters. The *DIV* value was computed in connected (in comparison to base model) blocks *PSD* and *LF*, software realized in the system interrupt routine from external input signal – *ref* As the time reference for phase shift there was the *TIM* register value taken. TIM register value with known *DIV* division factor and clock f_{clk} could be used for time measurement. The actual time period (T_{ACT}) of the loop outgoing signal (f_{out}) measured in the moment of *ref* interrupt routine handling (j – iteration) is equal to:

$$T_{AKT_j} = \frac{CNT_j \cdot DIV_j}{f_{clk}} \tag{1}$$

and the difference (T_{DEL}) between the demanded time period (T_{DES}) and the real one (T_{ACT}) computed from the error value equation:

$$e_j = n - CNT_j \tag{2}$$

with the presumption of the error filtration for disturbances influence minimization on control loop as follows:

$$\Delta n_j = K_P e_j + K_I \sum_{i=0}^{j} e_i \tag{3}$$

is equal to:

$$T_{DEL\,j} = \frac{\Delta n_j \cdot DIV_j}{f_{clk}}$$

and also:

$$(4)\ T_{DEL_j} = T_{AKT_j} - T_{DES\,j} = \frac{DIV_j\,(CNT_j - \Delta n_j)}{f_{clk}} \quad . \tag{5}$$

To compute the new value DIV_{j+1} based on the current one equation (5) should be transformed and solved as shown below:

$$\frac{DIV_j\,(CNT_j - \Delta n_j)}{f_{clk}} = \frac{DIV_{j+1} \cdot n}{f_{clk}} \Rightarrow DIV_{j+1} = \frac{DIV_j\,(CNT_j - \Delta n_j)}{n} \quad . \tag{6}$$

To optimize computing equation (6) and short division operation to one core clock the *n* value was set to 1024 to achieve enough resolution and reduce division by n to bit shift operation.

There was used proportional-integral (PI) filter structure in the LF block with anti-windup algorithm of 2nd order. Appropriate gains K_p and K_i values were set based on the article [9]. There were proved that for the linear discrete model gains that gives stability and noise cancellation should be computed from the follow equations:

$$K_P + K_I = 1 \wedge K_I = K_P{}^2 \quad . \tag{7}$$

Finally K_p = 0,62 and K_i = 0,38 were taken as the LF block gains.

When the PLL worked and the resolution of the position sensor was much improved it becomes possible to implement further algorithms for optimal turn-on and turn-off angles for the corresponding excited phase. There was proposed an easy to implement approach in [10], where energetic efficiency was taken account.

3. Experimental results

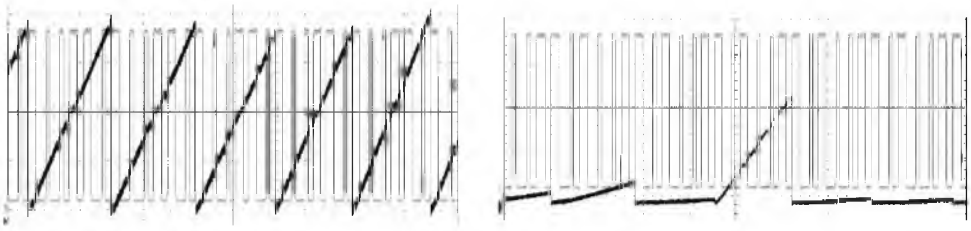

Fig. 7. SPLL in the action, Ki = Kp = 0.5, 200 [rpm]; no anti-windup mechanism

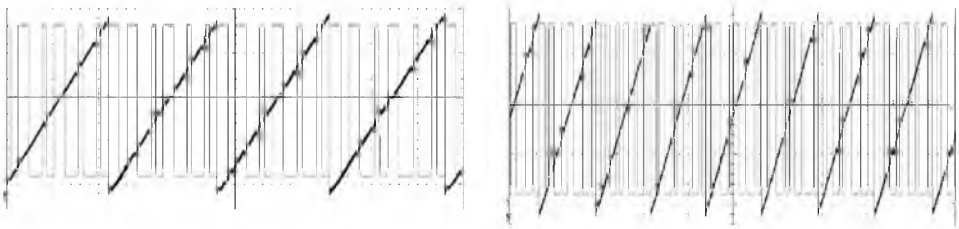

Fig. 8. SPLL in the action, Ki = 0.38, Kp = 0.62, 100 [rpm]; 500 [rpm], PI filter with anti-windup, high dynamic

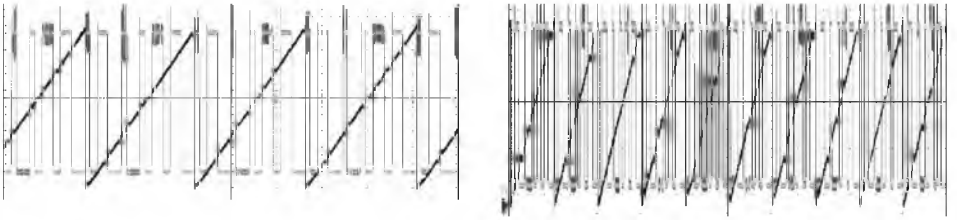

Fig. 9. SPLL in the action, Ki = 0.38, Kp = 0.62, 200 [rpm]; 1000 [rpm], PI filter with anti-windup, steady state

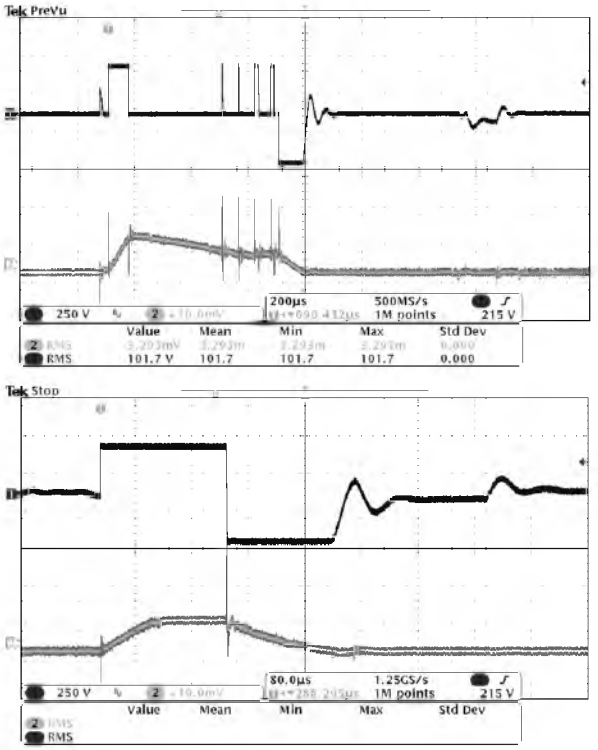

Fig. 10. Phase voltage (1) and current (2) at speeds: 2000 [rpm] and 7000 [rpm], supply voltage: 230 VAC

Researches on the implemented PLL was made based on the oscilloscope NCO (*Numerical Controlled Oscillator*) register value plots. The n value in the presented experimental results was set to 1024, what is equal to 0,8 [V] (vertical DIV was set to 200 [mV/DIV]). Plots from Fig. 7 were show instability of the PLL what was the result of lack of anti-windup algorithms. There was PLL work presented on the Fig. 8 for the optimal gains at the low speeds and high dynamics, where phase locked loop gives the biggest errors (up to 5 [%] in the example). Fig. 9 with couple of oscillograms was presented SPLL at steady states.

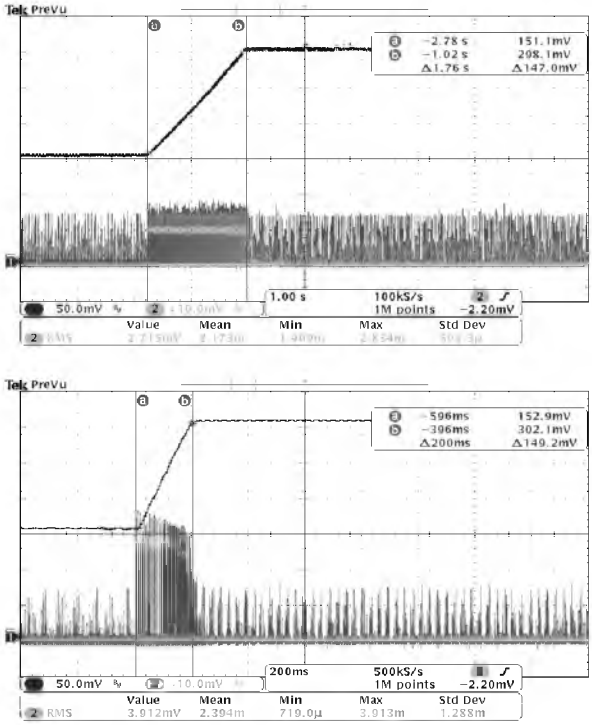

Fig. 11. Speed step response (1) with corresponding phase current (2); changing speed set point from 1000 to 2000 [rpm]; current limitations: 36 [%] and 100 [%] of rated value; process control time: 1,76 [s] and 0,20 [s]; supply voltage: 230 VAC

Thanks to the experiments over the PI structures and its gain sets it was proved that proposed solution algorithm and SPLL implementation follows the theoretical analysis and was well suited to the presented SRM drive.

Phase voltage, current and rotor speed plots as the base motor control process variables at the different operation point were shown to confirm well-working machine supplied from the system presented in the Fig. 3.

4. Summary

The article that extends the main topic from [3] in the field of single line position sensor usage in efficient control of switched reluctance motor was begin with introduction to SRMs. There was pointed the simplicity of SRM mechanical construction as the control complexity was. The laboratory stand was described with the dedicated control system, where the proposed algorithms was verified. The nature of the position feedback signal was presented and the coding schema for the phase synchronizing method. Next, the low resolution of the position sensor problem was introduced. Adaptive method for reference signal resolution

increasing with use of software phase locked loop were described. Moreover, original, well-suited for STM32F1 embedded system SPLL structure corresponding to reference one was shown. Finally, there were confirmed theoretical analysis, dependencies and stability of practical implementation in the target device by experimental results.

Phase voltage, current and rotor speed plots at the different operation point were shown to confirm working of the machine supplied from the system. Presented results and analysis are the base for further researches in the field of the switched reluctance motor drives optimal control in wide-speed range with high dynamics.

References

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