

Sensorless Stator Flux Oriented Control for Startup Gas Turbine

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ARTICLE INFO	ABSTRACT
<p>Article History: Received 20 January 2018 Received in revised form 10 February 2018 Accepted 5 March 2018 Available online 13 March 2018</p>	<p>This paper introduces a novel hybrid rotor-position estimation technique for wound-field synchronous motors (WFSM) powered by load-commutated inverters (LCI), operating continuously from standstill through turbine ignition speed. At low speeds, where signal-injection techniques excel, a high-frequency injection-based estimator provides initial rotor-angle information. As speed increases past this low-speed region, a model-based stator-flux observer seamlessly takes over both position estimation and firing-pulse generation for the thyristor bridge. By combining these two complementary estimation strategies, the proposed algorithm overcomes limitations inherent in each individual method—namely, poor low-speed observability for flux observers and the energy losses associated with continuous injection at higher speeds. The result is reliable commutation of the load-commutated inverter's thyristors across the entire speed range, from zero to nominal. In addition, we present a new stator-flux-oriented control architecture tailored for LCI-fed WFSMs. This structure enhances the motor's power factor and yields a faster dynamic response in the speed controller, while simplifying the overall drive design to reduce manufacturing costs. The efficacy of the hybrid estimation algorithm and the novel control structure is demonstrated through detailed MATLAB/Simulink simulations. Results confirm seamless transition between estimation modes, robust commutation under varying operating conditions, improved power quality, and accelerated speed regulation—validating the approach as a practical, cost-effective solution for high-performance WFSM drives.</p>
<p>Keywords: Load Commutated Inverter, Sensorless Control, Stator Flux Oriented Control, Wound Field Synchronous Motor</p>	

1. INTRODUCTION

LCI fed WFSM is a high power and high speed driver which uses in most of industrial field like as gas power plant, rolling mill and mining, start up high power synchronous motor and compressor [1-6]. Regarding to compliance between LCI and WFSM and using of thyristor without any device for forced commutations and over current protection, LCI fed WFSM is the best solution for high speed and high power application like as start up gas turbine [7-10]. Structure of LCI is shown in Fig. 1. It can be observed that this structure includes thyristor rectifier

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on grid side and a thyristor inverter on machine side which are connected together by two inductors in dc-link. Switching inverter modes and machine phases current are listed in Table 1.

Self-control is traditional method for start up control [11]. This method needs rotor position in order to firing pulse generation and speed rotor determination which are done by position sensors. Applying these sensors increases manufacturing and maintenance cost and decreases reliability of drive.

According to mentioned problems, different position estimation methods have been proposed [12-20]. Methods of position estimation could be classified to injection-based [12-15] and observer-based [16-20]. Dependency on motor parameters and low accuracy at low speed are the main issue of observer-based method.

Problems of second method (injection), increasing losses and noise, lack of accuracy in existence high frequency harmonic could be introduced. Because of these problems, in section 2 a hybrid method is introduced for firing pulse generation and position estimation. In this method, position estimation is done at low speed by injection way and after rising speed of rotor, firing pulse generation and position estimation are performed by closed-loop stator flux observer. Coupling between control of flux and torque is another difficulty in self-control method. In order to decouple them, For the first one, has calculated synchronous machine’s flux equation in stator flux reference frame (M-T) and used them for stator flux oriented control of voltage source inverter (VSI) fed WFSM. In [20], changing control procedure of , a new method has been proposed for stator flux oriented control of LCI fed WFSM. In section 3, speed controller stated in , are modified which are resulted improvement of dynamic response and reduction of manufacturing cost. Result of MATLAB simulation is mentioned in section 4. Finally, conclusion and discussion of proposed method are stated in section 5.

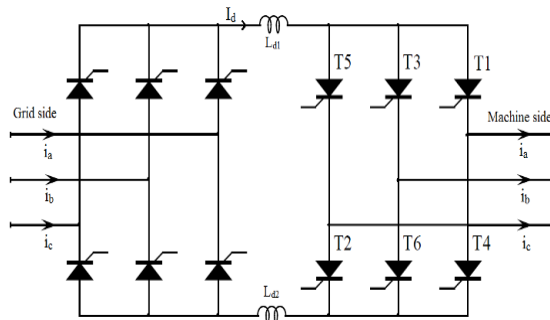


Fig. 1. LCI structure

Table 1. Inverter switching mode

Mode	Mode1	Mode2	Mode3	Mode4	Mode5	Mode6
Current	T ₆ , T ₁	T ₁ , T ₂	T ₂ , T ₃	T ₃ , T ₄	T ₄ , T ₅	T ₅ , T ₆
i_a	I _d	I _d	0	-I _d	-I _d	0
i_b	-I _d	0	I _d	I _d	I _d	-I_d
i_c	0	-I _d	-I _d	0	0	I_d

2. HYBRID POSITION ESTIMATION

Reference [12] has introduced a method based on injection to estimation rotor position at zero to final speed. In this method, by using a step-down chopper in feeding field and filtering inducted voltage which is produced by first field current harmonic and calculation of its envelope, position of rotor has been estimated. However, if field voltage controller output was zero, this method would not be applicable. Moreover, due to existence of high frequency harmonic in LCI, accuracy of that was decreased at high speed. To solve mentioned issue, field feeding is controlled by a class D chopper (Fig. 2) in proposed method which makes possible for controller to provide high frequency

signal in feeding. Even if output of field voltage controller was zero, switching would be done so that the average of voltage became zero. Switching frequency of CH1 and CH2 is 1 KHz. If CH1 and CH2 were on, voltage of field feeding would be V_s and if not, became $-V_s$. After using class D chopper, all procedure of position calculation are same as stated method in [12]. Rotor position is given by [12] :

$$\theta = \frac{1}{p} \tan^{-1} \left(\frac{E_{VW_fh1} + \frac{1}{2}(E_{UV_fh1} + E_{WU_fh1})}{\sqrt{3}/2(-E_{UV_fh1} + E_{WU_fh1})} \right) \quad (1)$$

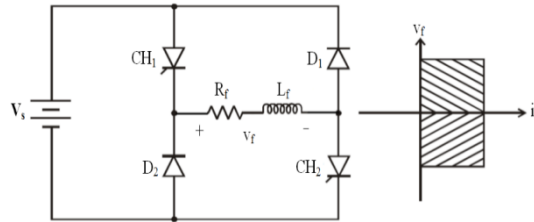


Fig. 2. Class D chopper with operation mode

Fig.3 shows phase diagram of M-T stator flux reference frame with respect to d-q rotor frame and α - β stator frame. Related relationship of them has specified in [20]. Fig.4 shows structure of closed-loop observer for stator flux with procedure of position and rotor speed calculation. As stator flux is constant during start up, a closed-loop observer can be designed simply. The inputs of observer are line voltage, line current and stator flux reference. In first block, using Clarke transformation inputs are transferred to stator frame, then magnitude and phase of stator flux are calculated at second block and currents are transferred from stator frame to stator flux frame by helping stator flux angle. Torque angle and position and speed of rotor are determined in last block.

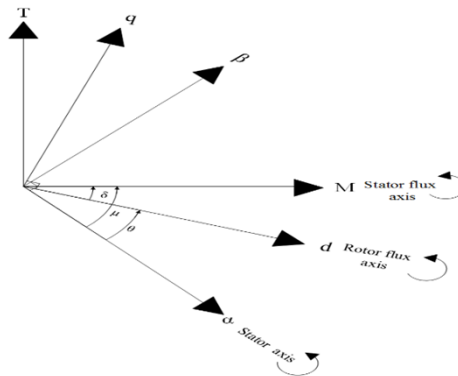


Fig. 3. M-T frame with respect of d-q and α - β frame

Following is transformer function between input and output of observer:

$$T(s) = \frac{1}{s + k_c} \quad (2)$$

Equation (2) is a low pass filter with cutoff frequency k_c caused to position estimation was able to delete DC error in sensor. Fig. 5 shows Bode diagram of (2) with $k_c=10$ and ideal integrator. It is seen that in frequency less than cutoff frequency, difference between magnitude and phase of filter has been increased in comparison to ideal integrator and observer error has been raised at frequencies less than cutoff frequency filter.

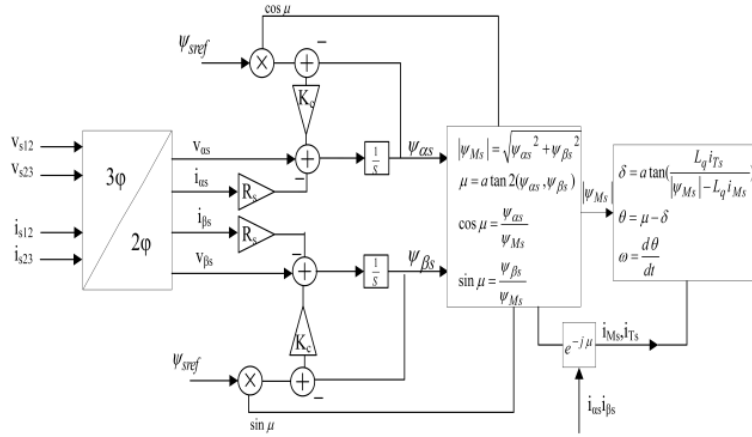


Fig. 4. Structure of closed-loop stator flux observer

In suggested hybrid algorithm, injection method has been applied at start up and low speed. In comparison between injection estimation and observer position outputs and reduction the differences their degree to less than 2 degree, field feeding switching are deleted and in continuing output of observer is chosen for position estimation. When output of injection position estimation is applied, firing pulse generation is done considering rotor position and using introduced manner in [11]. After using an observer, it is performed regarding to position of stator flux and mentioned method in [20]. When an observer is used, need to determine power factor angle is necessary in order to successful thyristor's commutations. It can be expressed as function of overlap angle (μ) and turn off angle (γ).

$$\varphi = \gamma + \frac{\mu}{2} \tag{3}$$

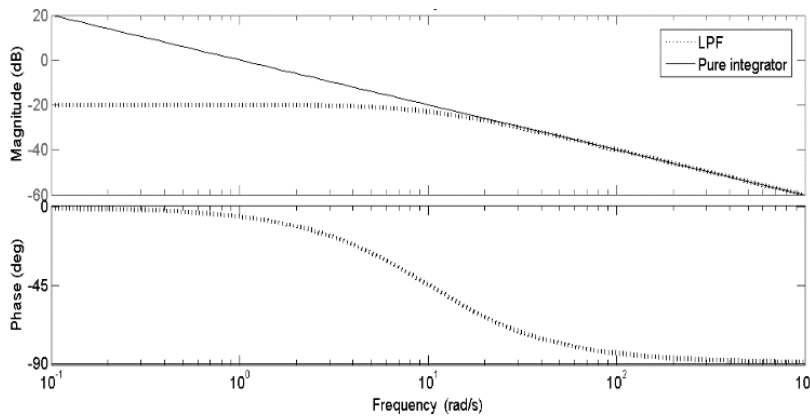


Fig. 5. Bode diagram of lowpass filter and ideal integrator

3. DRIVE CONTROL METHOD

In order to drive control, vector control in stator flux reference frame has been applied. Modified structure of speed controller has been shown in fig. 6. In this structure dc-link current is calculated by machine phases current. Thus dc-link current sensor is removed. Dc-link current is achieved by summation of absolute phases current and division by two. Output of internal PI controller is considered as dc-link voltage reference in proposed method and use of nonlinear relationship between firing angle and output voltage of rectifier, firing angle is calculated. Also According to (3) power factor angle estimation has been replaced instead of lookup table values that will result to improve machine power factor. Due to currents of phase which are limited to 1.5 times of rated current during start up, a limiter with clamping anti-wind up has been used in external loop of cascade PI controller. Block diagram of

evident that overshoot and settling time substantially have been decreased. According to (3), power factor angle estimation for successful thyristor's commutations has represented in fig. 16. This estimation is applied in order to firing pulse generation and helps to improve power factor of machine, because if lookup table was used, power factor angle shall be chosen such large value to provide successful thyristor's commutations.

Table 2. Machine Parameters

$L_{md} = L_{mq} = 11 \text{ mH}$	$R_s = 0.26 \Omega$
$L_{ls} = 1.14 \text{ mH}$ $L_{lf} = 2.1 \text{ mH}$	$R_f = 0.13 \Omega$
pole pairs=1	$J = 25 \text{ K.m}^2$

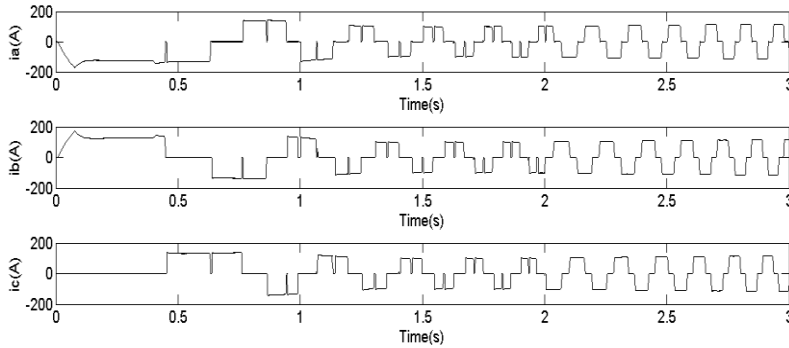


Fig. 8. Machine phase current

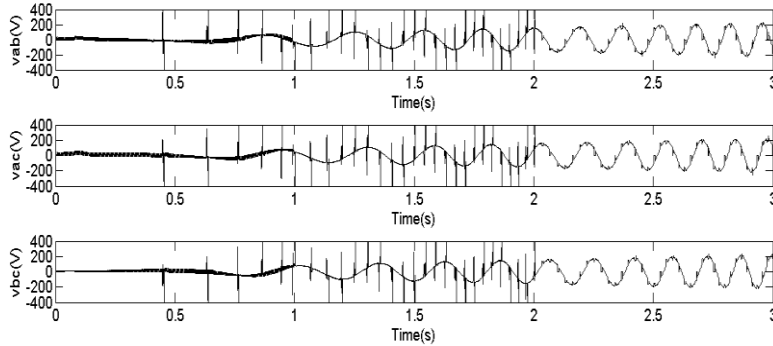


Fig. 9. Machine line voltage

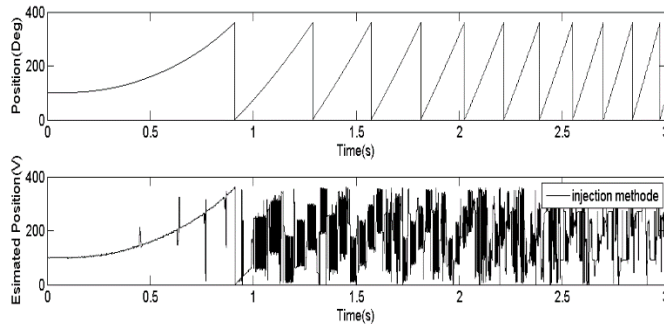


Fig. 10. Position estimation based on injection method

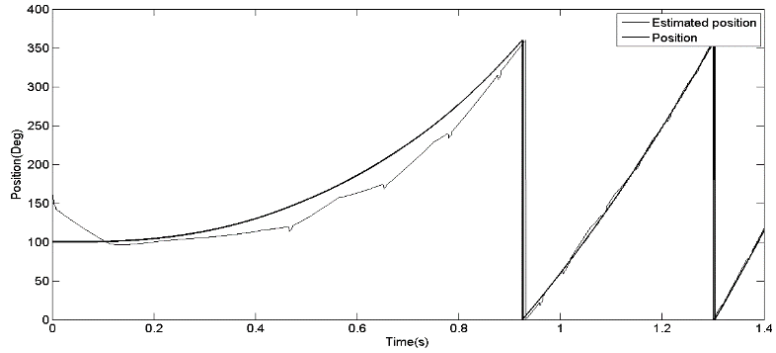


Fig. 11. Position estimation based on observer method

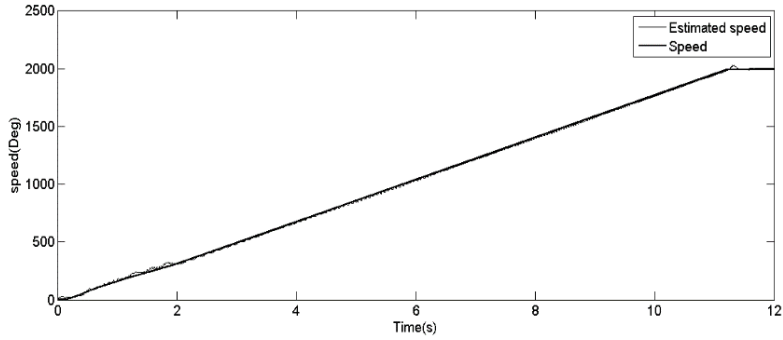


Fig. 12. Real speed with its estimation

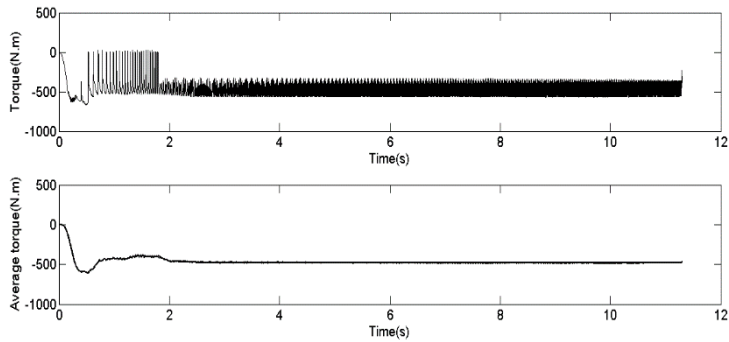


Fig. 13. Output torque and average of that

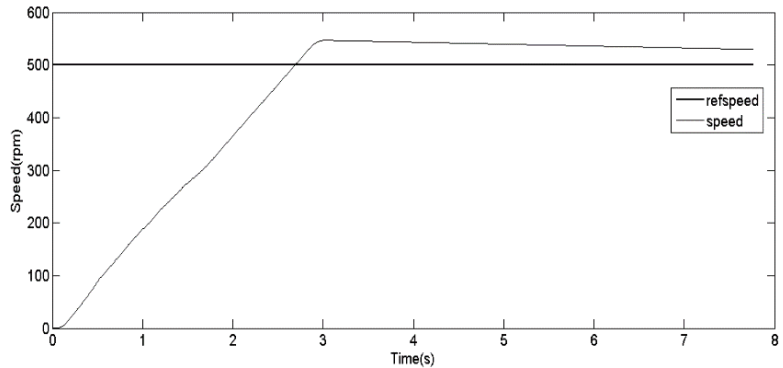


Fig. 14. Speed step response without using clamping

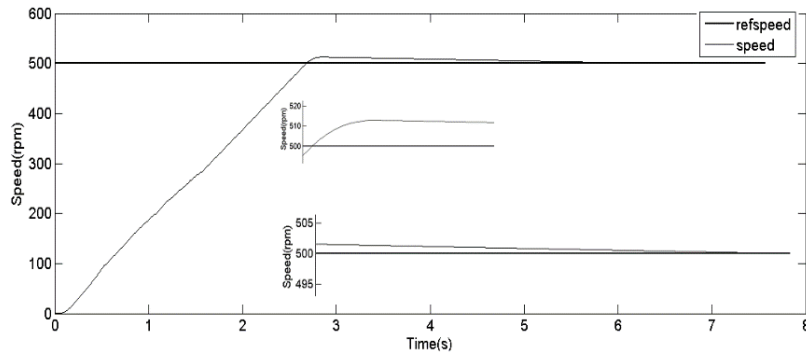


Fig. 15. Speed step response with using clamping

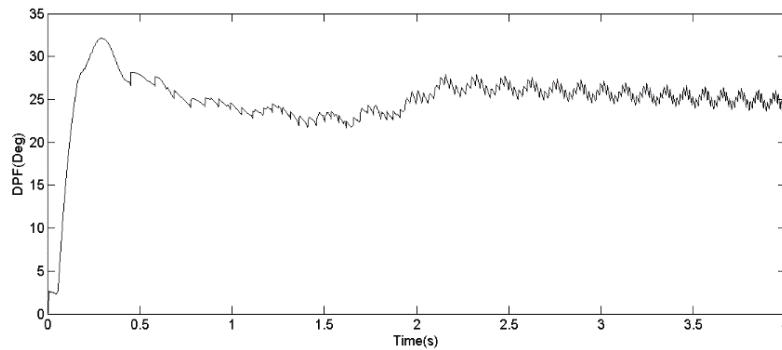


Fig. 16. Power factor angle estimation

5. CONCLUSION

In section I, a hybrid method was introduced in order to position estimation and firing pulse generation of thyristors and simulation result in section IV proved efficiency of this method. In proposed method, knowing value of stator resistance is only requirement. As observer was applied in closed loop, if variation of rotor resistance was 2 times of rated value during startup, error would be less than 4 degree. To conclude, advantages of introduced method are:

- Initial position of rotor detection without error
- Successful thyristor's commutations from startup to final speed
- Minimum dependency on machine parameter
- Being less harmonic and noise in comparison to injection methods
- Robustness against of wrong measurements

Finally, a new structure of speed control was introduced and manufacturing cost was reduced by elimination of dc-link current and voltage sensor. Also, dynamic response of speed was considerably improved with using clamping anti-windup method in external loop of cascade controller. Furthermore, machine power factor was improved by using power factor angle estimation compared to using lookup table.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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