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Sensorless Stator Flux Oriented Control for Startup Gas Turbine

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ABSTRACT

This paper proposes a hybrid position estimation method for load commutated inverter (LCI) fed wound field synchronous motor (WFSM) at zero speed up to turbine ignition speed. In this method injection based position estimation method is used at low speed. Then a stator flux observer is applied to firing pulse generation and position estimation.

With use of proposed algorithm the problems of other position estimation are reduced and thyristor's commutations at zero up to final speed are well done. In this paper a new structure has been introduced for stator flux oriented control of LCI fed WFSM which improves power factor and dynamic response of speed controller. Moreover, manufacturing cost is reduced. Finally proposed algorithm and structure are simulated in MATLAB Simulink.

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 WSFM 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 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.

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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.

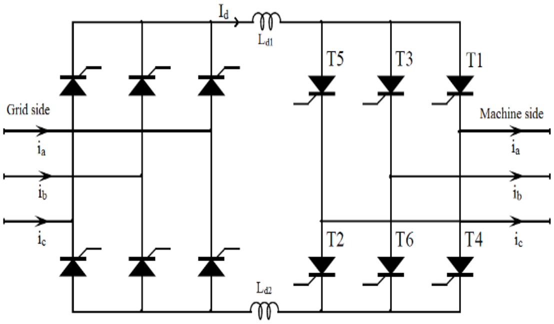

Fig. 1. LCI structure

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 Vs and if not, became –Vs. After using class D chopper, all procedure of position calculation are same as stated method in [12]. Rotor position is given by [12] :

$$\theta = \frac{1}{p}\tan^{-1}\left(\frac{E_{VW\_fh1} + \frac{1}{2}(E_{UV\_fh1} + E_{WU\_fh1})}{\sqrt{3}/2(-E_{UV\_fh1} + E_{WU\_fh1})}\right) \tag{1}$$

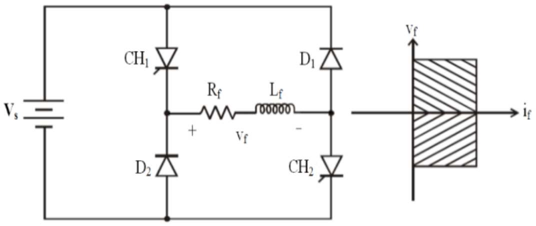

Fig. 2. Class D chopper with operation mode

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.

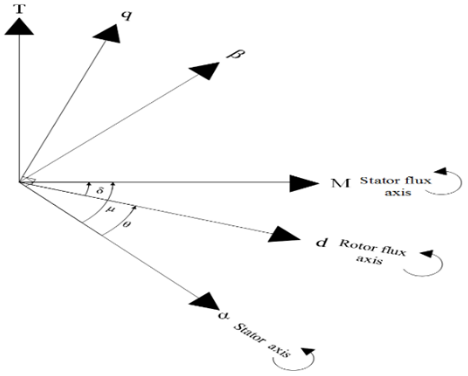

Fig. 3. M-T frame with respect of d-q and α-β frame

Following is transformer function between input and output of observer:

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

Equation (2) is a low pass filter with cutoff frequency kc caused to position estimation was able to delete DC error in sensor. Fig. 5 shows Bode diagram of (2) with kc=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.

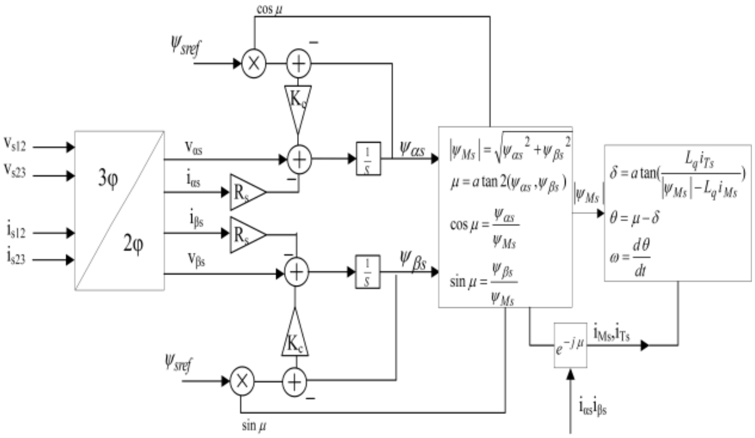

Fig. 4. Structure of closed-loop stator flux obsever

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 angel (μ) and turn off angel (γ).

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

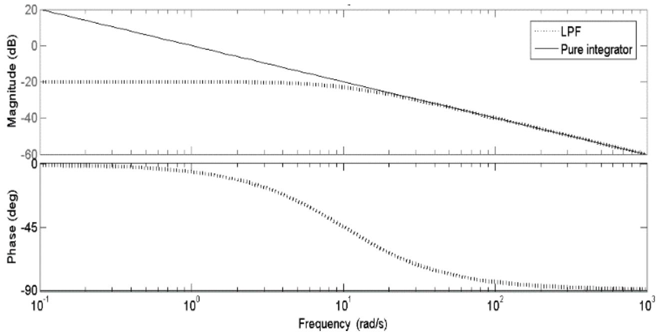

Fig. 5. Bode diagram of lowpass filter and ideal integrator

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 clamping method is shown in fig. 7. When output of controller reaches to up and down level of limiter and sign of output controller is same as error, integrator will go out from controller. This work is lead to decrease settling time and over shoot of speed dynamic response.

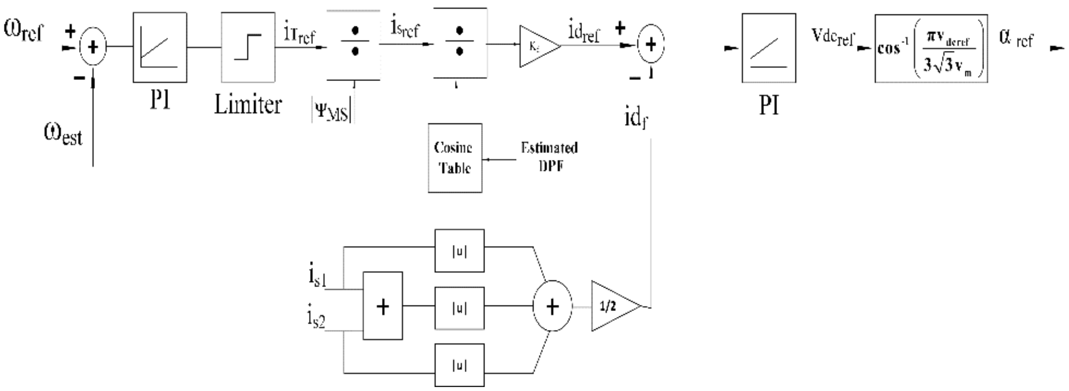

Fig. 6. Speed controller structure

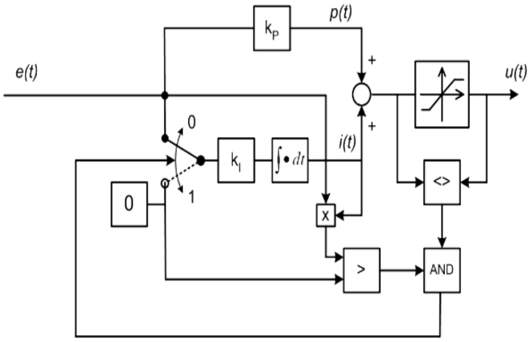

Fig. 7. Clamping anti-wind up block diagram

4. SIMULATION RESULTS

The proposed algorithm and structure have been simulated in MATLAB Simulink. Synchronous machine with cylindrical rotor 111.9 KVA, 762 V and 60 Hz has been considered according to below Table 2. Each dc-link inductors is 0.1H.

Fig. 8 illustrates current phases of machine. As voltage of terminals machine are not so enough to thyristor's commutations at speeds less than 6% of rated speed, so dc-link pulsing has been applied. Fig. 9 demonstrates line voltage of machine. Applied dc-link pulsing is reason of spiking in primary start up time. Furthermore, injection method causes to produce high frequency at first second of start up. Rotor position with its estimation based on injection and observer method has been shown in fig. 10, 11 .Estimation based on injection method can specify initial position of rotor without any error. At low speed, error value is less than 2 degree except firing pulse generation times. This value rises after firing pulse generation and it does not make problem for firing pulse generation. Average difference between both estimation methods reach less than 2 degree at t=0.99 and switching in feeding field is stopped, after that output based on observer method is applied. When rotor gets speed, error of observer position output reduces to less than 3 degree.

Rotor speed with its estimation is shown in fig.12 and 2000 rpm is considered as final speed. In despite of rotor position, speed has estimated based on observer method at zero speed up to final speed.

Output torque with its average in 0.1 second is shown in fig. 13. It is seem that when machine gets speed and goes to load commutations step, average of torque will be constant which is the principle advantage of vector control way. Fig. 14, 15 illustrates step response of machine speed for 500 rpm as input with and without using clamping. It is 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 mH	$R_s = 0.26\ \Omega$
L_{ls}=1.14mH L_{lf} =2.1mH	$R_f = 0.13\ \Omega$
pole pairs=1	J=25 K.m^2

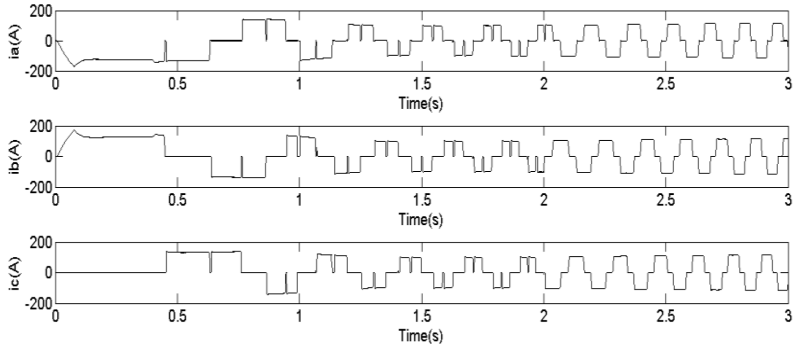

Fig. 8. Machine phase current

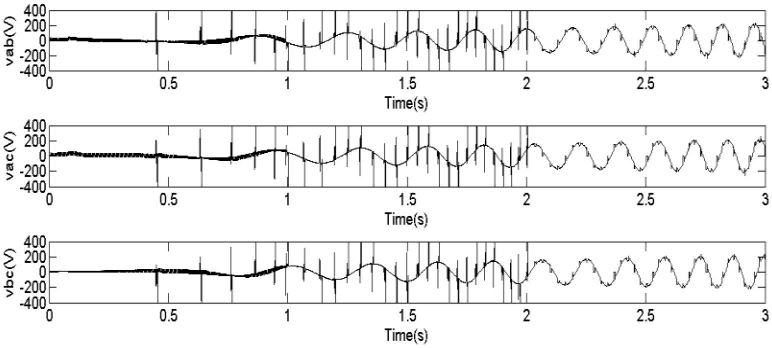

Fig. 9. Machine line voltage

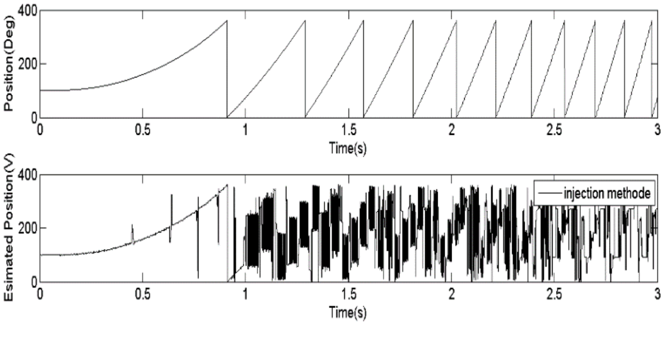

Fig. 10. Position estimation based on injection method

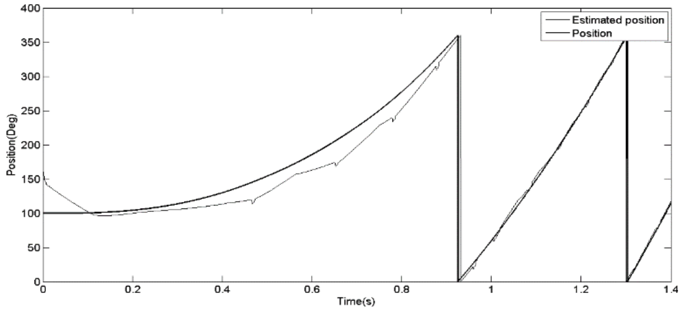

Fig. 11. Position estimation based on observer method

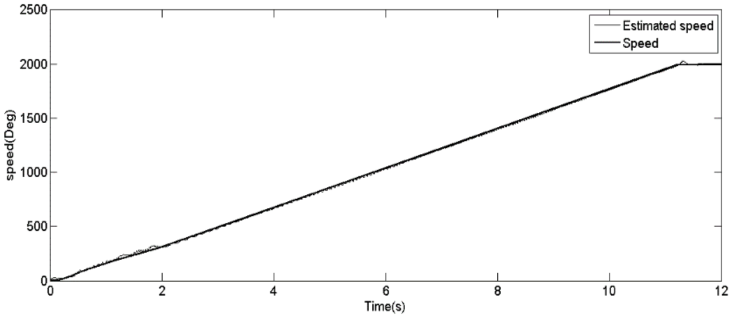

Fig. 12. Real speed with its estimation

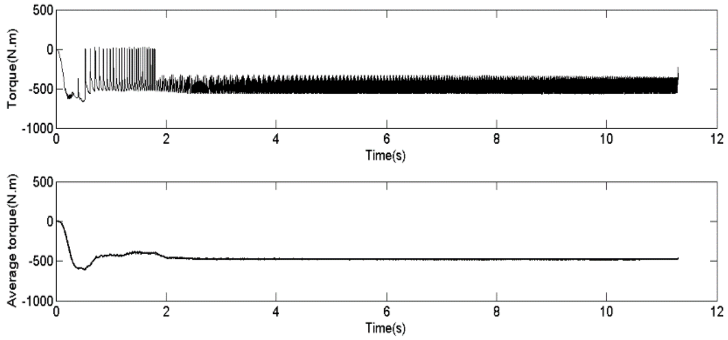

Fig. 13. Output torque and average of that

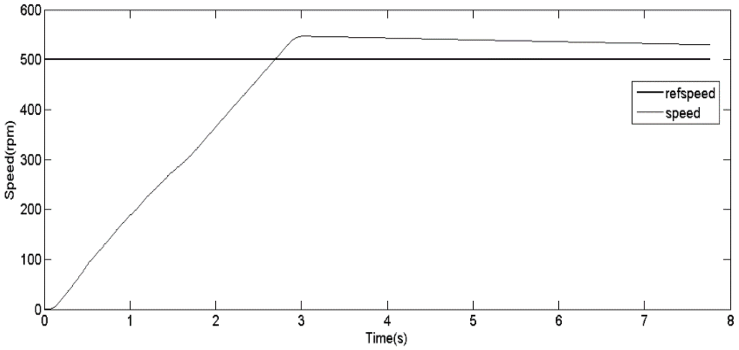

Fig. 14. Speed step response without using clamping

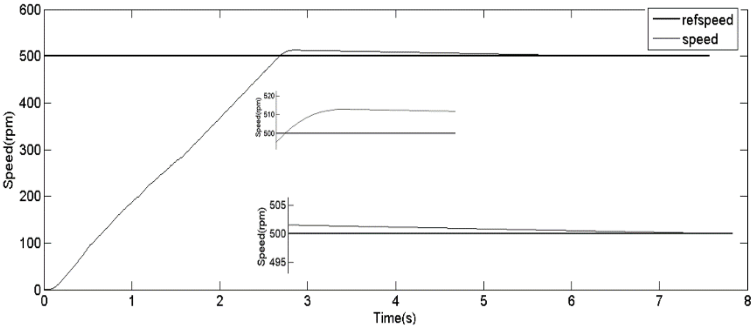

Fig. 15. Speed step response with using clamping

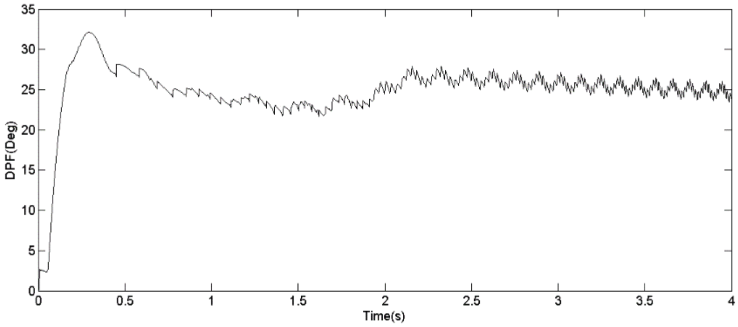

Fig. 16. Power factor angle estimation

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.

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