**Novel Nonlinear Control Structure for Vector Control of SPIM Drive using BS\_PCH**

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| **Article Info** |  | **ABSTRACT** |
| ***Article history:***  Received Apr 17, 2019  Revised Jul 22, 2019  Accepted Aug 3, 2019 |  | This paper presents a novel structure combining the PCH and BS nonlinear control for sensorless vector control of the six phase induction motor (SPIM). The outer speed and flux loop controllers design is based on the BS technique using the integral tracking errors action to improve its robustness. It is different from the research performed on backstepping control with integral action before, the control law used in this proposal does not make the increase of the number of system state so as not increase the complexity of differential equations resolution. To enhance more the performance of SPIMD, PCH scheme is used in the inner current loop controllers. In this proposed PCH current controller, the stabilization of controller is achieved via system passivity. In particular, the interconnection and damping matrix functions of the port-controlled Hamiltonian system are shaped so that the physical (Hamiltonian) system structure is preserved at the closed-loop level and the closed-loop energy function is equal to the difference between the physical energy of the system and the energy supplied by the controller. The proposed control design is based on combination PCH and BS techniques improve significantly performance and robustness. The proposed sensorless speed control scheme is validated through Matlab-Simulink. |
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1. **INTRODUCTION**

In recent decades, the multiphase motor drives are widely used in much applications due to their inherent features such as higher torque density, greater efficiency, reduced torque pulsations, fault tolerance, and reduction in the required rating per inverter leg [1]. Especially, These drives are often considered in some applications such as locomotive traction, electrical ship propulsion, in high power applications such as automotive, aerospace, military and nuclear [2]. With its reliable working characteristics and high failure tolerance nowadays, this motors are even considered in the small power applications requiring high reliability and fault tolerance, where are expected that the loss of one or more phases the machine still can provide a significant electromagnetic torque to continue operating the system. Among the many types of multiphase motors, SPIM is one of the most widely used multiphase motors.

As the three phase induction motor, when uncertainties and disturbances are appreciable, traditional control techniques using PID control for SPIM drives are not able to guarantee optimal performance or can require a considerably time consuming and plant dependent design stage. Therefore, to overcome these drawbacks the nonlinear control techniques have been followed, such as, for instance, linear output feedback control [3,4], Sliding mode (SM) [5-6], Backstepping control (BS) [8-12], Fuzzy Logic (FL) control [13-14] neural networks (NN) control [15-17], predictive control, [18], Hamiltonian control [19-24]. Among these techniques, the BSC design techniques have received great attention due to its systematic and recursive design methodology for nonlinear feedback control. The BSC design can be used to force a nonlinear system to behave like a linear system in a new set of coordinates. The major advantages are that it has the flexibility to avoid cancelations of useful nonlinearities and pursues the objectives of stabilization and tracking. However, the detailed and accurate informations about system dynamics are required when designing traditional BSC. To overcome this drawback many strategies have been proposed, in [25] the authors proposed a new BS control scheme using a dynamical induction motor model based on the tranditional BS control with the unknown of the damping coefficient, the motor inertia, the load torque and the uncertainty of the machine parameters. The tests carried out without applying a load torque. However, the speed ripple and the performance of the tracking the reference speed is not good, and it also does not guarantee a total rejection of the load torque disturbance. In [26,27], an integral version of the control and an adaptive observer using the backstepping technique was proposed. The results show the good performance of the control law and the observer, but it may be noted that the problem with this method is the complexity of solving differential equations, which require more computing time for processor, since the model will be increased by two states. In [10] proposed a BS design method for both the control and observer, by adding the integral error tracking component to increase the stability of the transmission system, this method for good dynamic response, precise controls. However, the torque ripple is recorded as quite large, the performance at low speed range and regenerating modes not reported in [10]. From the above analysis it is easy to see that the BS control, which represents a precise model based control method, was difficult to obtain satisfactory control performance when using independently, especially in the cases applyed to control the nonlinear systems. Therefore, to solve this problem, beside continue to improve BS strategy, another appoach have paid more and more attention to the composite control strategy which combines BS method with other control methods, such as sliding mode control [28-30], neuron network [ 31-35], fuzzy logic system (FLS) [36,37]. In this paper, the author proposes a new combined control structure: The BS controller is applied in outter speed closed loop control, the model parameters of SPIM (Rr, rotor flux) are update the controller to minimize the effect of parameter changes on the controller's performance, the BS-based controller design, the integral error tracking component added to improve its sustainability. In addition, to further enhance the performance of the SPIMD system, the authors proposed a new structure combining BS and PCH, a proposed PCH for inner current control loop to improve performance and ensure the stability, accuracy speed response for the drive system, enhance the robustness for the sensitivity of changes in machine parameters, load disturbance. The effectiveness of this proposed control structure is verified by simulation using MATLAB/ Simulink.

The paper is organized into five sections, in section 2, the basic theory of the model of the SPIM and the SPIM drive are presented. Section 3 introduces the proposed BS\_PCH cotroller. Simulation and discuss are presented in Section 4. Finally, the concluding is provided in Section 5.

**2. MODEL OF SPIM DRIVES**

The system under study consists of an SPIM fed by a six-phase Voltage Source Inverter (VSI) and a DC link. A detailed scheme of the drive is provided in Fig.1. By applying the Vector Space Decomposition (VSD) technique introduced in [18], the original six-dimensional space of the machine is transformed into three two-dimensional orthogonal subspaces in the stationary reference frame (D-Q), ( x - y) and (zl -z2). This transformation is obtained by means of 6 x 6 transformation matrix:

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|  | (1) |

In order to develop SPIM model for control purposes, some basic assumptions should be made. Hence, the windings are assumed to be sinusoidally distributed, the magnetic saturation, the mutual leakage inductances, and the core losses are neglected. The electrical matrix equations in the stationary reference frame for the stator and the rotor may be written as

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|  | (2) |

where: [V], [I], [R], [L] and [Lm] are voltage, current, resistant, self and mutual inductance vectors,  
respectively. P is differential operator. Subscript r and s related to the rotor and stator resistance respectively. Since the rotor is squirrel cage, [Vr] is equal to zero. The electromechanical energy conversion only takes place in the DQ subsystem:

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| --- | --- |
|  | (3) |

where *δr* is the rotor angular position referred to the stator as shown in Fig. 1.

As these equations implies, the electromechanical conversion, only takes place in the D-Q subspace and the other subspaces just produce losses. Therefore, the control is based on determining the applied voltage in the *αβ* reference frame. With this transformation, the 6PIM control technique is similar to the classical three phase IM FOC. The control for the motor in the stationary reference frame is difficult, even for a three phase IM, so the transformation of SPIM model in a dq rotating reference frame to obtain currents with dc components[1] của 1 is necessary, a transformation matrix must be used to represent the stationary reference fame (α-β) in the dynamic reference (d - q). This matrix is given:

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|  | (4) |

The field oriented control (FOC) is the most used strategy in the industrial field. Its objective is to improve the static and dynamic behavior of asynchronous machine unlike the scalar control. It allows decoupling the electromagnetic quantities in order to make the control similar to DC machine. The principle of the FOC is to align the d axis of the rotating frame (Dq(d-q)) with the desired flux as shown in Fig. 1. Therefore, the flux will be controlled by the direct component of the stator current (isd) and the torque by the quadratic component (isq). In this case we obtain:

  
Using Eqs. (1) and (4), the new model motor dynamics is described by the following space vector differential equations:

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| --- | --- |
|  | (5) |

where 

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| Figure 1. A general scheme of an SPIM drive |

The new expression of the electromagnetic torque and the slip frequency are given by:

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| --- | --- |
|  | (6) |
|  | (7) |

**3. THE PROPOSED BS\_PCH COTROLLER FOR VECTOR CONTROL OF SPIM DRIVES**

**3.1. The proposed BS controller for outer speed control and rotor flux loops**

The purpose of this study is to design a simple control law but for high dynamic and establishing performance, eliminating load disturbance and effect of motor parameter variations. The influence from the change of parameters and the load disturbance can be significantly reduced by adding a tracking error integration when designing the BS speed controller and update the rotor resistance for BS control. BS techniques are a systematic and recursive method for synthesizing nonlinear control rules. The stability and performance of the subsystems is studied by Lyapunov theory [2]. Therefore, at each step of the design, a virtual command is created to ensure the convergence of subsystems.



Fig. 2. *The virtual inputs* isq *and* isd*.*

As the rotor speed and flux are the tracking objectives, the tracking errors is defined as

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|  | (8) |

The error dynamical equations are

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|  | (9) |

To obtain the virtual controller of speed and rotor flux loop, the following Lyapunov function candidate is considered:

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|  | (10) |

Differentiating *V* :

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|  | (11) |

where:

, kω, kѰ are positive design constants that determine the closed-loop dynamics. To V' <0, the stabilizing virtual controls are chosen as

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|  | (12) |

We obtain:

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|  | (13) |

The virtual controls in (12) are chosen to satisfy the control objectives and also provide references for the next step of the PCH design. Eq. (12) can be expressed as Fig.2.

**3. 2 The inner current loop controllers using PCH**

A PCH system with dissipation is a representation of the form:

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| |  | | --- | |  | | (14) |

where  represents the dissipation. The interconnection structure is captured in matrix *g*(*x*) and the skew symmetric matrix  , *H*(*x*) is the total stored energy function of the system. We define the state vector, input vector and output vector are as follows, respectively



The Hamiltonian function of the system is given by

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|  | (15) |

Equation of the SPIM be described in a synchronously rotating dq- reference frame (5) can then be rewritten in the PCH form (14) with:

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| |  | | --- | |  | | (16) |

Suppose we wish to asymptotically stabilize the system (19) around a desired equilibrium xo, a closed-loop energy function Hd (x) is assigned to the system which has a strict minimum at x0 (that is, Hd (x) > Hd (x0) for all x . x0 in a neighborhood of x0 ). The feedback stabilization theory of PCH system is given as follows [6]. Given J(x), R(x), H(x) , g(x) and the desired equilibrium xo. Assume we can find a feedback control u = α(x) , Ra(x) ,Ja(x) and a vector function K(x) satisfying:

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| --- | --- | --- |
| |  | | --- | |  | | (17) |

and such that

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| |  | | --- | |  | | (18) |

The closed-loop system:

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|  | (19) |

will be a PCH system with dissipation.

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| |  | | --- | |  | | (20) |

where *Ha* is the energy added to the system and x0 will be a stable equilibrium of the closed-loop system. The expected Hamiltonian energy storage function is defined as

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| |  | | --- | |  | | (21) |
| |  | | --- | | where: | | (22) |
|  | (23) |

where, J1 , r1 and r2 are undetermined interconnect and damping parameters. According to equations (17)-(22), the controller of the current inner loop of the motor is

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| |  | | --- | |  | | (24) |

The rotor flux used in the equation (12), (24) cannot be measured. This component is identified by VM and is presented in section 2.3.

**4. SIMULINK AND DISCUSSION**

In order to verify and evaluate the performance of the BS\_PCH cotrol scheme for vector control of SPIM drive system, as shown in Fig. 6 has been simulated at different speed ranges through Matlab simulation software. Tests in this section are conducted based on recommended benchmark tests [15], [17]. SPIM parameters: 1HP, 220V, 50 Hz, 4 pole, 1450 rpm. Rs = 10.1Ω, Rr = 9.8546Ω, Ls = 0.833457 H, Lr = 0.830811 H, m = 0.783106H, Ji = 0.0088 kg.m2. Rs is nominal value of stator resistance.



**Test 1:** Tracking Reference

Test 1 is conducted based on recommended Benchmark tests in [15]. In this test, the reference speed are imposed from 650 rad/s increased to 125 rad/s at 3s, 50% rated load applied at 6s. The results in Fig 4a shows the tracking reference performance of the BS\_PCH scheme based on vector control is very well. Comparing with [15, Fig.8a], it is easy to see that the BS\_PCH controller give responses faster, more accurate and better the tracking reference performance than PI controller and NN controller in [15, Fig. 7a, Fig. 8a]. The dq stator current and torque responses ( Figs. 4a ) show that the BS\_PCH vector control provides less current and torque oscillations than both the conventional and NN vector control in [15, Fig. 7c,d; Fig. 8c,d]. In order to assess the robustness of the proposed scheme for load disturbance at 6s, observe the speed response in Fig. 4 a we see that error in tracking the speed increase not significantly at 6s, the real speed instantly converges to the reference speed. For test in [15], there was an error in tracking the speed reference for both conventional vector control and NN vector control [15, Fig.7a, Fig.8a], these errors in tracking the speed reference are higher than that appeared in BS\_PCH vector control scheme.

**Test 2:** Detuning Effects

This test is implemented to evaluate the performance of the proposed BS\_PCH vector control under motor parameter variation condition and load disturbance. The extreme conditions are surveyed with the rotor resistance value was setup increased Rr' = 3Rr at 2.5s, the reference speed are imposed from 650 rad/s increased to 125 rad/s at 3s, 50% rated load applied at 6s. Figs. 4b show the speed, torque and current responses of the proposed BS\_PCH vector control scheme, respectively. These simulation results show that the proposed control scheme can provide the performance well when facing the parameter uncertainty and load disturbance. The speed and current responses are almost unaffected until 50% rated load has been applied to motor. When applying load, error speed tracking and ripple current and torque increased slightly. However, comparing to NN control [15, Fig.10a] and conventional PI control in [15, Fig.9a], it is easy to see that the proposed scheme in this paper give better performance, more robustness for the uncertain motor parameter of and load disturbance. The results in Fig. 4b show that the torque and current oscillations of the proposed in this paper less than the conventional PI vector control [15 , Fig. 9(b,c)] and NN control [ 15, Fig.10 (b,c)]. The PCH scheme handle current loops quite efficiently, the compensation function Ha added to keep system always work stably at reference values. The dq stator current responses in extreme condition Rr increased 300%, 50% rated load are better than NN control [15].

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| a. | b. |

Fig 4. BS\_PCH vector control with setting: a. Nominal rotor resistance; b. Rr\*=3Rr

**Test 3**

In Test 3, two cases are examined based on recommend [17, Fig. 7-10].

Case 1, the reference speed changes without load, the results are shown in Figure 5.

Case 2, the speed is fixed at 1000rpm during the survey time, the load torque of 100% is rated at 7s (instead of 75% rated load as [17]), the results are shown in Figure 6.

From the simulation results, we can be seen that the dynamic performance of the BS\_PCH controller is very good. It does not appear the speed and current ripple, the controlled value converges and follow very rapidly the reference value during the survey period (Figure 5; Figure 6). The convergence time of the speed is significantly improved compared to the controller proposed in [17, Fig. 7 c, Fig. 9 c]. On the other hand, when observing effect of the load disturbance at 7s in case 2 (Figure 6 at 7s), it is easy to see its robustness to load disturbances, there is no oscillation or significant speed reduction recorded, compared to the PI controller and the controller proposed in [17, Fig. 9 a] the SM\_FL controller is proposed in [17, Fig. 9 c] to handle better load disturbance, however, the load disturbance still make reduce the speed at 7s then the motor speed converges with a stable reference value.

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| Fig. 5. The speed and torque responses in case of speed variations without load |
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| Fig. 6 The speed and torque responses in case of constant speed |

**5*.* CONCLUSION**

This paper presents a new approach to indirect vector control of induction motors. Two nonlinear controllers, one of Backstepping control (BSC) and the other Port Controlled Hamiltonian (PCH) define a new control structure for vector control of SPIM drive systemt, enables very good static and dynamic performance of the sensorless drive system (perfect tuning of the speed reference values, fast response of the motor current and torque, high accuracy of speed regulation), and robust for the machine parameter variations, load disturbances. The simulation results and discussion in section 4 confirmed the good dynamics and robustness of the proposed control algorithm based on the BS\_PCH.

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