

Decoupled Vector Control of Series-Connected Synchronous Motor

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Abstract--Series Connected Synchronous Motor (SCSM) is a slip ring induction motor whose stator and rotor windings are connected in series. This motor runs synchronously with supply frequency at double nominal speed when runs as normal induction motor (IM). Like synchronous motors, this motor is not self starting and it starts with the same methods as the conventional synchronous motor. This motor is suitable for high speed applications. With a suitable controller and inverter, IM is capable of a fast torque response, peak torque of several times the rated torque. In this paper, a decoupled vector control for SCSM drive has been introduced. The vector control drive provides a wide range of speeds, high torque capability and high efficiency.

Keywords--Series connected synchronous motor, decoupled vector control, induction motor, and synchronous motor.

I. NOMENCLATURE

The symbols used in this paper are as follows:

i_{ar}, i_{br}, i_{cr}	: rotor currents in phases a, b and c, A
i_{as}, i_{bs}, i_{cs}	: stator currents in phases a, b and c, A
i_{dr}, i_{qr}	: rotor currents in q-d axes respectively, A
i_{ds}, i_{qs}	: stator currents in q-d axes respectively, A
i_d, i_q	: currents in the q-d axes respectively, A
L_d, L_q	: self inductance of d & q axes respectively, H
L_s, L_r	: stator & rotor self inductance respectively, H
M	: mutual inductance between rotor & stator, H
p	: number of machine poles
P	: differential operator
R_s, R_r, R_a	: stator, rotor and armature resistances, Ω
v_{ds}, v_{qs}	: stator voltages in the q-d axes
v_{dr}, v_{qr}	: rotor voltages in the q-d axes
v_d, v_q	: voltages in the q-d axes
ω	: angular speed, rad/s
T_L	: load torque, Nm
θ	: angle between d-axis and stator a_s -axis
	: angle between d-axis and rotor a_r -axis

II. INTRODUCTION

The principle of operation of the series connected synchronous machines for generator mode of operation was studied and analyzed using d-q model [1], Floquet theory [2] and phasor diagram [3]. SCSM is basically a three phase slip ring induction machine whose stator and rotor windings are connected in series with sequence of two phases reversed as shown in Fig. 1. With reference to Fig. 2, synchronous mode of operation is possible when stator and rotor MMFs rotate synchronously opposite to each other at an absolute speed equal to half rotor speed. This machine is capable of operating at higher speeds than conventional induction or synchronous motors fed by same supply frequency. Since rotor and stator windings are connected in series, this machine can operate at higher voltage levels without

affecting conductor insulation requirements. Theory and analysis of SCSM was presented in [4]. It was reported that after pulling out of synchronism, the motor still operates at less than synchronous speed. In a later paper [5], transient performance of series connected induction motors at less than synchronous speed was explained. Theory and analysis based on a d-q model has been presented in [6]. Whereas, in [7], the motor mode of operation for series connected machines has been studied based on a phasor diagram representation.

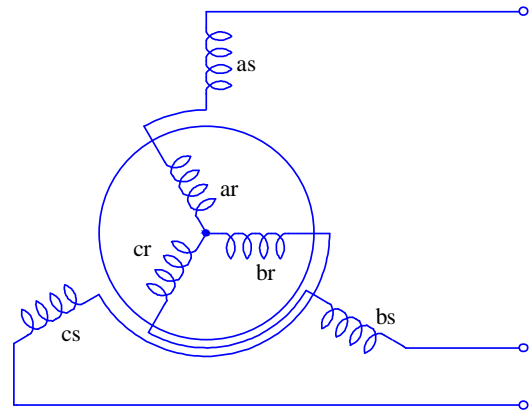


Fig. 1 Schematic diagram of SCSM

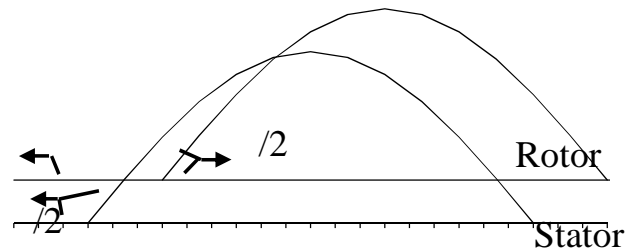


Fig. 2 Stator and rotor MMF's

In order to control the SCSM, position and speed sensors are indispensable because both current and voltage should be controlled depending on the rotor position. The decoupled vector control technique can be used so that the SCSM can achieve the dynamic performance capabilities of the separately excited DC machine, while retaining the general advantages of AC over DC motors. Moreover, the vector control drive provides a wide range of speeds, high torque capability and high efficiency. However, conventional vector control of SCSM drives requires a motor position sensor to correctly orient the current vector orthogonally to the flux. In such a way, it is possible to directly control the torque by acting simply on the amplitude of the stator current. Thus, a high degree of torque control over a wide speed range including the standstill can be achieved [9]. In the present paper, a decoupled vector control for SCSM drive is introduced. Vector control of SCSM not only can achieve

fast dynamic response with less complexity and parameter-independent controller, but also can prevent demagnetization of the motor and allow maximum efficiency operation.

II. D-Q MODEL REPRESENTATION

To analyze this machine, a reference frame rotates synchronously with stator and rotor MMFs is chosen. Since the rotor actually rotates at double reference frame speed and with reference to Fig. 3, the following relation holds for every rotor position:

$$i_{ds} = i_{dr} \quad (1)$$

Reversing stator and rotor phase sequence windings is expressed mathematically by [6]:

$$i_{abc_r} = -i_{abc_s} \quad (2)$$

Equivalent stator and rotor d-q currents in terms of actual phase currents and mutual displacements are given by the well known transformations [7]:

$$\begin{aligned} i_{ds} &= \frac{2}{3} \cos \theta_s : \cos s < \frac{2f}{3} & \cos s > \frac{2f}{3} & i_{ar} \\ i_{qs} &= \frac{2}{3} \sin \theta_s : \sin s < \frac{2f}{3} & \sin s > \frac{2f}{3} & i_{cr} \end{aligned} \quad (3)$$

and

$$\begin{aligned} i_{ds} &= \frac{2}{3} \cos \theta_r : \cos r > \frac{2f}{3} & \cos r < \frac{2f}{3} & i_{as} \\ i_{qs} &= \frac{2}{3} \sin \theta_r : \sin r > \frac{2f}{3} & \sin r < \frac{2f}{3} & i_{bs} \end{aligned} \quad (4)$$

Substituting by (1) and (2) into (3) and comparing the result with (4) yield:

$$\begin{aligned} i_{ds} &= i_{dr} = i_d \\ i_{qs} &= -i_{qr} = i_q \end{aligned} \quad (5)$$

Implementing the conditions derived in (5) to the d-q model results in the interconnections between axes equivalent coils shown in Fig. 4. It is seen that:

$$\begin{aligned} v_d &= v_{ds} < v_{dr} \\ v_q &= v_{qs} > v_{qr} \end{aligned} \quad (6)$$

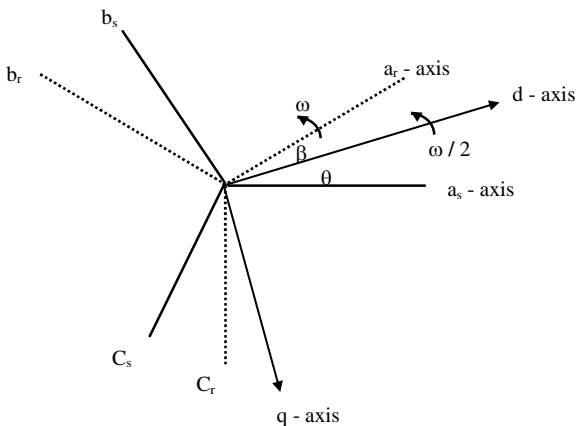


Fig. 3 Axis of 2-pole, 3-phase symmetrical SCSM

The relation between d-q axes voltages and currents can be expressed as [8]:

$$\begin{aligned} v_d &= R_a i_d + L_d \frac{di_d}{dt} - L_q P_n i_q \\ v_q &= R_a i_q + L_q \frac{di_q}{dt} + L_d P_n i_d \end{aligned} \quad (7)$$

where

$$\begin{aligned} R_a &= R_s < R_r \\ L_d &= L_s < L_r < 2M \\ L_q &= L_s < L_r > 2M \end{aligned} \quad (8)$$

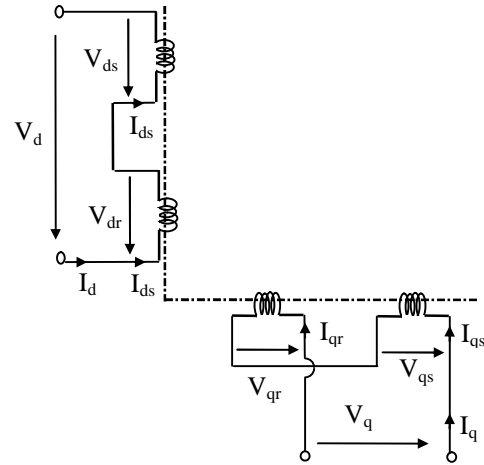


Fig. 4 Basic circuit model of the SCSM.

The series connection between stator and rotor phase windings resulted in effective saliency as indicated by the difference in axes inductances which shows synchronous operation of this machine.

III. DECOUPLED VECTOR CONTROL

Torque control in AC machines can be achieved by controlling the motor current. In contrast to the DC machines, in an AC machine, both the magnitude and phase angle of the stator current need to be controlled [10]. This is achieved by defining a time-varying vector which corresponds to a sinusoidal flux wave moving in the air gap of the machine. When referring the mmf wave of the stator current to this flux wave, it is realized that only the quadrature axis component of the mmf wave is contributing to the torque, whereas the direct axis component affects the magnitude of the flux. Hence, the stator current phasor is defined in a frame of reference defined by the time-varying field or in field coordinates [11]. This indicates a close correspondence to the DC machines, with the direct axis component of the stator current vector being analogous to the field current and the quadrature axis component to the armature current [12].

Vector control provides decoupled control of the rotor flux magnitude and the torque producing current, with a very fast, near step response in torque achievable. The vector control method applies stator current amplitude and position control, allowing near instantaneous change in the phase of the currents. So, in special reference frame, the expression for the electromagnetic torque of the smooth air-gap machine is similar to that of the separately excited DC machine. This suggests that torque control of the series connected synchronous machine can be performed by the decoupled control of the flux-and torque-producing components of the stator currents, which is similar to

controlling the field and armature currents in the separately excited DC machine [13].

The stator current phasor in the d-q axis synchronously rotating frame has two components, namely the magnetizing current component and torque producing current component. The generated torque is the product of two components [14]. By keeping the magnetizing current component at value, the motor torque is linearly proportional to the torque producing component, which is similar to the control of a separately excited DC motor. It is to be noted that the stator can be adjusted by controlling the d-q axis current components. In order to achieve maximum torque per ampere with linear characteristics, i_d is adjusted to a certain value, resulting in the orientation of all the linkage flux in the d-axis. Hence, a constant torque can be obtained by ensuring that i_d is kept constant [15].

IV. SYSTEM DYNAMIC EQUATIONS

Substituting p operational operator $= 0$ (steady state condition), the general SCSM dynamic equations (7) will tend to [16]:

$$v_d \approx R_a i_d + \dot{\psi}_q \quad (9)$$

$$v_q \approx R_a i_q + \dot{\psi}_d \quad (10)$$

And the electromechanical torque will be:

$$T_L \approx \frac{3}{2} \frac{p}{2} \psi_d i_q \quad (11)$$

Hence, the electric torque depends only on the quadrature axis current i_q . A constant torque can be obtained by ensuring that i_q is kept constant at a certain negative value since this machine has a negative saliency [17].

V. TRANSIENT PERFORMANCE OF DECOUPLED VECTOR CONTROLLED SCSM

The stator of the SCSM has to be supplied from an inverter, which converts a DC voltage to AC variable voltage, the frequency of which corresponds to the speed of the rotor. Therefore, a computer simulation is conducted to attain the SCSM model in abc (3-phase) and dq0 (two-axis) frames as shown in Fig. 5. The voltages and currents can be detected. The actual speed is compared to the speed reference and the speed error is processed in the PI speed controller to obtain the torque component of the current reference i_q^* . The main algorithm of the conventional vector control is to decouple the air gap flux and torque channels in the drive system; this can be performed by decoupling the two components of that current, one producing the air gap flux and the other producing the torque. Therefore, an independent control of torque and flux is achieved. In order to realize this required decoupling; the flux producing component of current i_d should be forced to a certain negative value, resulting in the orientation of all the linkage flux in the d-axis [18].

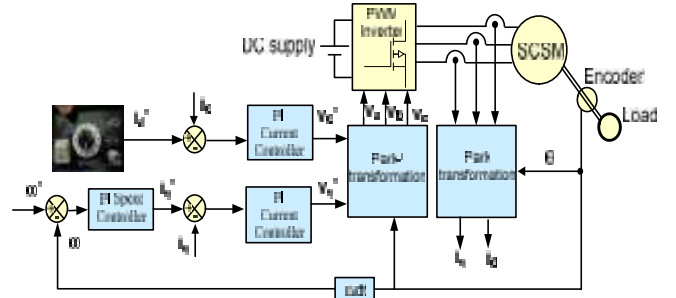


Fig. 5 Block diagram of the decoupled vector-controlled SCSM drive system.

A. Effect of varying the speed while maintaining load torque

A step change from a speed of 528 rad/sec to a motor speed of 100 rad/sec was applied at time 0.5 second, while keeping the load torque constant at $T_L=1.94$ Nm. Fig. 6 shows the behavior of the system according to the step change of the speed command signal while maintaining constant torque.

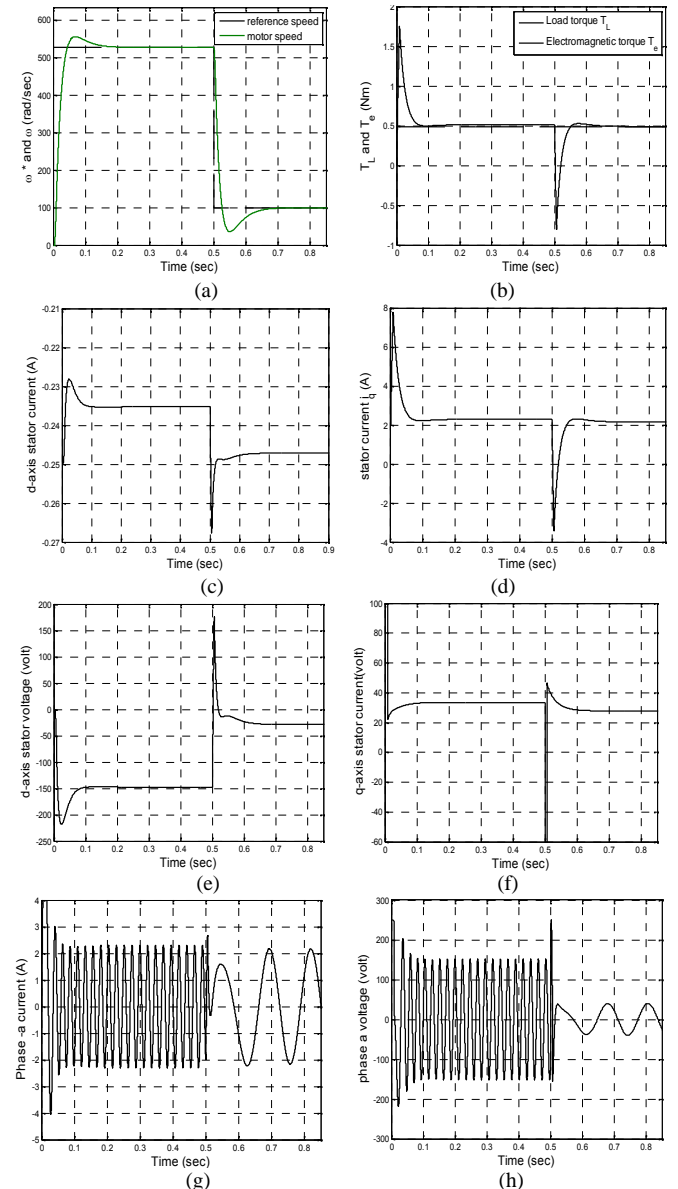


Fig. 6 Relationship between time and: (a) ω^* and ω , (b) T_L and T_e , (c) i_d , (d) i_q , (e) v_d , (f) v_q , (g) i_a , (h) v_a .

From the above figure, it is noted that:

- i. The motor output speed responds fast to the command signal.
- ii. Since i_d is the flux producing component of stator current, it remains constant (condition of vector control), regardless of any variation in the speed.
- iii. Since i_q is the torque-producing component of current, it is affected by the load change and not the speed change. Therefore i_q remains constant.
- iv. The peak value of the sinusoidal phase-a-current i_a remains constant due to the constancy of both i_q and i_d but its frequency will change [19].
- v. The phase a voltage v_a decreases due to the decrease of the command speed.

B. Effect of varying the load torque while maintaining constant speed

A step change from 1.94 to 0.75 Nm is applied to the load command signal T_L at time 0.4 sec, while keeping the command speed constant at 250 rad/sec. Fig. 7 shows the behavior of the system according to the step change of the command load torque T_L , while maintaining constant speed.

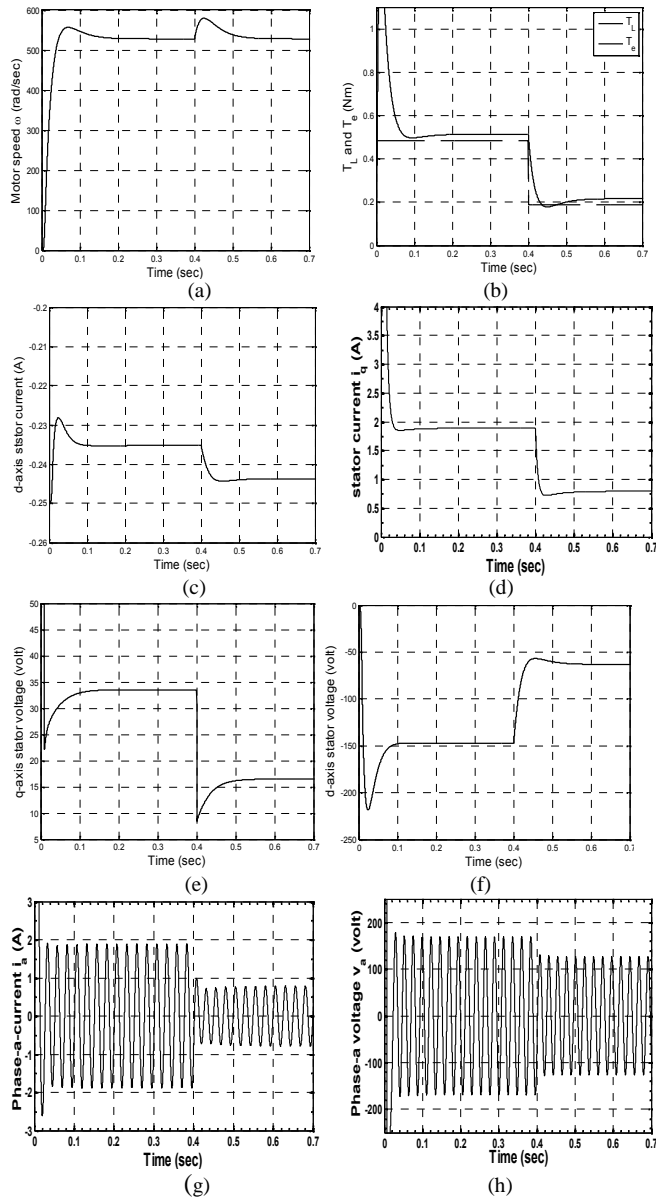


Fig. 7 Relationship between time and: (a) Motor speed ω , (b) T_L and T_e , (c) i_d , (d) i_q , (e) v_q , (f) v_d , (g) i_a , (h) v_a .

From the above figures, it is clear that:

- i. The electromechanical torque responds fast to the command load torque.
- ii. The d-axis stator current i_d remains constant, when varying the load torque.
- iii. The q-axis stator current i_q increases due to the increase of the load torque. This response is analogous to the separately excited DC motor where $T_{dc} \propto I_a I_f$. The behavior of the IPMSM becomes exactly like that of the DC motor where $T \propto i_q i_d$.
- iv. The peak value of the sinusoidal phase-a-current i_a , will increase, while its frequency remains constant. From the above discussion, i_q will increase due to the increase of the torque and i_d will remain constant, consequently, the magnitude of i_a will increase [20].
- v. The phase a voltage v_a decreases slightly according to the decrease of the load torque.

In vector control system, both flux and torque control the magnitude and frequency of stator voltage and current through a coordinate change in a manner such that the coupling effect in SCSM is avoided.

VI. CONCLUSION

Generalized machine theory was applied for SCSG and d-q model was presented. The model introduced machine, and load representations. D-Q model evaluates performance at transient and steady state. The results can be considered as useful guides to operate and design three phase SCSM. Simulation results show validity of the model to analyze transient state. A decoupled vector control for SCSM drive has been presented. One of the most important advantages of the vector control is its ability to change the magnitude, the frequency, and the phase angle of the phase supply voltages. Thus, by applying field oriented control to the series connected synchronous machine, it will behave exactly like a separately excited DC machine, due to the independent control of flux and torque. The simulation results verify that using the vector control method, the SCSM can be operated over a wide speed range, including near zero speed, with rapid, accurate torque control and perfect momentary overload capabilities.

VIII. REFERENCES

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IX. APPENDIX

TABLE I.
SCSM RATING

Poles	4
Rated Power	600 W
Nominal voltage	220 V
frequency	50 Hz
Rated p.f	0.85