Fuzzy Logic Based Speed Control of a Five-Phase Series-Connected Two-Motor Drive System Fed from SVPWM VSI

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Abstract

A five-phase two-motor drive system with series connection of stator windings and decoupled dynamic control is considered in the present paper. The two-motor drive system is supplied from a single five-phase Space Vector Pulse Width Modulation (SVPWM) Voltage Source Inverter (VSI) and controlled using vector control scheme, provided that the stator windings are connected in series with appropriate phase transposition. The concept has been developed under the assumption that the inverter voltages are controlled in the stationary dq-reference frame. A fuzzy logic based speed controller has been constructed and used to drive the two-motor in this work. The two-motor system, inverter system, and the fuzzy controller models are implemented and tested using Simulink/Matlab facilities. The presented results show the validity of the model to do well for the sake of speed control under different operating conditions.

السيطرة على سرعة منظومة ثنائية المحركات توالي الربط خماسية الاطوار مجهزة بالقدرة من SVPWM VSI باستعمال تقنية السيطرة المضببة

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الخلاصة

يتناول هذا البحث طريقة السيطرة الديناميكية المنفصلة على سرعة منظومة ثنائية المحركات خماسية الاطوار توالي الربط لملفات الاجزاء الساكنة. منظومة المحركات مجهزة بالقدرة من SVPWM VSI مسيطر عليه بطريقة المتجه وعلى شرط ان تكون اطوار المحركات مربوطة بترتيب مناسب . تم السيطرة على سرعة المحركات بواسطة السيطرة على فولتيات المبدل باستعمال الهيكل المرجعي dq الثابت. تم بناء منظومة سيطرة مضببة من أجل السيطرة على سرعة المحركات المستعملة في هذا البحث. ان تمثيل وفحص النموذج الرياضي للمحركات ومجهز القدرة ومنظومة السيطرة تم باستعمال برامجيات Simulink/Matlab. تبين النتائج المقدمة في البحث على قابلية المسيطر المضبب في التحكم بسرعة منظومة المحركات تحت مختلف الظروف التشغيلية.

1. Introduction

Ever since the inception of the first five-phase variable speed drive in 1969, five-phase machines have been considered as a good alternative to three-phase machines. This especially holds true for high-power and safety-critical variable speed applications, where a five-phase drive can be realized using inverters with smaller rating per leg[1,2]. Five-phase (and multiphase in general) machines also enable an improvement in the noise characteristics of the drive, a reduction in the stator winding losses, and hence an improvement in the efficiency, and torque ripple minimization[2,3].

As far as series connection of multi-phase machines is concerned, it is shown that a specific method of stator winding series connection leads to the placement of the flux/torque producing equivalent circuits of the two machines in two orthogonal and therefore mutually decoupled subspaces of the five-phase system[2].

On the basis of considerations, mentioned in [4], concerning the way and number of the multi-phase machines that can be connected in series for the specified number of supply phases, one can conclude that for a five-phase supply (n=5) it is possible to connect two five-phase machines in series and supply them from a single five-phase source. By introducing an appropriate phase transposition in this series connection, it was reasoned that the two machines could be controlled completely independently, using basic vector control schemes, although they are supplied from the common five-phase source. The major advantage of such a two-motor drive system is the reduction of the number of required inverter legs, when compared to an equivalent two-motor three-phase drive system (from six to five). This translates into increased reliability, due to a smaller number of components[1].

The connection diagram for a five-phase series-connected two-motor drive is shown in Fig.1[1]. The phase transposition introduced in the series connection of the two five-phase stator windings makes flux/torque producing currents of one machine non-flux/torque producing currents for the other machine, and vice versa [5,6]. Capital letters denote the inverter phases, while lower case letters identify the motor phases, according to the spatial distribution of phases.

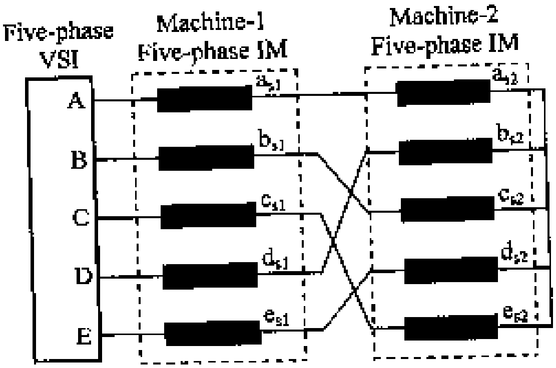

Fig.1 Five-phase series-connected two-motor drive system.

Many efforts have been carried out to analyze and control multi-phase series-connected motors for even[7-12] and odd[1,2,5,13-15] number of phases. All these efforts deal with field oriented models of the series-connected motors. Also, they use indirect (feed-forward) rotor flux-oriented controllers for the sake of speed control of the used series-connected motors. The control is performed through controlling the VSI supply system.

In the present work, dq stationary reference frame models are derived for the five-phase series-connected two-motor system under consideration and the used SVPWM VSI supply system. These models ensure full decoupling of control of the two motors.

A PD-like fuzzy + I controller will be used, instead of indirect rotor flux-oriented controller, to perform closed loop speed control of the motors.

2. Model of the two-motor drive

Inverter phase-to-neutral voltages are related to individual machine phase voltages through:

$$\underline{v}^{INV} = \begin{bmatrix} v_A \\ v_B \\ v_C \\ v_D \\ v_E \end{bmatrix} = \begin{bmatrix} v_{as1} + v_{as2} \\ v_{bs1} + v_{cs2} \\ v_{cs1} + v_{es2} \\ v_{ds1} + v_{bs2} \\ v_{es1} + v_{ds2} \end{bmatrix} \qquad \ldots(1)$$

Where indexes "1" and "2" identify the two machines in Fig.1 and index "s" stands for stator. Relationships between source currents and individual stator phase currents of the two motors are (with the aid of Fig.1):

$$\bar{i}^{INV} = \bar{i}_{s1} = \begin{bmatrix} i_A \\ i_B \\ i_C \\ i_D \\ i_E \end{bmatrix} = \begin{bmatrix} i_{as1} \\ i_{bs1} \\ i_{cs1} \\ i_{ds1} \\ i_{es1} \end{bmatrix} = \begin{bmatrix} i_{as2} \\ i_{cs2} \\ i_{es2} \\ i_{bs2} \\ i_{ds2} \end{bmatrix} \quad \ldots(2)$$

The procedures mentioned in [1,2,16] can be followed with Eqs.(1) and (2) to reach the dq stationary reference frame model of the five-phase series-connected two-motor drive:

$$v_d^{INV} = (R_{s1} + R_{s2})i_d^{INV} + (L_{ls1} + L_{ls2} + L_{m1})\frac{di_d^{INV}}{dt} + L_{m1}\frac{di_{r1d}}{dt}$$

$$v_q^{INV} = (R_{s1} + R_{s2})i_q^{INV} + (L_{ls1} + L_{ls2} + L_{m1})\frac{di_q^{INV}}{dt} + L_{m1}\frac{di_{r1q}}{dt}$$

$$v_x^{INV} = (R_{s1} + R_{s2})i_x^{INV} + (L_{ls1} + L_{ls2} + L_{m2})\frac{di_x^{INV}}{dt} + L_{m2}\frac{di_{r2d}}{dt}$$

$$v_y^{INV} = (R_{s1} + R_{s2})i_y^{INV} + (L_{ls1} + L_{ls2} + L_{m2})\frac{di_y^{INV}}{dt} + L_{m2}\frac{di_{r2q}}{dt}$$

$$0 = R_{r1}i_{r1d} + (L_{lr1} + L_{m1})\frac{di_{r1d}}{dt} + L_{m1}\frac{di_d^{INV}}{dt} + \omega_{r1}\left[(L_{lr1} + L_{m1})i_{r1q} + L_{m1}i_q^{INV}\right]$$

$$0 = R_{r1}i_{r1q} + (L_{lr1} + L_{m1})\frac{di_{r1q}}{dt} + L_{m1}\frac{di_q^{INV}}{dt} - \omega_{r1}\left[(L_{lr1} + L_{m1})i_{r1d} + L_{m1}i_d^{INV}\right]$$

$$0 = R_{r2}i_{r2d} + (L_{lr2} + L_{m2})\frac{di_{r2d}}{dt} + L_{m2}\frac{di_x^{INV}}{dt} + \omega_{r2}\left[(L_{lr2} + L_{m2})i_{r2q} + L_{m2}i_y^{INV}\right]$$

$$0 = R_{r2}i_{r2q} + (L_{lr2} + L_{m2})\frac{di_{r2q}}{dt} + L_{m2}\frac{di_y^{INV}}{dt} - \omega_{r2}\left[(L_{lr2} + L_{m2})i_{r2d} + L_{m2}i_x^{INV}\right]$$

$$T_{e1} = P_1 L_{m1}\left[i_{r1d}i_q^{INV} - i_{r1q}i_d^{INV}\right] \quad \ldots(3)$$

$$T_{e2} = P_2 L_{m2}\left[i_{r2d}i_y^{INV} - i_{r2q}i_x^{INV}\right]$$

The motor-load torque equation is:

$$T_{ek} = J_k\frac{d\omega k}{dt} + F_k\omega_{rk} + T_{lk} \quad \ldots(4)$$

where:

v_d^{INV} and v_q^{INV} =Inverter "d" and "q" voltages.

v_x^{INV} and v_y^{INV} =Inverter "x" and "y" voltages.

i_d^{INV} and i_q^{INV} =Inverter "d" and "q" currents.

i_x^{INV} and i_y^{INV} =Inverter "x" and "y" currents.

R_{sk}= Machine-k stator resistance.

L_{lsk}=Machine-k stator phase leakage inductance.

L_{mk}=2.5M_k.

M_k=Mutual inductance between stator phases of machine-k.

i_{rkd} and i_{rkq} =Machine-k d and q rotor currents.

ω_{rk}=Machine-k rotor angular speed.

T_{ek}=Electromagnetic developed torque of machine-k.

P_k=Number of poles of machine-k.

J_k=Moment of inertia of machine-k.

F_k=Viscous friction constant of machine-k.

T_{lk}=Load torque of machine-k.

k=1 or 2 (machine-1 or machine-2).

System of Eqs.(3) and (4) represents the qd stationary reference frame model of the two series-connected motors. This model is implemented using Simulink/Matlab softwares. The motors parameters are given in the Appendix.

3. Space vector modulation scheme for five-phase VSI

Power circuit topology of a five-phase voltage source inverter is shown in Fig.2. The inverter input dc voltage (2E) is regarded as being constant.

The model of the five-phase VSI power circuit can be developed through analyzing inverter circuit shown in Fig.2. This leads to the following relationships between load's phase-to-neutral voltages and inverter leg voltages[17,18]:

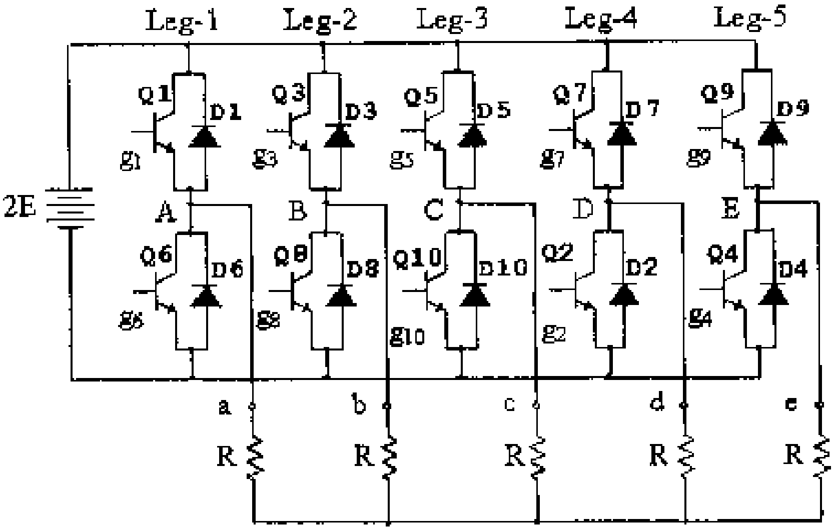

Fig.2 Five-phase voltage source inverter power circuit.

$$
\begin{aligned}
v_a &= (4/5)v_A - (1/5)(v_B + v_C + v_D + v_E) \\
v_b &= (4/5)v_B - (1/5)(v_A + v_C + v_D + v_E) \\
v_c &= (4/5)v_C - (1/5)(v_A + v_B + v_D + v_E) \\
v_d &= (4/5)v_D - (1/5)(v_A + v_B + v_C + v_E) \\
v_e &= (4/5)v_E - (1/5)(v_A + v_B + v_C + v_D)
\end{aligned} \qquad \ldots(5)
$$

Where the inverter leg voltages (v_A to v_E) take the values of ± 0.5 of the DC supply. The DC voltage "E" is taken to be 360 V.

Since a five-phase VSI is under consideration, one has to deal here with five-dimensional space. Hence two space vectors have to be defined, each of which will describe space vectors in one two-dimensional subspace (αβ and xy)[17]. The third subspace is a zero sequence space vector. This zero sequence subspace cannot be excited due to assumed star connection of the system.

Space vectors of phase voltages are defined in stationary reference frame, using power-invariant transformation, as[17,18]:

$$
\begin{aligned}
\overline{v}_{\alpha\beta} &= \frac{2}{5}\left[\overline{v}_a + \overline{a}\,\overline{v}_b + \overline{a}^2\,\overline{v}_c + \overline{a}^3\,\overline{v}_d + \overline{a}^4\,\overline{v}_e\right] \\
\overline{v}_{xy} &= \frac{2}{5}\left[\overline{v}_a + \overline{a}^2\,\overline{v}_b + \overline{a}^4\,\overline{v}_c + \overline{a}^6\,\overline{v}_d + \overline{a}^8\,\overline{v}_e\right] \\
&= \frac{2}{5}\left[\overline{v}_a + \overline{a}^2\,\overline{v}_b + \overline{a}^4\,\overline{v}_c + \overline{v}_d + \overline{a}^3\,\overline{v}_e\right]
\end{aligned} \qquad \ldots(6)
$$

where $\overline{a} = 1\underline{/72^\circ}$

Using Eqs.(5) and (6), one can write 2^5 space vectors for αβ-subspace and 2^5 space vectors for the xy-subspace. These 32 cases for each subspace represent the different combinations of the on/off states for the ten switches of the five-phase VSI. If the upper switch of the VSI is triggered, then the inverter leg voltage takes of value 'E". While, if the lower switch is turned on, then a voltage of "-E" is assigned to the leg voltage.

These space vectors have four magnitudes: Large magnitude with 0.6472 p.u. value (v_l), medium magnitude with 0.4 p.u. value (v_m), small magnitude with 0.2472 p.u. value (v_{sm}), and zero magnitude space vectors. The angle between adjacent space vectors is 36° which is half the angle of spatial displacement of the five-phase machine windings. αβ and xy space vectors are shown in Figs.3 and 4.

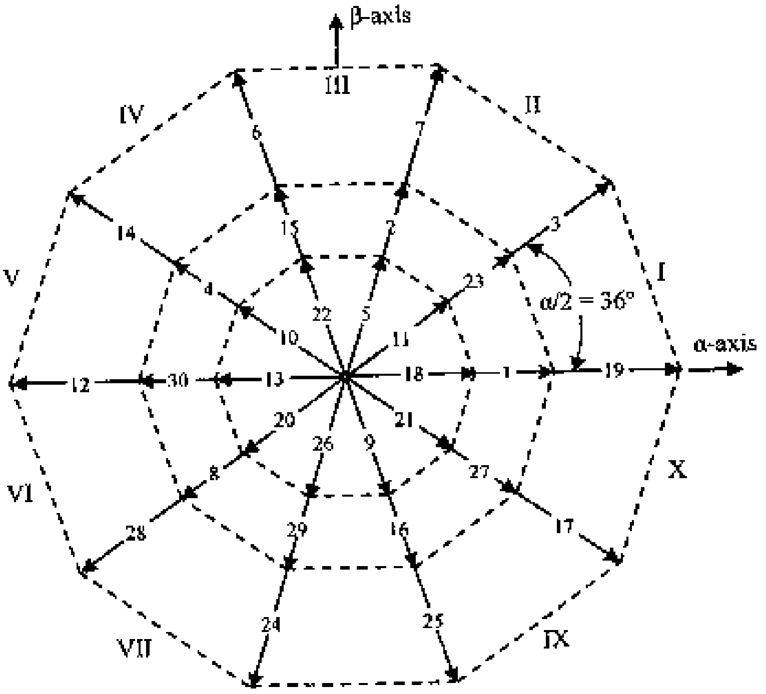

Fig.3 Five-phase VSI phase voltage space vectors in the α-β plane.

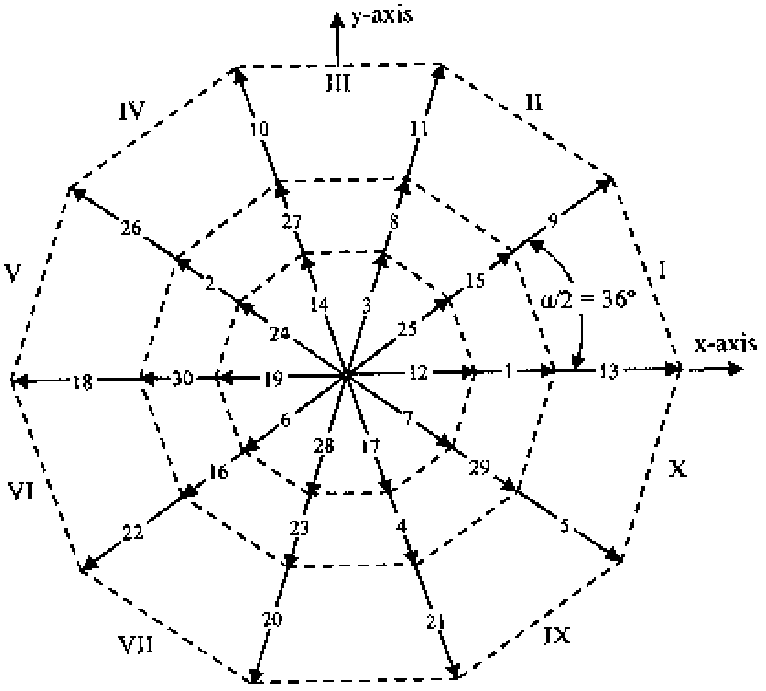

Fig.4 Five-phase VSI phase voltage space vectors in the x-y plane.

The number of active space vectors, either for αβ or xy-subspaces, which can be utilized for each sector in a five-phase VSI is four. Thus, two large and two medium space vectors are used for each sector[19].

The switching pattern and the sequence of the space vectors that utilize two medium and two large neighboring space vectors for sector-I in αβ-subspace is shown in Fig.5. The remaining sectors for the two subspaces can be constructed in a similar manner.

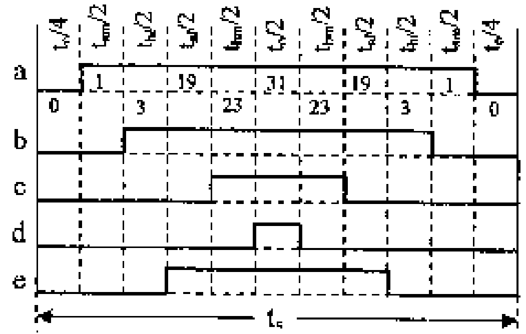

Fig.5 Switching pattern (sector-I) with utilization of medium and large neighboring space vectors for αβ-subspace.

The times t_o, t_{am}, t_{bm}, t_{al}, and t_{bl} are the times of application of zero, medium, and large space vectors. These times can be calculated using the method mentioned in reference [17]. These times control the width of the on/off states of the ten inverter switches during each switching cycle (t_s), i.e, control the switching pulses width (PWM).

A Simulink model for the generation of the inverter switching pulses in the αβ and xy planes for the five-phase VSI can be constructed using Figs.4 and 5, the switching patterns for the ten sectors for the two subspaces, and the equations that calculate the times of application of different space vectors.

The whole Simulink model of the VSI supply system is shown in Fig.6.

Where:

v^*_{s1} is the reference voltage for αβ-plane switching pulses generator.

v^*_{s2} is the reference voltage for xy-plane switching pulses generator.

f_k is the operating frequency of machine-k.

st_k is a trigger pulse to prevent sudden change of the space vector angle of machine-k..

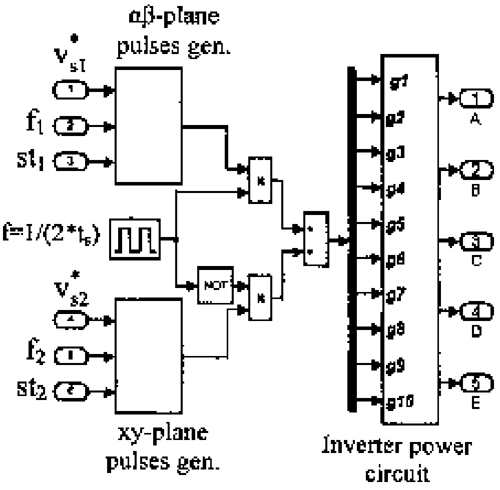

Fig.6 The whole Simulink model of the VSI supply system.

The five-phase output voltages from this model are transformed to qd and xy components in order to match with the dq model of the five-phase series-connected two-motor system. This transformation is done using the abc/αβ decoupling power invariant transformation matrix[1,2].

4. PD-like fuzzy + I speed controller

In this work two Proportional Derivative (PD) fuzzy + Integral (I) speed controllers are used to do the task of closed loop control of the two-motor drive. The simulink model of this PD-like fuzzy + I controller is shown in Fig.7. The fuzzy part of this controller, i.e., PD-controller, has to deal with two signals, the normalized error $\dot{e}(t)$ and the change of normalized error $\Delta\dot{e}(t)$ signals. For any pair of these two signals, it should work out the required control normalized command signal $\dot{v}_{sk}$.

The Direction control output of this model is used for speed direction control. If it is equal to 1, the motor will rotate in a specified direction, while, if it is -1, a reverse rotation results. The idea beyond this is through changing the sign of the angular frequency. This is equivalent to motor supply phase sequence changing. If this output is zero, the motor will stop.

From this model:

K_n is the normalization factor.

K_{dn} is the denormalization factor.

K_p is the proportional gain factor.

K_d is the derivative gain factor.

K_i is the integral gain factor.

This PD-like fuzzy + I controller has an integrator with positive edge reset of the signal "Start". This reset is important in the case of speed reversal. The reset will be accomplished near zero speed.

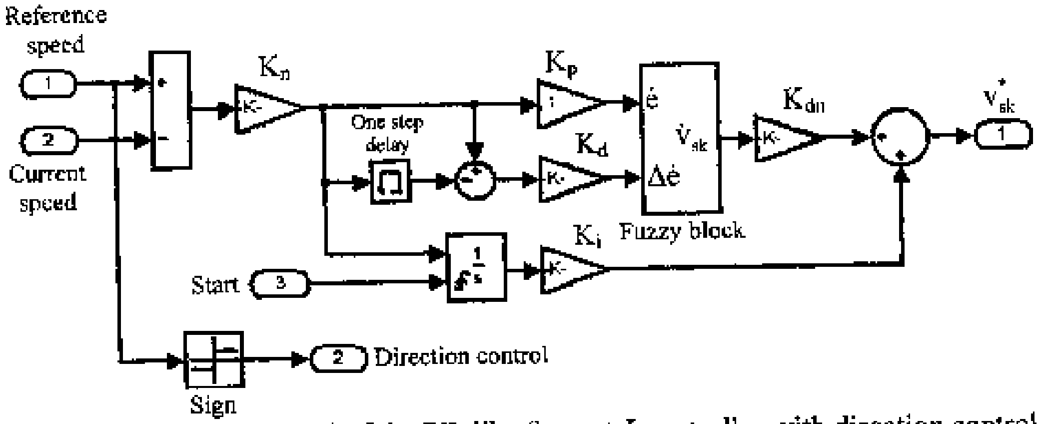

Fig.7 Complete simulink model of the PD-like fuzzy + I controller with direction control for machine-k.

Trial and error method is used to estimate the factors K_n, K_{dn}, K_p, K_d, and K_i. Values of 1/1950, 0.65, 1, 6500, and 6.2 respectively are found to fairly satisfy full range of speed under different operating conditions.

Triangular and half trapezoidal membership functions are used for the input and out of the fuzzy part. The input membership functions for both machines are shown in Fig.8.

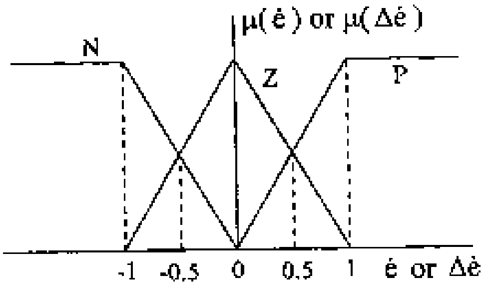

Fig.8 The input membership functions.

where:

$\mu(\dot{e})$ is the membership degree of the normalized input error signal $\dot{e}$.

$\mu(\Delta\dot{e})$ is the membership degree of the normalized change of error signal $\Delta\dot{e}$.

N is the Negative membership function.

Z is the Zero membership function.

P is the Positive membership function.

The output membership functions of the PD-like fuzzy part are shown in Fig.9.

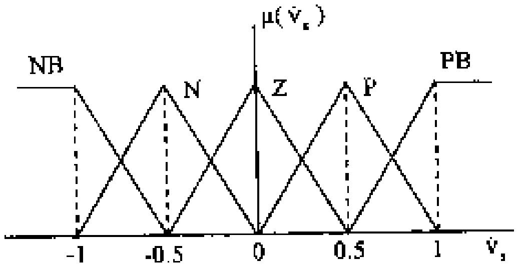

Fig.9 The output membership functions.

where:

$\mu(\dot{v}_s)$ is the membership degree of the normalized control signal $\dot{v}_s$.

NB is the Negative Big membership function.

PB is the Positive Big membership function.

In the second stage of the fuzzy controller, the normalized error and change of error signals are processed using 9 rules (3*3) as shown in Table-1.

Table-1 Rules of the fuzzy logic controller.

$\dot{e}$ \ $\Delta\dot{e}$	N	Z	P
N	NB	N	Z
Z	N	Z	P
P	Z	P	PB

Finally, in the defuzzyfication stage a crisp value of the output variable $\dot{v}_s$ is obtained using the centre of area method.

The whole simulink/Matlab model of the two series-connected machines (modeled in dq stationary reference frame as given in Eqs.(3) and (4)), inverter supply system and the two controllers is shown in Fig.10.

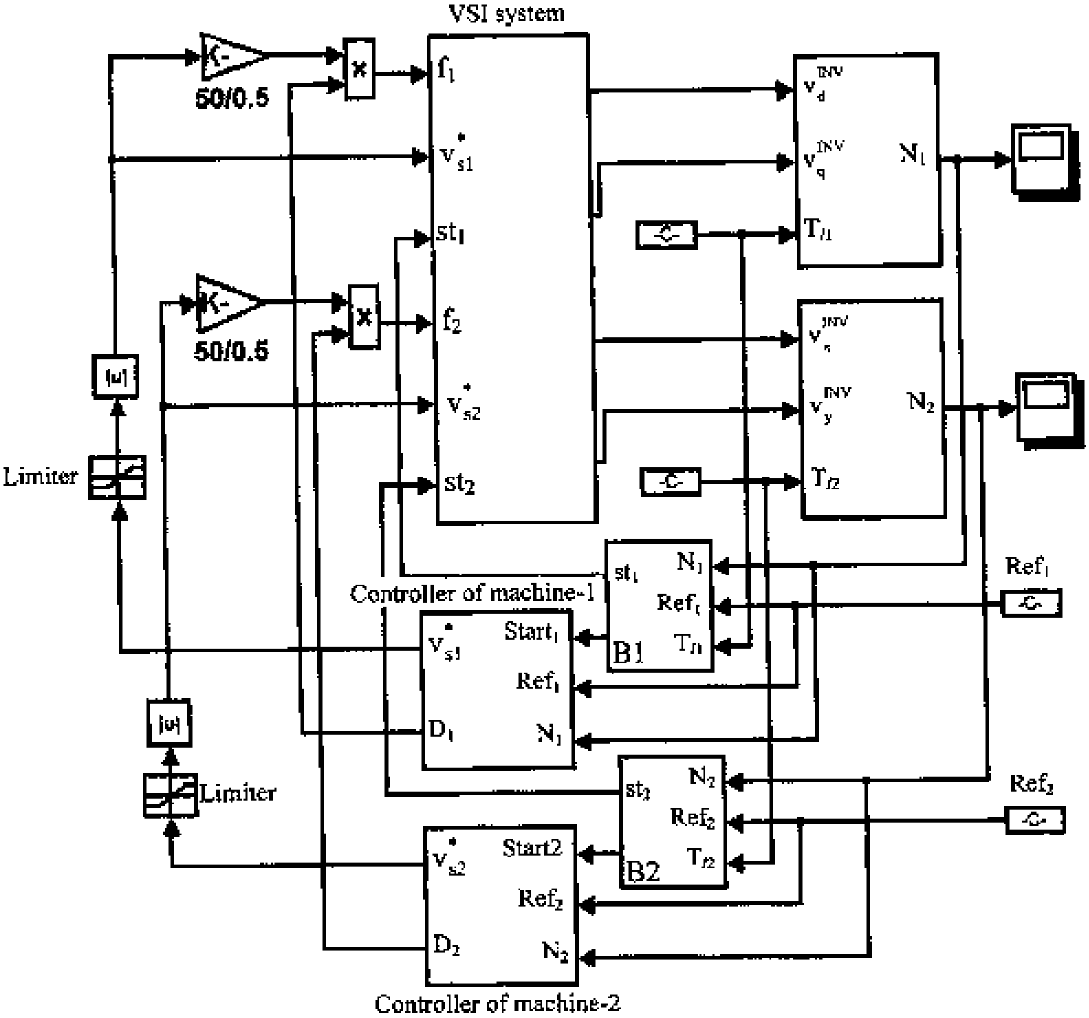

Fig.10 Complete simulink model of the system under consideration.

Where blocks B1 and B2 are used to sense the reference speeds (Ref_1 and Ref_2) variations, load torques (T_{l1} and T_{l2}) variations and speeds (N_1 and N_2) reversal to generate pulses $start_1$ and st_1 for for machine-2 control.

5. Simulation results

The derived model for the five-phase series-connected two-motor drive system using the designed fuzzy controller is tested under different operating conditions. The results of the tests are shown in Figs.11-18.

Phase 'a' voltages of machine-1 and machine-2 with their fundamental figures, white color, shown in Figs.11 and 12 when $f_1=f_2=50$ Hz and $v^*_{s1}=v^*_{s2}=0.5$ p.u. prove applicability of the inverter in generating the required ac voltages.

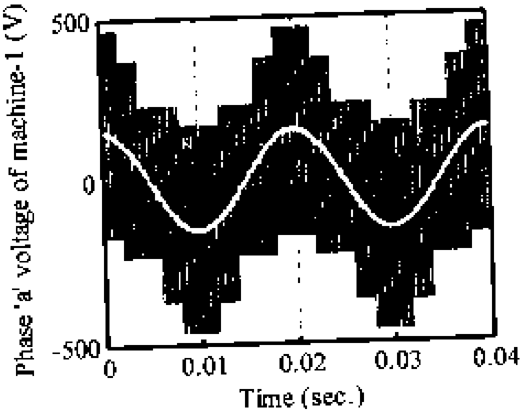

Fig.11 Phase 'a' voltage of machine-1, total and fundamental.

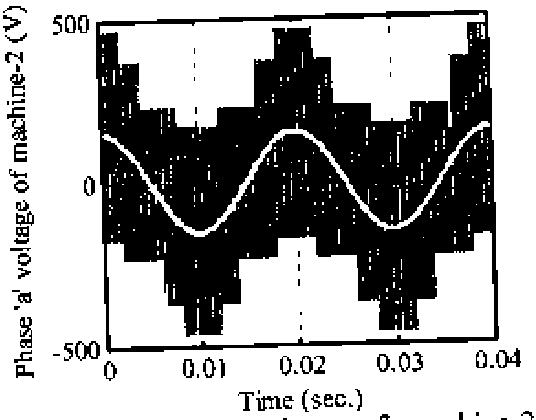

Fig.12 Phase 'a' voltage of machine-2, total and fundamental.

In the first test regarding the motors operation, the two machines are started in the same direction toward their set speeds. Machine-2 starting is delayed by 0.4 sec. Then different speed transients are initiated for the two machines. The speed responses of the two machines shown in Fig.13 prove the ability of the controller to successfully guides both machines to their final speeds. Furthermore, Speed responses (Fig.13), torques (Fig.14), currents i_{as1} and i_{as2} (Fig.15) show that starting or speed transient of any machine has no influence on the other. This proves the goal of decoupling of control of the two series-connected machines. Also, Fig.15 shows that the VSI supply frequency changes proportionally with the speed set point.

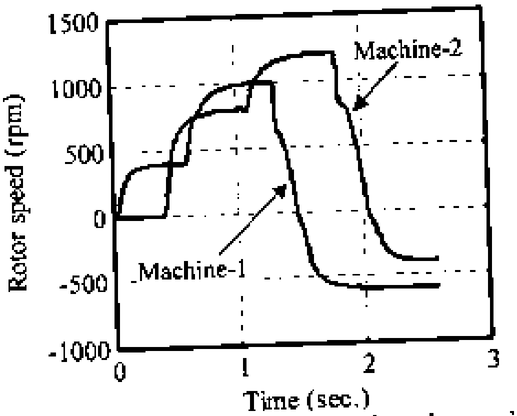

Fig.13 Rotor speed with sudden change in reference speed at no-load condition.

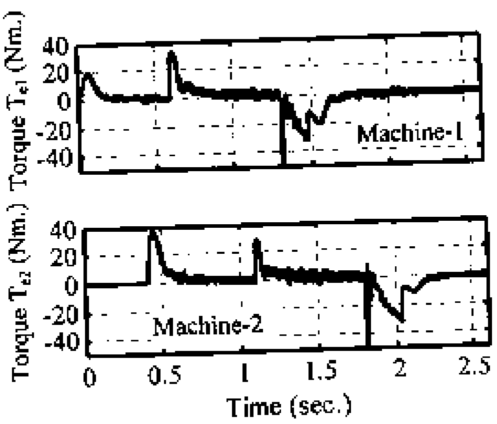

Fig.14 Electromagnetic developed torques with sudden change in reference speed at no-load condition.

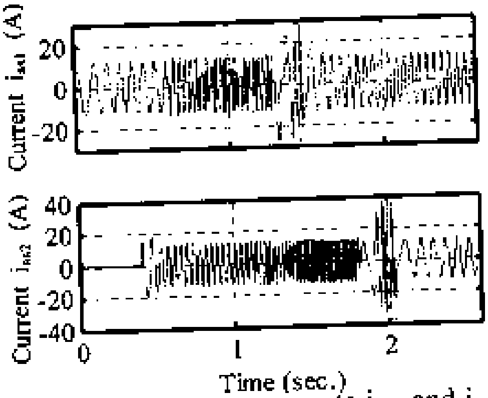

Fig.15 Instantaneous currents i_{as1} and i_{as2} at starting and speed transients.

In the second test, the two machines are started in opposite directions and speed reversals are initiated for them when they reach their steady state speeds, see Fig.16.

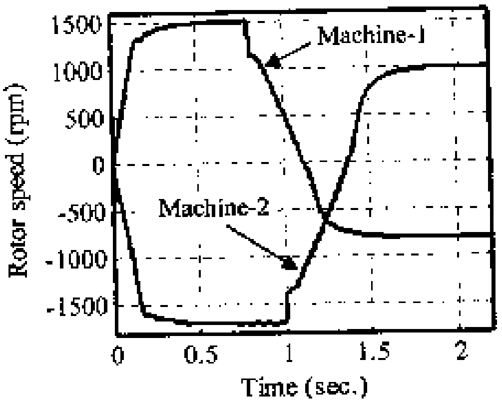

Fig.16 Rotor speed with sudden change in reference speed at no-load condition.

Finally, both machines are subjected to sudden full load application and removal. The test results are shown in Figs.17 and 18. These two figures prove that the controller will successfully do its role to gain back machines set speeds after load transients. Also, load transient of one machine will not affect the other.

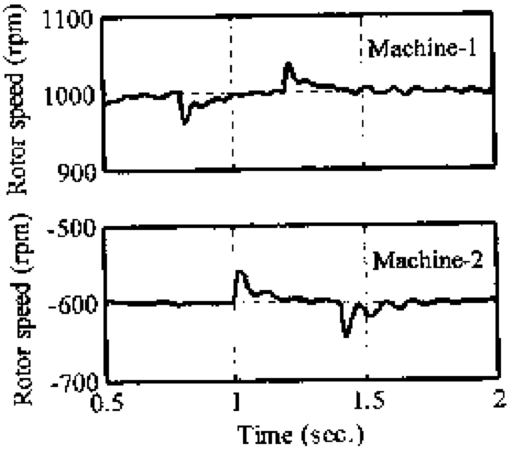

Fig.17 Rotor speed of machine-1 and machine-2 under sudden full load application and removal.

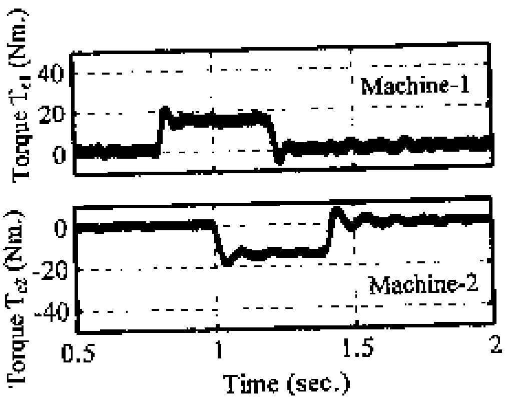

Fig.18 Electromagnetic developed torque under sudden application and removal of full load torque.

6. Conclusions

The feasibility and applicability of a series-connected two-motor drive has been studied in this paper. One of the main benefits of this connection is the full control decoupling between the motors in the group despite of connection to a common VSI.

A simulink/Matlab model for a five-phase series-connected two-motor drive system supplied from SVPWM VSI and controlled by PD-like fuzzy + I controller has been derived and tested.

Simulation results show that good performance is achieved even with hard transients such as starting, large speed step change, speed reversal, and sudden full load/unload conditions. Also, these results prove the decoupling of control of the two machines.

A comparison between the results gained using the proposed controller with previous work[2] using rotor field oriented control, shows that both methods serve well for the sake of gaining the set-point speed as shown in Fig.19. But, one can see that the proposed method is more efficient in reaching the final set-point with no overshoot and almost no steady state error.

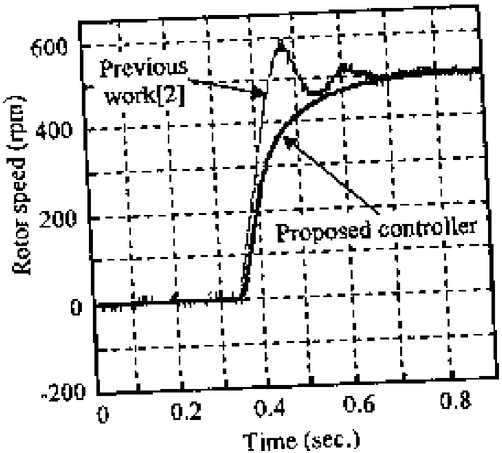

Fig.19 Comparison of rotor speed for two-motor drive using proposed controller with that gained in a previous work.

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8. Appendix

Two similar five-phase induction motors are used which have the following per phase data:

Parameter	value	unit
No. of poles	4	
Frequency	50	Hz
Voltage	110	V
Full load	14/5	Nm.
R_s	0.78	Ω
R_r	0.66	Ω
L_{ls}	3.45	mH
L_{lr}	3.45	mH
L_m	29.7	mH
J	0.0435	Kg.m^2
F	0.005	Nm.sec