Induction Machine/Syn-Rel Two-Motor Five-Phase Series-Connected Drive

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***Abstract*—Multimotor drives, based on utilization of multiphase machines, have been proposed recently. Independent vector control of all the machines of the group can be achieved while using a single multiphase voltage source inverter supply, provided that the stator windings are connected in series in an appropriate manner. The concept is applicable to any system phase number greater than or equal to five. Detailed theoretical and simulation studies have been reported for multiphase multimotor drive configurations of this type and it has been suggested that the concept is valid regardless of the type of ac machines. This paper examines operation of such a drive system when a five-phase induction machine is connected in series with a five-phase synchronous reluctance machine and provides detailed experimental verification of the possibility of independent control of the two-motor drive comprising five-phase motors of different types. The operating principles of the drive system are at first reviewed and a brief description of the experimental system is then given. An extensive presentation of experimental results, collected from a laboratory setup, is further provided. It is shown that fully independent and decoupled vector control of the two machines results, although a single supply source is used.**

***Index Terms*—Experimental verification, five-phase, multimotor drives, multiphase machines, vector control.**

I. INTRODUCTION

THE origin of multiphase drives can be traced back to 1969 when a five-phase induction motor drive was considered in order to reduce the torque ripple found in three-phase six-step inverter fed machines. The interest in multiphase motor drives has substantially increased during the last decade, because of the potential advantages they offer for certain specific applications. The main driving forces behind this accelerated development have been three specific application areas, namely ship propulsion, "more-electric" aircraft, and traction (railway, electric vehicles, and hybrid electric vehicles). In general, multiphase drives have two distinct features that make them an attractive solution compared to the three-phase counterpart in these application areas. First, the required power per-phase rating of the inverter is reduced, which is especially important in high-power (railway traction, ship propulsion) and high-current (electric and hybrid electric vehicles) applications. Second, there are additional degrees of freedom available to control multiphase machines. These additional degrees of freedom are typically utilized for one of the two purposes. Torque production can be increased through injection of higher-order stator current harmonics. This is particularly attractive in applications, where space is at a premium, such as ship propulsion [1]. Alternatively, the additional degrees of freedom can be used to significantly improve the fault tolerance of the drive and allow the drive to operate normally with a loss of one or more phases [2]. Fault tolerance is of major importance in applications such as "more-electric aircraft" [3] and railway traction [4].

Since vector control of any ac machine requires only two currents for flux/torque production when only the fundamental of the field is utilized, the remaining degrees of freedom can be used for an entirely different purpose, to control other machines within a multimotor group. This constitutes the main idea behind the concept of series-connected multiphase multimotor drive systems, initially proposed in [5] and further developed for the two-motor five-phase drive with a single five-phase voltage source inverter (VSI) supply in considerable detail in [6].

This multiphase multimotor drive system concept is applicable to any supply phase number greater than or equal to five. Generalizations to all possible even and odd phase numbers have been reported in [7] and [8], respectively, where appropriate winding connections and the number of connectable machines as a function of the VSI phase number were investigated. Studies [7] and [8], apply to series connection of symmetrical multiphase machines (with spatial displacement between any two consecutive phases of $2\pi/n$, where n is the number of phases). However, the concept of series connection can be extended to asymmetrical machines as well, where stator winding consists of two or more three-phase windings shifted in space by an appropriate angle. A series-connected two-motor drive comprising two six-phase asymmetrical machines (two three-phase windings with a 30° spatial shift) has been reported in [9] (V/f control rather than vector control was analyzed). The configuration with two asymmetrical six-phase machines [9] is believed to be less attractive for real world applications than the five-phase two-motor drive elaborated here. This is so, since the five-phase two-motor drive offers a saving in the number of inverter legs compared to both asymmetrical six-phase two-motor drive of [9] and the standard two-motor two-inverter three-phase drive.

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Vector control of the two series-connected machines can be achieved by using either current control in the stationary reference frame or current control in the rotating reference frame. While both possibilities are viable, it has been shown that current control in the rotating reference frame leads to an increase in parameter sensitivity [10]. This is so since the decoupling voltages become functions of parameters of both machines, due to the need to compensate voltage drops in one machine caused by the flow of the flux/torque producing currents of the other machine through its windings. The conclusion of [10] is that current control in the stationary reference frame is better suited to series-connected multiphase multimotor drive systems. It is for this reason that current control based on inverter output phase currents is implemented in this paper.

The theoretical and simulation considerations of [5]–[8] have so far been confirmed experimentally only for two-motor six-phase drives. As already noted, asymmetrical six-phase drive (consisting of two asymmetrical six-phase machines) was studied and tested in [9]. In contrast to this configuration, a symmetrical six-phase two-motor drive, comprising a six-phase and a three-phase machine and examined in detail experimentally in [11]–[13], is believed to hold much better prospect of acceptance by the drives industry. The difference in potential applicability stems from the fact that the symmetrical six-phase drive involves two machines of the different phase number, thus limiting the effect of the increased stator winding losses to only one machine (six-phase) [11]–[13]. The detailed considerations related to future applications of such a drive system, which are perceived to be in the high-power range, are given in [11], [12].

Two-motor five-phase drive, considered here, is characterized with one specific advantage when compared to the two-motor six-phase drives, a saving of one inverter leg. This advantage may make it a viable solution for one specific application area where the negative effect of the increase in the stator winding loss in both machines due to the series connection can be minimized. The perceived application is for two-motor winders and is discussed in detail, in the paper.

The concept of series-connected multiphase multimotor drives is in principle independent of the machine type. Experimental investigations of the six-phase two-motor drives [9], [11], [12] have utilized two induction machines, while the study of [13] applies to a combination of an induction and a permanent magnet synchronous machine. This paper utilizes, for the first time, a Syn-Rel, connected in series with an induction machine. Both machines and the VSI are here five-phase (in contrast to [9], [11]–[13]), so that an experimental proof of the existence of decoupled control in the two-motor five-phase drive is provided. A summary of the operating principles, detailed in [5], [6] and based on the assumption of sinusoidal spatial flux distribution in the ac machines, is provided first. This is followed by a brief description of the experimental system and the procedure used to verify the decoupling of dynamics of the two machines in the experimental investigation. Results of various experiments are then presented. Excellent and independent dynamics are demonstrated, thus confirming that the control of the two machines is truly decoupled, although they are connected in series and the supply is provided from a single five-phase VSI. Finally, potential applicability of the drive system for two-motor winder sections is addressed.

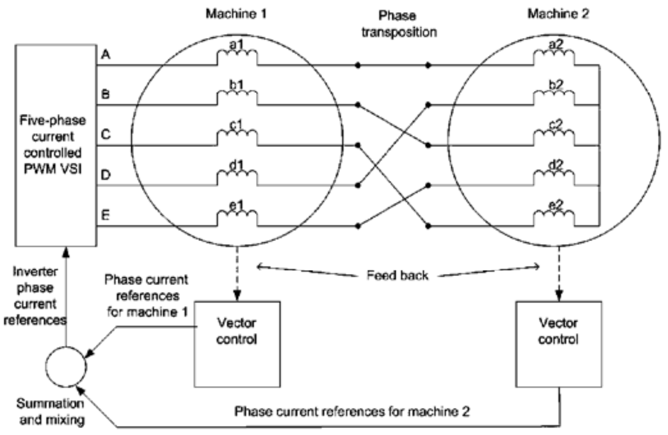

Fig. 1. Vector control of a five-phase series-connected two-motor drive.

II. CONFIGURATION AND OPERATING PRINCIPLES OF THE FIVE-PHASE TWO-MOTOR DRIVE

An illustration of the complete vector controlled drive system is given in Fig. 1. Stator windings of the two machines are connected in series via a phase transposition [5], [6]. The phase transposition is introduced so that the five-phase currents that produce rotating magnetomotive force (MMF) in the first machine do not produce rotating MMF in the second machine and vice versa [5], [6]. In other words, flux/torque producing currents for one machine appear as non-flux/torque producing currents in the other machine and vice versa. The supply is a five-phase VSI, whose outputs are identified with capital letters A, B, C, D, and E, while lower case letters (a, b, c, d, and e) identify phases of the two machines according to the spatial distribution of the stator windings (spatial displacement between any two consecutive phases is $\alpha = 2\pi/5 = 72^\circ$).

As a consequence of the phase transposition shown in Fig. 1, inverter phase voltages are related to individual machine phase voltages through

$$\begin{aligned} &\nu_A = \nu_{a1} + \nu_{a2} \quad \nu_B = \nu_{b1} + \nu_{c2} \\ &\nu_C = \nu_{c1} + \nu_{e2} \quad \nu_D = \nu_{d1} + \nu_{b2} \\ &\nu_E = \nu_{e1} + \nu_{d2} \end{aligned} \tag{1}$$

while the correlation between inverter output currents and machine phase currents is given with

$$\begin{aligned} &i_A = i_{a1} = i_{a2} \quad i_B = i_{b1} = i_{c2} \\ &i_C = i_{c1} = i_{e2} \quad i_D = i_{d1} = i_{b2} \\ &i_E = i_{e1} = i_{d2} \end{aligned} \tag{2}$$

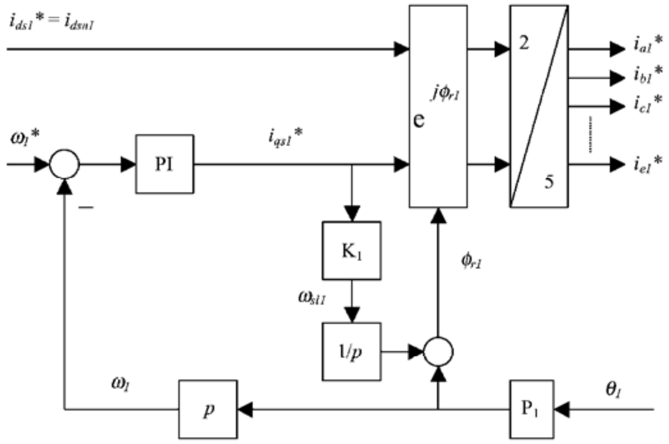

Fig. 2. Indirect rotor flux oriented controller for the five-phase induction machine $(K_1 = 1/(T_{r1}^* i_{ds1}^*), p \equiv d/dt)$.

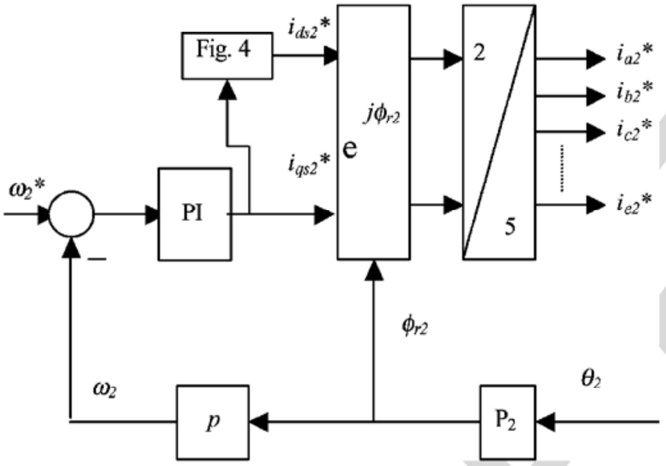

Fig. 3. Rotor flux oriented controller for the five-phase Syn-Rel.

Machine 1 is the induction machine, while machine 2 is the Syn-Rel in the tests.

Any of the available vector control algorithms can be used for either of the two machines of the group. The simplest possibility, utilized here, is the application of the indirect rotor flux oriented (RFO) control. Fig. 2 illustrates indirect RFO controller for the five-phase induction machine assuming operation in the base speed region only. The five-phase Syn-Rel is operated in the base speed region as well and the corresponding vector controller is shown in Fig. 3. Individual phase current references of the two machines are then created, using the power variant transformation and Figs. 2 and 3, according to the following expressions $(k = 2/5)$:

$$\begin{aligned}
i_{a1}^* &= k\left[i_{ds1}^* \cos\phi_{r1} - i_{qs1}^* \sin\phi_{r1}\right]\\
i_{b1}^* &= k\left[i_{ds1}^* \cos(\phi_{r1} - \alpha) - i_{qs1}^* \sin(\phi_{r1} - \alpha)\right]\\
i_{c1}^* &= k\left[i_{ds1}^* \cos(\phi_{r1} - 2\alpha) - i_{qs1}^* \sin(\phi_{r1} - 2\alpha)\right]\\
i_{d1}^* &= k\left[i_{ds1}^* \cos(\phi_{r1} - 3\alpha) - i_{qs1}^* \sin(\phi_{r1} - 3\alpha)\right]
\end{aligned}$$

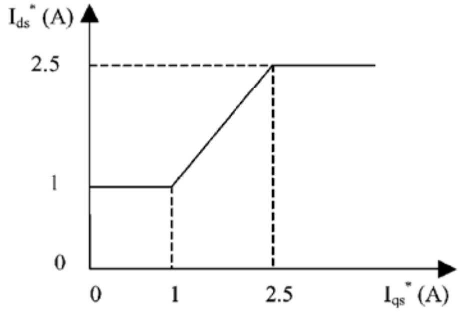

Fig. 4. Variation of stator d-axis current reference as function of the q-axis current reference (rms values) for the Syn-Rel.

$$\begin{aligned}
i_{e1}^* &= k\left[i_{ds1}^* \cos(\phi_{r1} - 4\alpha) - i_{qs1}^* \sin(\phi_{r1} - 4\alpha)\right]\\
i_{a2}^* &= k\left[i_{ds2}^* \cos\phi_{r2} - i_{qs2}^* \sin\phi_{r2}\right]\\
i_{b2}^* &= k\left[i_{ds2}^* \cos(\phi_{r2} - \alpha) - i_{qs2}^* \sin(\phi_{r2} - \alpha)\right]\\
i_{c2}^* &= k\left[i_{ds2}^* \cos(\phi_{r2} - 2\alpha) - i_{qs2}^* \sin(\phi_{r2} - 2\alpha)\right]\\
i_{d2}^* &= k\left[i_{ds2}^* \cos(\phi_{r2} - 3\alpha) - i_{qs2}^* \sin(\phi_{r2} - 3\alpha)\right]\\
i_{e2}^* &= k\left[i_{ds2}^* \cos(\phi_{r2} - 4\alpha) - i_{qs2}^* \sin(\phi_{r2} - 4\alpha)\right].
\end{aligned}\tag{3}$$

Stator d-axis current reference of the induction machine is 2.5 A (rms). Stator d-axis current reference of the Syn-Rel is varied with the stator q-axis current reference (Fig. 4). Stator q-axis current reference limit is 5 A (rms) for both machines.

Individual phase current references of the two machines (3) are further summed, according to the phase transposition of Fig. 1, in order to create the inverter phase current references

$$\begin{aligned}
i_A^* &= i_{a1}^* = i_{a2}^* \qquad & i_B^* &= i_{b1}^* = i_{c2}^*\\
i_C^* &= i_{c1}^* = i_{e2}^* \qquad & i_D^* &= i_{d1}^* = i_{b2}^*\\
i_E^* &= i_{e1}^* = i_{d2}^*.
\end{aligned}\tag{4}$$

Assuming ideal current control in the stationary reference frame inverter reference currents of (4) equal inverter actual currents of (2).

III. Experimental Setup

A laboratory setup is constructed in order to prove the existence of decoupled dynamic control in the series-connected two-motor drive system experimentally. The system incorporates a five-phase induction machine and a five-phase Syn-Rel, connected in series, according to Fig. 1. The experimental setup is illustrated in Fig. 5. It utilizes two three-phase 14/42 A/A (continuous rms/transient peak) inverters with the common dc link, each of which is equipped with a Texas Instruments' TMS320F240 DSP. All five currents are measured using LEM sensors and digital signal processors (DSPs) perform closed loop inverter phase current control in the stationary reference frame, using digital form of the ramp-comparison method. Inverter switching frequency is 10 kHz. The first inverter controls inverter A, C, E currents, while the second inverter controls

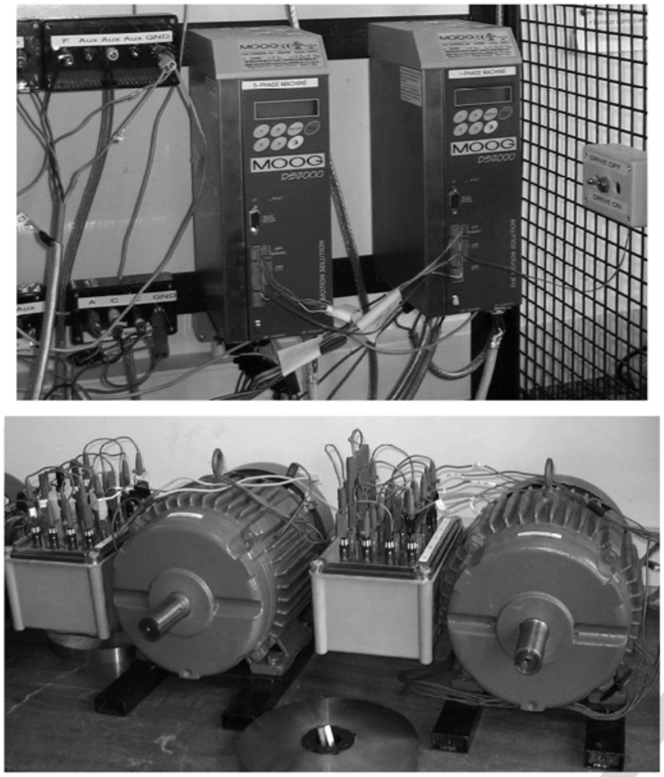

Fig. 5. Five-phase inverter (top) and two series-connected five-phase machines (bottom: Syn-Rel to the left and IM to the right).

B, D currents of Fig. 1. Pulse width modulation (PWM) ripple is filtered out in the DSPs using finite-impulse response (FIR) filters, which average 2^n equidistant samples taken during one switching period. Current signal, which is now PWM-ripple-free, is further used as the input of the current controllers. The inverter current references are passed to the DSPs from a PC, through a dedicated interface card. The control code operates on the PC and is written in C. It performs closed loop speed control and calculations according to (3) and (4), on the basis of the indirect rotor flux oriented control schemes of Figs. 2 and 3.

The five-phase machines are four-pole, 60-Hz machines with 40 slots on stator. These were obtained from 7.5 hp, 460-V three-phase induction machines by designing new stator laminations and a five-phase stator winding. The rotor is the original three-phase machine rotor, unskewed, with 28 slots, for the five-phase induction machine. For the Syn-Rel, the rotor of the induction machine was cut out, giving a ratio of the magnetizing d–q-axis inductances of approximately 2.85. The two machines are equipped with resolvers and control operates in the speed-sensored mode at all times. Various experimental tests are performed in order to verify the independence of the control of the two machines. The results are reported in Section IV.

IV. EXPERIMENTAL RESULTS

The approach adopted in the experimental investigation is the following. Both machines are excited and are then brought to a certain steady state operating speed. A speed transient is initiated next for one of the two machines, while the speed reference of the other machine is left unaltered. Provided that the control is truly decoupled, operating speed of the machine running at constant speed must not change when the transient is initiated for the other machine. However, due to the fast action of the speed controller, some very small variations of the speed could be unobservable. The ultimate proof of the fully decoupled control is therefore the absence of any variation in the stator q-axis current command of the machine running at constant speed, since this indicates absence of any speed error at the input of the speed controller. In addition to the results obtained in this manner, which follows from the methodology of [11]–[13], further proof of the control quality is provided by the experimental results obtained for the same transient, when only one machine is controlled. For this purpose both machines are still connected, according to Fig. 1. However, the rotor of one machine is mechanically blocked so that it stays at standstill and its phase current references are removed from (4) in the software. Hence, these results apply to the vector control of a single five-phase machine (either IM or Syn-Rel). The reason for leaving the second machine connected [which now behaves as a static resistance-inductance *(RL)* load] is to ensure the same operating conditions for the current controllers as in the case when both machines are running. Experimental results, shown further on, include stator q-axis current references (peak value), measured speed responses, and, in certain cases, a comparison of the inverter current reference and actual inverter current for one of the five phases. The machines are under no-load conditions, except for the loading/unloading transients.

In the first test, Syn-Rel runs at 400 r/min, while the induction machine is initially at 0 r/min. Step speed command of 800 r/min is then given to the induction machine Results of this acceleration test are shown in Fig. 6. Speed of the five-phase Syn-Rel, as well as its stator q-axis current reference, remain undisturbed during the acceleration transient of the induction machine, indicating complete decoupling of the control. Measured and reference inverter phase current are in excellent agreement in both steady state and transient operation.

Corresponding speed and stator q-axis current traces, obtained when the Syn-Rel is effectively only a static RL load, are shown in Fig. 7. Comparison of the results given in Figs. 6 and 7 shows that the speed response of the induction machine, as well as the stator q-axis current reference, are practically identical regardless of whether the second machine is operational or not. The duration and nature of both the speed and q-axis current reference transients are the same. Thus it follows that the transient performance of the induction machine is not affected by its connection to the Syn-Rel within the two-motor drive.

Further evidence of undisturbed operation of the five-phase Syn-Rel during a transient of the induction machine can be found in Figs. 8 and 9, where the induction machine is decelerated from 1000 r/min to standstill, at first within the two-motor drive and then with Syn-Rel ineffective (i.e., RL load). Operation of the single five-phase induction motor drive during deceleration,

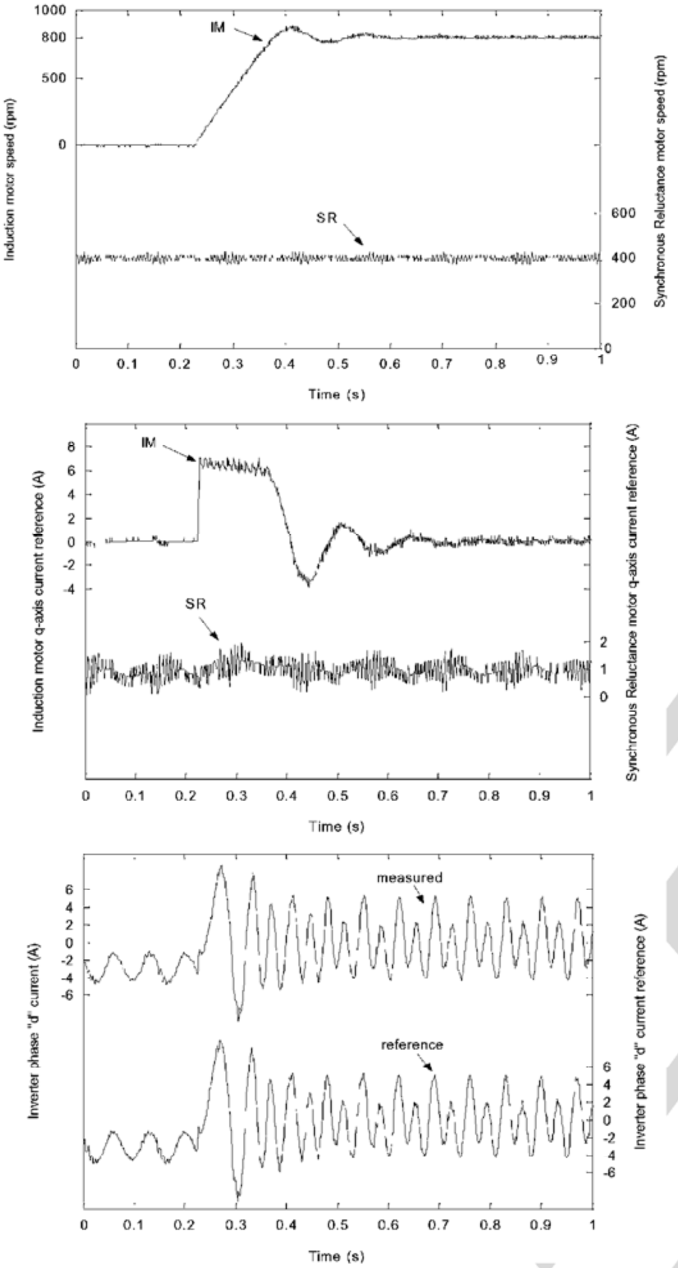

Fig. 6. Behavior of the two-motor drive during IM's acceleration from 0 to 800 r/min (Syn-Rel at 400 r/min).

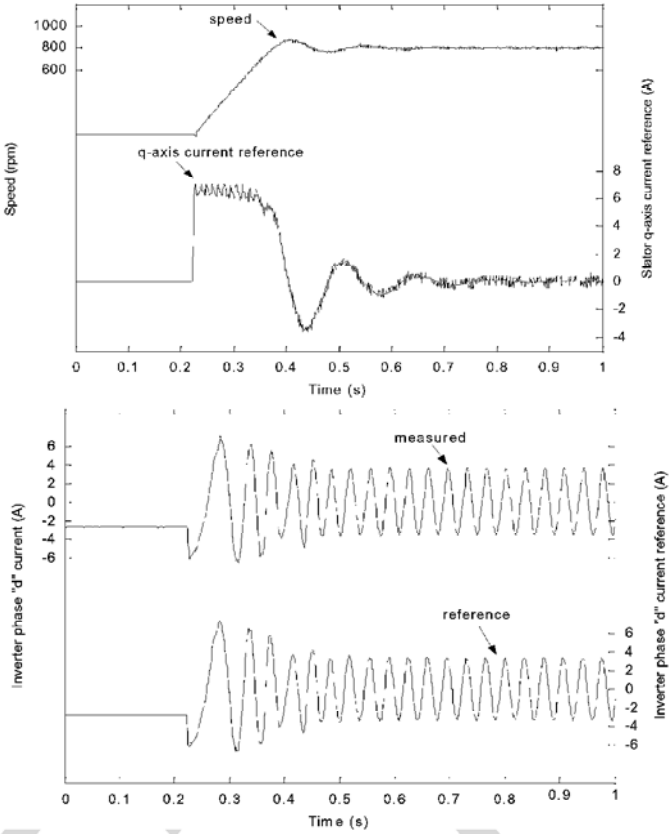

Fig. 7. Acceleration of the single five-phase IM drive from 0 to 800 r/min.

illustrated in Fig. 9, compares very favorably with results of Fig. 8. A further test, shown in Fig. 10, is the induction machine speed reversal from 300 to −300 r/min. Syn-Rel's speed reference is maintained at 400 r/min for both deceleration and speed reversal transients of Figs. 8 and 10, respectively. Excellent decoupling of control is achieved during reversal as well.

The situation is changed in the second group of tests. The speed of the induction machine is now held constant, while a transient is initiated for the Syn-Rel. In the first test, the induction machine runs at 600 r/min, while the Syn-Rel accelerates from standstill to 500 r/min (Fig. 11). For the purpose of comparison, performance of a single five-phase Syn-Rel drive during acceleration is illustrated in Fig. 12. The same traces are shown again in Fig. 13, where the induction machine is kept at 500 r/min, while the Syn-Rel decelerates from 800 r/min to standstill. Very much the same conclusions apply here again. It follows from Figs. 11 and 13 that there is negligible coupling between the controls of the two machines, since initiation of a transient for the Syn-Rel hardly has any effect on behavior of the induction machine.

One observes a very small, practically negligible, variation of the stator q-axis current reference of the induction machine during the Syn-Rel's transient. No such variation is observable in the speed responses. One important observation is that the Syn-Rel operates in steady state under no-load conditions with a certain non-zero value of the stator q-axis current reference. This provides compensation of the machine's losses, neglected in the vector controller of Fig. 3 (stator iron losses and mechanical losses). Steady state q-axis current reference under no-load conditions is speed dependent and increases as the speed (frequency) increases. Variation in stator q-axis current reference produces a corresponding variation in the d-axis current reference when, due to the specific method of stator d-axis current reference setting, applied here (Fig. 4). Hence there is some inevitable, very small, fluctuation in the stator q-axis current reference of the Syn-Rel in some tests.

The last two tests are related to the loaded operation of the two-motor drive. For this purpose induction machine is connected to a dc generator (not shown in Fig. 5), while the Syn-Rel

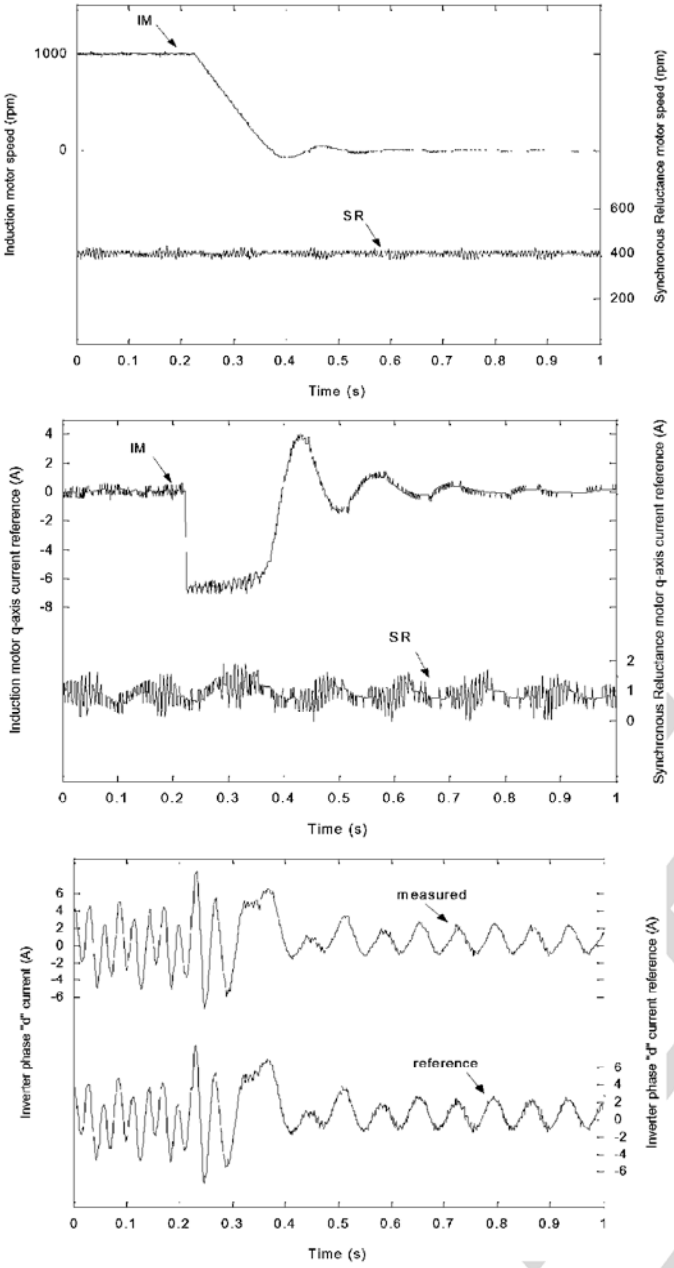

Fig. 8. Behavior of the two-motor drive during IM's deceleration from 1000 to 0 r/min (Syn-Rel at 400 r/min).

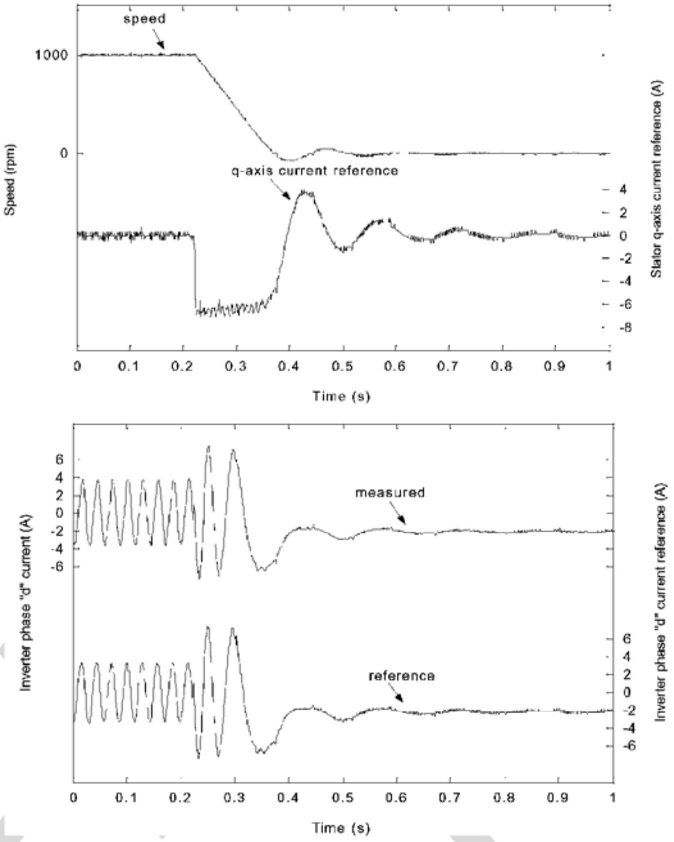

Fig. 9. Deceleration of the single five-phase IM drive from 1000 to 0 r/min.

still runs under no-load conditions. The induction machine is at first loaded from no-load operation in a step-wise manner while running at 500 r/min, with Syn-Rel at 300 r/min (Fig. 14). Next, step unloading is initiated from loaded operation at 300 r/min with a higher load torque (stator q-axis current), with Syn-Rel at 500 r/min (Fig. 15). As evidenced by responses in Figs. 14 and 15, Syn-Rel operation is not affected by loading/unloading of the induction machine, since there are no observable variations in either speed or stator q-axis current reference during the transients. It should be noted that the induction machine speed controller was tuned for no-load operating conditions. Hence, the connection of the dc generator of a substantial inertia leads to rather oscillatory stator q-axis current responses in transients depicted in Figs. 14 and 15.

V. APPLICABILITY OF THE TWO-MOTOR DRIVE

When compared to an equivalent two-motor three-phase drive, series-connected five-phase two-motor drive provides a saving of one inverter leg, easiness of the complete vector control algorithm implementation within a single DSP, and means for direct utilization of the braking energy that does not have to circulate through the inverter [6]. The major and serious disadvantage is an increase in the stator winding losses in each of the two machines, since flux/torque producing currents of both machines flow through the windings of both machines. Hence this drive system does not hold prospect for any type of general-purpose applications, where speeds and loads of the two machines can take arbitrary values.

However, it is believed that the scheme of Fig. 1 may offer considerable saving in the installed inverter power (compared to the standard solution with three-phase motors and VSIs) in two-motor constant-power drives of the winder type. For example, a typical paper machine involves nowadays a number of separate drives for various sections, which are independently controlled with synchronization provided by the master controller. The two consecutive sections of a winder system are typically with very different operating conditions. While one machine runs at low

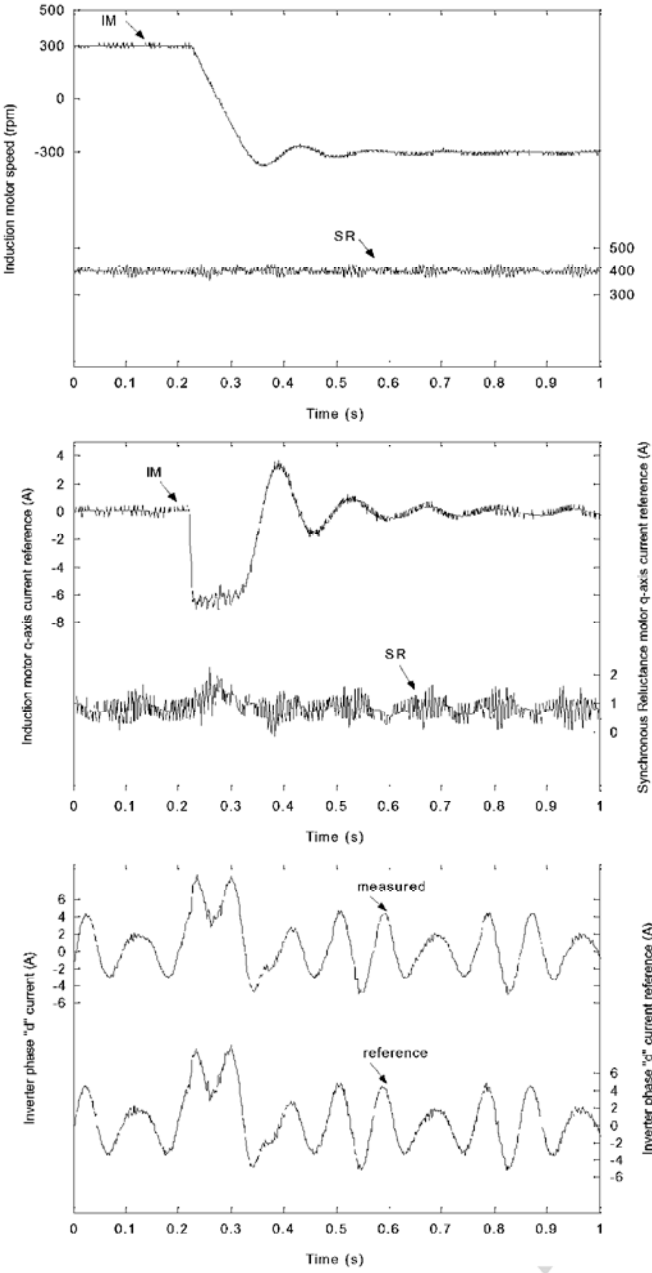

Fig. 10. Behavior of the two-motor drive during IM's reversal from 300 to −300 r/min (Syn-Rel at 400 r/min).

speed (low voltage) with high torque (current), the other machine runs at high speed (high voltage) and low torque (low current), and vice versa. It is precisely these very different operating conditions that may make the drive structure of Fig. 1 a viable solution, especially if surface-mounted permanent magnet synchronous machines are used. Due to the very different torque and speed requirements on the two motors, it should be possible to attain operation at all speeds/torques with the total stator winding loss in each machine that does not exceed the rated one. In other words, there should be no requirement for de-rating of the motors due to the increased stator winding loss, although the total loss would be still higher (and efficiency, therefore is lower) than with two single independently-controlled three-phase drives, meaning that the running costs would be higher. The increase in the running cost would however be more than offset by the reduction in the capital outlay for the inverter supply. Due to the operation of the two motors under opposing speed/torque requirements in the constant power region, the rating of the inverter for the series-connected two-motor drive can be practically equal to the rating of just one motor. This applies to both voltage and current (and thus total power) rating. This contrasts favorably with the current solution, where two fully-rated three-phase inverters are required for supply and control of the two-motor drives in winders.

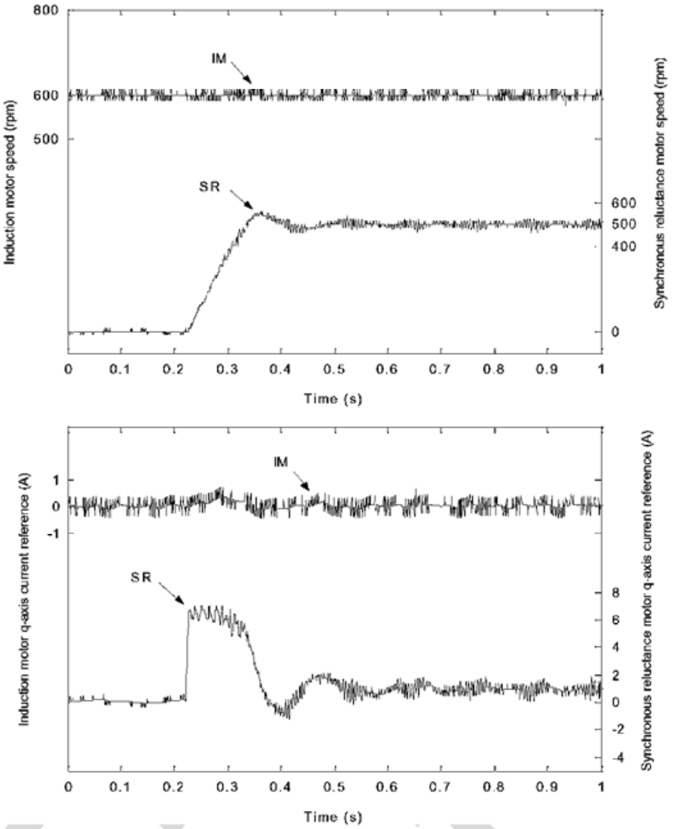

Fig. 11. Behavior of the two-motor drive during Syn-Rel's acceleration from 0 to 500 r/min (IM at 600 r/min).

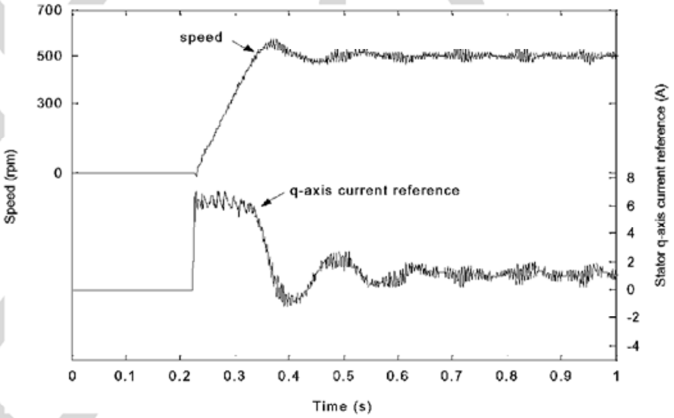

Fig. 12. Acceleration of the single five-phase Syn-Rel drive from 0 to 500 r/min.

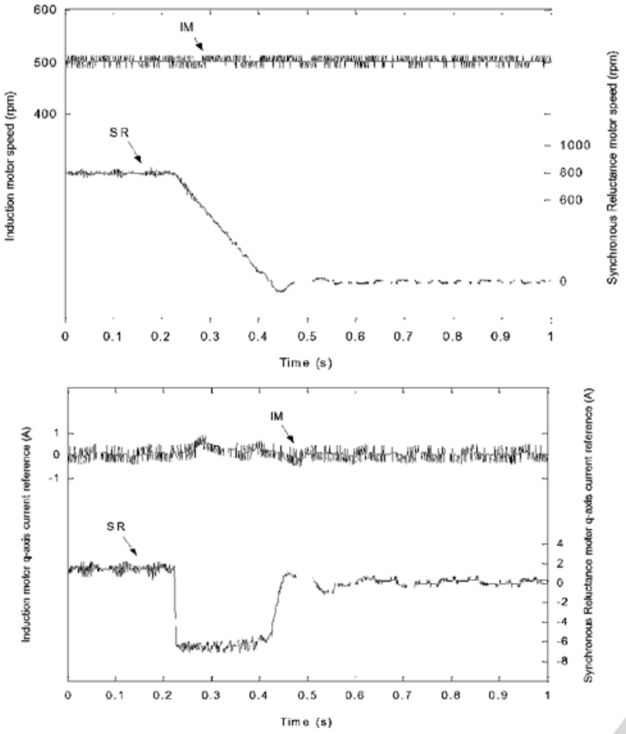

Fig. 13. Behavior of the two-motor drive during Syn-Rel's deceleration from 800 to 0 r/min (IM at 500 r/min).

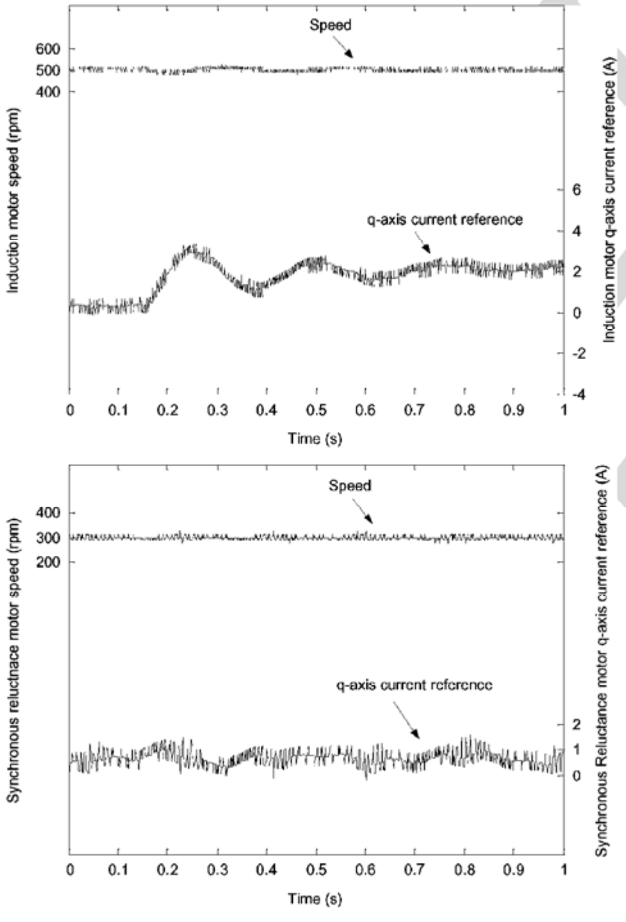

Fig. 14. Step loading of the induction machine at 500 r/min with Syn-Rel running at 300 r/min.

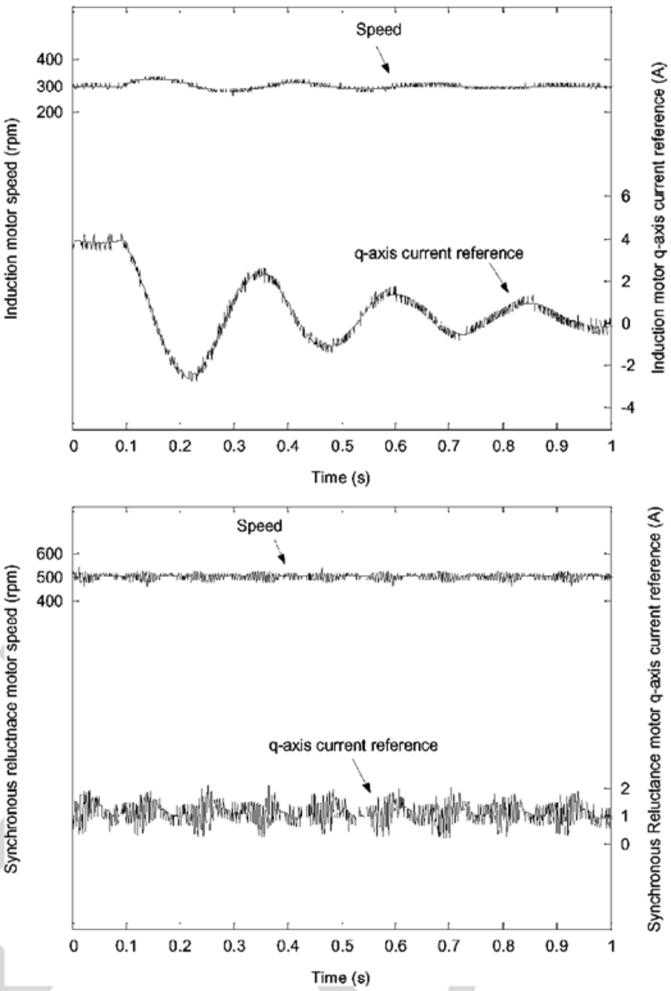

Fig. 15. Step unloading of the induction machine at 300 r/min with Syn-Rel running at 500 r/min.

VI. CONCLUSION

The paper examines operation of a series-connected five-phase two-motor drive and provides full experimental verification of the possibility of independent vector control of the two machines of different types in this configuration. A brief review of the operating principles is provided and an experimental setup, comprising a five-phase induction and a five-phase synchronous reluctance machine, is described. The emphasis is further placed on presentation of experimental results for various transients. By presenting the results of the same transient for single five-phase motor drives and series-connected two-motor drive it is proved that the control of the two series-connected machines is indeed decoupled. It is thus shown that the five-phase two-motor drive structure is applicable to all types of five-phase ac machine with sinusoidal flux distribution. It is believed that the best prospect for real-world industrial applications exists in the winder area, where the series-connected two-motor drive could provide a substantial saving on the capital cost. Although the efficiency of the system remains affected by the series connection, there should be no need to de-rate the machines in the series connection due to the increase in the stator winding loss.

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