Two Switch Adjustable-Speed Drive with Single-Phase Induction Machine

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***Abstract*- A novel low-cost drive with a single-phase induction machine for HVAC applications that can operate at either full or reduced speed is proposed. An experimental drive based on the presented setup has been developed and built to verify its practical viability and properties. The paper presents results of investigation obtained by means of numerical simulations as well as experiments and discusses the properties and characteristics of the drive.**

I. INTRODUCTION

The paper concerns a new low-cost drive setup utilizing a single-phase induction machine with speed control capability suitable for a relatively broad range of HVAC applications. The drive is specifically aimed at applications that do not require continuous speed control and enables the machine to efficiently operate at two different needed speeds.

The scheme of the system under investigation is shown in Fig. 1. The drive consists of a front-end voltage doubler followed by a one-phase inverter with two MOSFET or IGBT switches. The drive is designed to operate either at full speed with a supply frequency of 60 Hz or at reduced speed with a lower supply frequency. In the former case, the main winding of the motor is supplied with sinusoidal voltage directly from the mains. In this case, the single phase PWM inverter generates a voltage waveform with suitable magnitude and phase shift in relation to the mains for the auxiliary winding. During reduced speed operation both windings are fed from the inverter with a voltage having a constant frequency supplied by the inverter. The phase shift between the currents in the main and auxiliary windings is then achieved by the connection of an AC capacitor in series with the auxiliary winding.

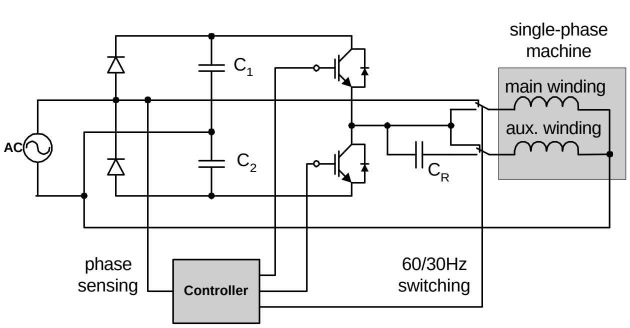

Fig. 1. System under investigation.

The main advantage of the proposed setup is that the power rating of the inverter can be lower in comparison to a classic adjustable-speed drive inverter for a single-phase induction machine. The inverter supplies only the auxiliary winding during full-speed operation and both windings in half-speed operation. This can result in smaller size of the drive and, therefore, in lower manufacturing costs of the drive as well.

Another important feature of this drive is the fact that it could continue to operate in the event of a failure of the semiconductor portion of the inverter. The motor would be, in such a case, supplied directly from the mains with the AC capacitor connected in series with the auxiliary winding.

II. NUMERICAL MODELING AND SIMULATIONS

The properties of the proposed drive setup have been analyzed by means of numerical simulation. The parameters of a practical 3/4 hp machine were used. A supply voltage of 220 V_{RMS} at the input of the drive was considered. A steady-state mathematical model was used to determine the operating points of the machine under various working conditions and to calculate the optimal parameters and setting of the drive.

First, full-speed operation was investigated. The inverter supplying the auxiliary winding was controlled to generate a voltage of the same amplitude but shifted by 86° from the phase of the mains to achieve phase quadrature of the currents. Fig. 2 shows the torque-speed characteristic of the drive. The solid line denoted T_e represents the resulting electromagnetic torque of the machine and the dotted line denoted T_r shows the amplitude of the torque pulsations. It can be noted that the machine has quite high starting torque when fed in this manner. The relatively high value of the torque ripple is mainly due to the limitation of the voltage amplitude generated by the inverter. Balanced operation would require the magnitude of the voltage for the auxiliary winding to be approximately 30% above the magnitude of the voltage supplying the main winding for this particular machine. This is, however, not achievable with the employed simple suboscillation PWM method [3].

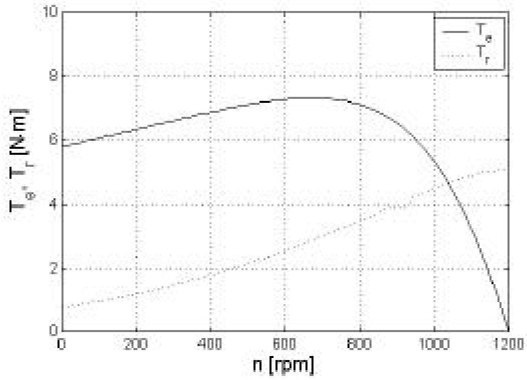

Fig. 2. Torque-speed characteristics, f = 60 Hz.

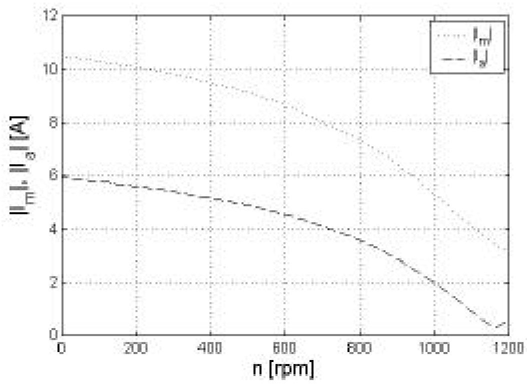

Fig. 3. Stator currents-speed characteristics, f = 60 Hz.

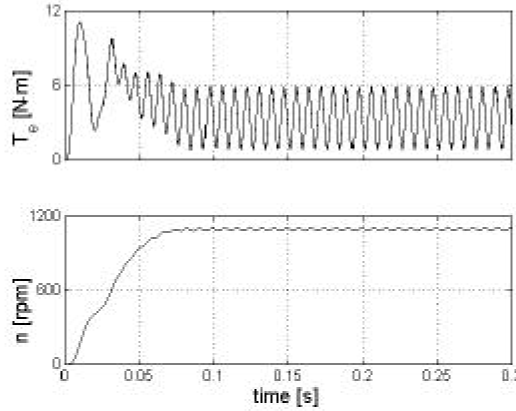

Fig. 4. Torque and speed at start, f = 60 Hz.

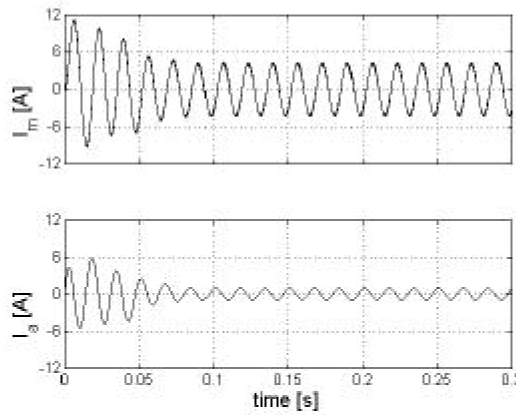

Fig. 5. Stator currents at start, f = 60 Hz.

The dependences of the magnitudes of currents in the main and auxiliary windings on the mechanical speed are presented in Fig. 2. It can be seen that the current in the auxiliary winding is significantly lower over the range of operating speed considered (with a slip of 6÷8%) implying a relatively small inverter.

The numerical simulation of the start of the machine is illustrated in Fig. 4 and 5. A fan load characteristic was considered in the simulation. Fig. 4 shows the resulting electromagnetic torque and the mechanical speed of the machine. The results confirm a higher content of torque pulsations in steady-state operation with the full load. This effect is, however, filtered to a great extent by the moment of inertia of the machine and the attached fan and has only a small effect on the mechanical speed. The waveforms of currents in the main and auxiliary windings are shown in Fig. 5.

Second, operation at a reduced speed was analyzed. The inverter produced a voltage waveform with an amplitude of 110 V_{RMS} and a frequency of 30 Hz. A capacitor of 30 μF was connected in series with the auxiliary winding. The torque-speed characteristic and the dependence of the torque ripple on the speed are in Fig. 6. The value of the torque pulsations has now a local minimum near the expected operating point. Fig. 7 shows the currents in the main and auxiliary windings together with the overall current drawn from the inverter. It can be noted that the amplitude of the current supplied by the inverter is comparable in both cases. The magnitude of the AC voltage across the capacitor plotted against the speed is in Fig. 8.

The results of a simulated start of the machine are in Figs. 9 through 11. The first two figures present the quantities corresponding to those in Fig. 4 and 5. Fig. 11 shows the resulting current supplied by the inverter and the voltage across the capacitor.

III. EXPERIMENTAL RESULTS

An experimental drive has been developed in order to verify the theoretical results and the practical viability of the proposed setup. The power stage of the drive was built utilizing readily available IGBT power. The control algorithm was implemented in a universal control board based on digital signal processor TMS320F240 from Texas Instruments. The board was connected to a PC through the RS232 interface, which enabled changes of control parameters in real time. The algorithm generated a PWM voltage waveform with variable amplitude and frequency with the possibility to synchronize the output with the line

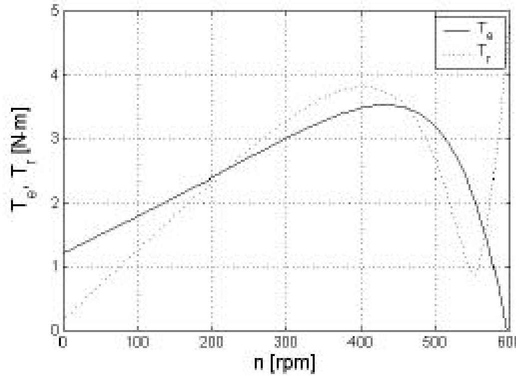

Fig. 6. Torque-speed characteristics, f = 30 Hz.

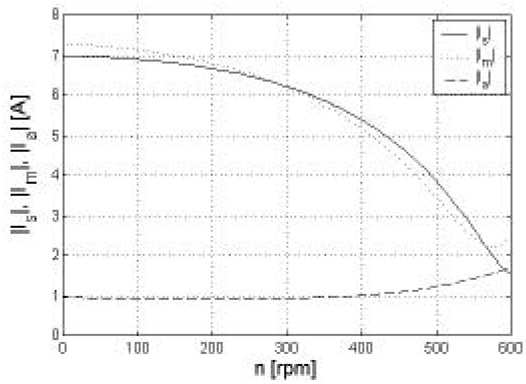

Fig. 7. Stator currents-speed characteristics, f = 30 Hz.

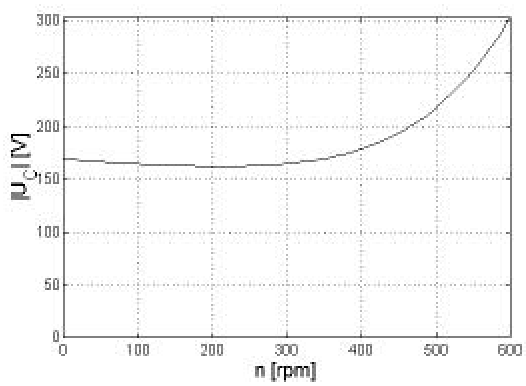

Fig. 8. Voltage across AC capacitor, f = 30 Hz.

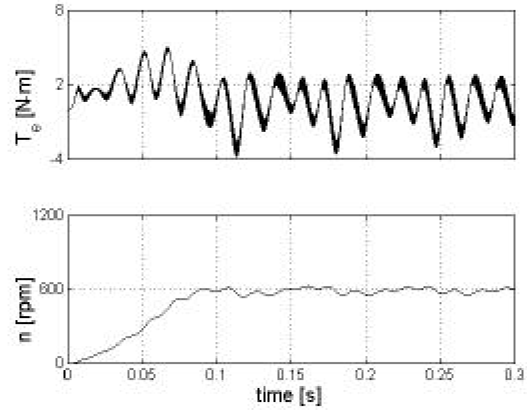

Fig. 9. Stator currents at start, f = 30 Hz.

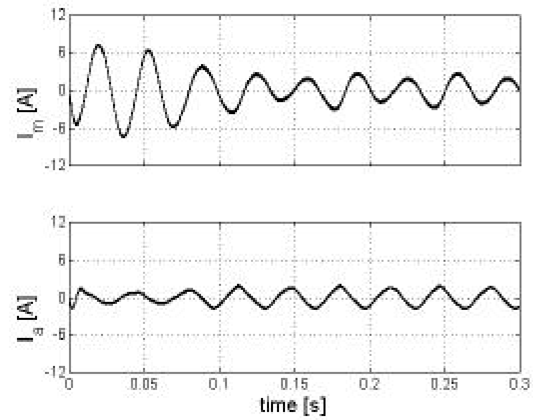

Fig. 10. Torque and speed at start, f = 30 Hz.

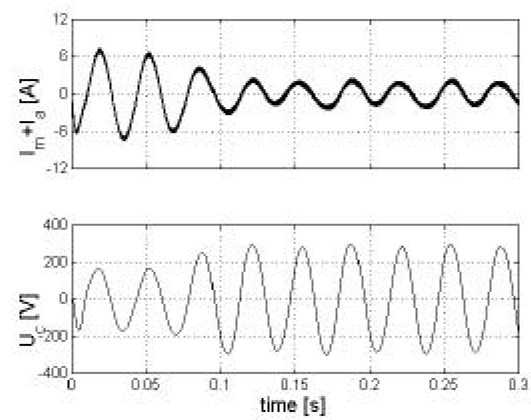

Fig. 11. Stator current and voltage across AC capacitor at start, f = 30 Hz.

voltage. It was also possible to adjust the phase shift between the line and the generated waveform.

The initial set of measurements has been done in order to verify the theoretical results and analyze the behavior of the practical drive. Operation both at full speed (60 Hz) and at half speed (30 Hz) has been tested for different load torque values

First, the results for the full speed operation are presented. Fig. 12 shows the shape of the stator current layer for the full speed operation when the phase shift between the voltages fed to the main and auxiliary windings is 90°. The motor was connected to a dynamometer and loaded by 270 W, rotating at 923 rpm. The value of the current in the auxiliary winding is multiplied by the ratio of the number of turns in the main winding to the number of turns in the auxiliary winding so that the shape directly indicates the

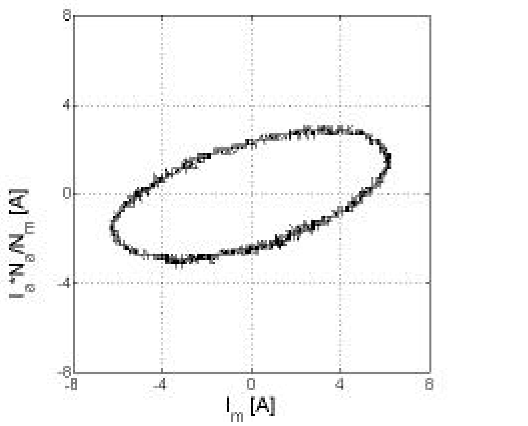

Fig. 12. Stator current layer, f = 60 Hz, φ = 0°.

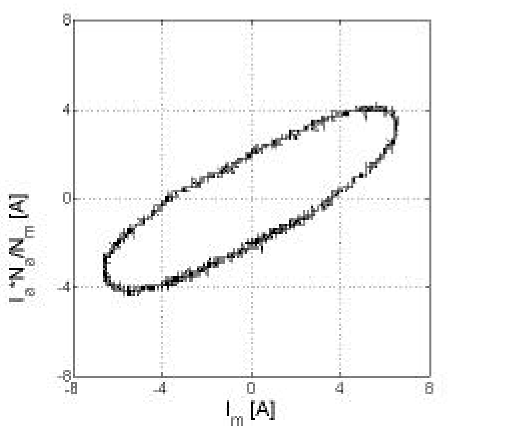

Fig. 13. Stator current layer, f = 60 Hz, φ = 15°.

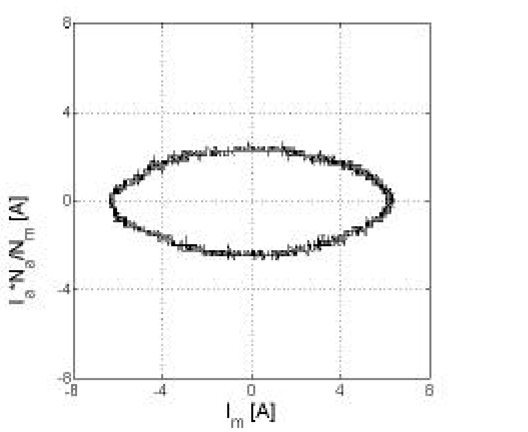

Fig. 14. Stator current layer, f = 60 Hz, φ = -15°.

quality of the supply voltage for the motor. The current layer forms an ellipse with the angular deviation of the main axis from the real axis of the reference frame. It means that the angle between the currents in the main and auxiliary windings is different from the optimal 90°, which is caused by different impedances of the main and auxiliary windings.

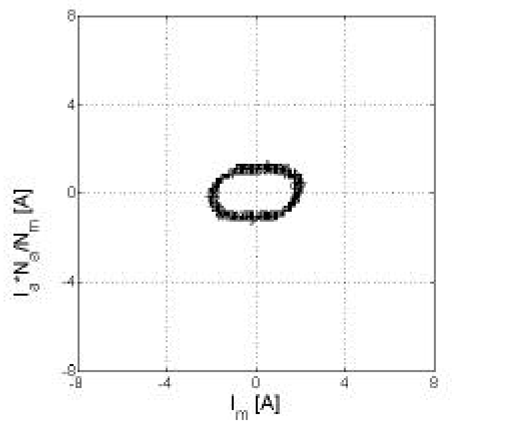

Fig. 15. Stator current layer, f = 30 Hz, C = 30 μF.

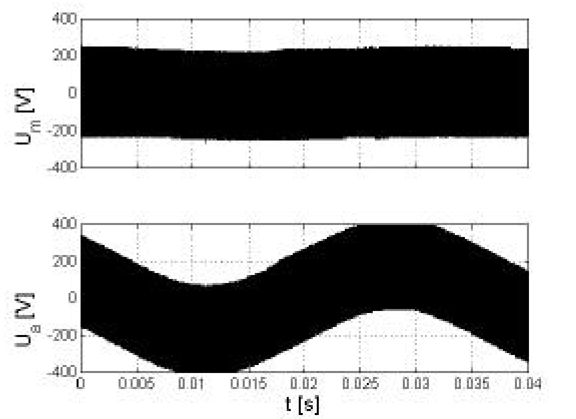

Fig. 16. Stator voltages, f = 30 Hz, C = 30 μF.

Operation with various phase shifts between the main and auxiliary winding supply voltages was tested. Fig. 13 illustrates the situation for 75° (871 rpm, 240 W) and Fig. 14 for 105° (921 rpm, 272 W). It can be noted that the latter case is more suitable for the given load and the pulsations of the electromagnetic torque are reduced.

Operation of the drive at half speed is illustrated in Figs. 15 and 16. An AC capacitor of 30 μF was used as a motor-run capacitor. The mechanical speed was 527 rpm and the load was 6.5 W. Fig. 16 shows the supply voltages at the stator windings terminals. It should be noted that the voltage stress for the auxiliary windings increased significantly in this mode of operation.

IV. CONCLUSIONS

The theoretical and experimental results have proved the viability of the proposed drive setup and a possibility of its use in the considered HVAC applications. The drive represents a low-cost solution how to increase the energy efficiency of the HVAC device. It enables the device to operate with lower output by controlling the speed allowing, therefore, for significant gain in energy efficiency in comparison to mechanical regulation of the output profile of the fan. The presented solution minimizes also the number of semiconductor switches used in the inverter.

The power electronics in the drive may be rated just for a fraction of the power consumed by the machine significantly reducing, therefore, the losses in the semiconductor components. This also results in a smaller heat sink as well as in lower manufacturing costs. The proposed design also enables temporary operation with the supply of the motor directly from the mains in the case of an inverter failure. This would, however, require use of an AC capacitor with a higher voltage rating.

In this paper a two speed drive operating at two discrete frequencies, 30 and 60 Hz has been considered. In general, the inverter can also operate over a wide range of frequencies less than 60 Hz if the load has a fan type characteristic. In such a case, the AC capacitor does not have the proper value that would correspond to the supply frequency and, therefore, the torque pulsations increase. However, this might not represent a serious problem for an HVAC type of applications and further research will be carried out in this area.

An experimental drive based on the proposed design was developed and is currently undergoing testing at the University of Wisconsin - Madison in order to analyze the real-operation properties of this design. The experimental results achieved so far suggest that the proposed drive can be a viable solution for the intended class of applications.

ACKNOWLEDGEMENT

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REFERENCES

[1] N.P. van der Duijn Schouten, B.M. Gordon, R.A. McMahon, M.S. Boger, "Integrated Drives as Single-Phase Motor Replacement," in *Conference Records IEEE/IAS Annual Meeting*, 1999, pp. 922-928.

[2] M.B.R. Correa, C.B. Jacobina, A.M.N. Lima, and E.R.C. da Silva, "Single-Phase Induction Motor Drives Systems," in *Conference Records IEEE/APEC*, vol. 1, 1999, pp. 403-409.

[3] D. Jang, D. Yoon, "Space Vector PWM Technique For Two-Phase Inverter-Fed Single-Phase Induction Motors," in *Conference Records IEEE/IAS Annual Meeting*, 1999, pp. 47-53.