Efficiency Investigation of an Induction Motor drive system with Three Different Types of Frequency Converters with focus on HVAC applications

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SUMMARY

This paper discusses the efficiency of induction motor drives for HVAC applications, based on measurements made on three 4kW induction motor drives. Both converter efficiency as well as induction motor efficiency is studied and in particular the total system efficiency is determined. Measurements have been performed on a 4kW induction motor fed by three different types of frequency converters. Converters A and B use an open loop, constant flux control, where B has a L-C filter on its output. Converter C uses an open loop, field weakening algorithm but also a special pulse width modulation (PWM) technique in order to reduce the switching losses in the converter. Simulations and measurements have shown that an efficiency improvement of the system can be achieved using a field weakening algorithm which improves the efficiency at light load with 18% at 30Hz which in particular is of importance in HVAC applications. At full load the difference in efficiency is negligible between system A and C but 3% lower using system B due to the sinus filter. Efficiency improvements were also accomplished by using the special PWM technique. It was also found that it is important to make a complete optimization of the energy efficiency. Using system B, with L-C filter, gives higher machine efficiency but a low overall efficiency due to high converter losses. As a general conclusion, it has been shown that system C was the best solution from an efficiency point of view for a typical HVAC application.

INTRODUCTION

Electrical machines for HVAC applications contributes to approximately 40% (320TWh) of the energy consumption of electrical machines in EU(1996) [1]. The flow from pumps and fans are often mechanically controlled by valves, which leads to a reduced efficiency of the system. A better approach is to allow the pump/fan to determine the flow [2]. This is done by using a frequency converter, adjusting the voltage and the frequency of the motor to meet the demand of the load. This type of drive system has become more common throughout the years due to the energy savings that can be made. The energy efficiency of an induction machine (IM) is relatively high at optimal load and speed. However, in many situations, the load is not optimal. A common practice regarding dimensioning of drive systems are to use a 10% marginal and then choose the next available size above this limit [3]. As a result, the drive system can in some cases become highly over dimensioned and will not be operating at its optimum. Furthermore, drive system used in HVAC applications are often season/weather dependent and will be operating at light load during extended time periods [4]. It is therefore of great importance to optimize the energy efficiency over the whole operating range. Hence, it is of interest to investigate efficiency improvements, both in the frequency converter but also in the IM which can be done with design and control of the system. However, this paper will be focused on the issues regarding control. There are several control techniques in order to minimize the losses in the converter. Techniques related to the minimization of the switching losses have been proposed in [5, 6]. However, the described technique in this paper is only mentioned briefly.

Efficiency improvements of the IM can be made using optimal volt/frequency control which is described in detail in [4] and will just be mentioned briefly in this paper.

The purpose of this paper is to investigate the different loss components in a drive system consisting of an IM fed by a frequency converter. Moreover a goal is to use measurements and simulation to determine the difference using three types of converter technologies.

SYSTEM DESCRIPTION

Measurements where made on three different types of frequency converters feeding an IM. The different systems are referred to as A, B and C.

The frequency converter used in system A was a 4kW converter using constant voltage/frequency ratio.

Converter B contained a 4kW frequency converter with same control as system A. The converter was also equipped with an internal L-C filter on its output, which reduced the harmonic content significantly compared to system A and C.

Converter C used a field weakening algorithm but also a special pulse width modulation (PWM) technique in order to reduce the switching losses in the converter. At each half period the switching was stopped for 60° when the phase voltage was around its peak voltage.

LOSS COMPONENTS IN AN INDUCTION MOTOR DRIVE

The drive system of consideration is an IM fed with a frequency converter, shown in figure 1. The different losses that occur in the IM are resistive losses in the stator and rotor, core, mechanical harmonic and stray losses.

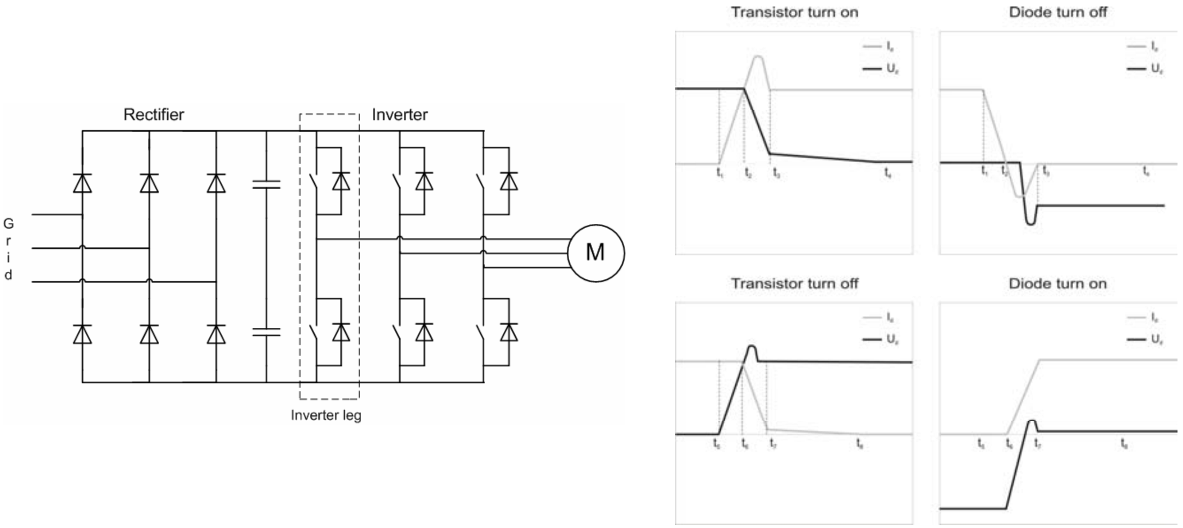


Figure 1a) Schematic figure of a frequency converter feeding an IM.

b) Turn on and turn off voltage and current waveforms

These losses has been measured separately according to the IEEE standard 112-1991 method B [7].

The different loss components in a frequency converter are much more complicated to measure/estimate due to the compact construction of the device. Hence, the measurement in this study did not consider these losses separately. Instead the total loss components of the frequency converters were measured. The loss components are on state losses in the diode rectifier and in the inverter stage and switching losses in the inverter stage.

IMPROVEMENTS IN ENERGY EFFICIENCY

The improvement in energy efficiency can be divided into two broad groups, the design of a drive system and the control of the system. This section will describe the factors that improve the energy efficiency related to system C which both falls under the category of control.

PWM switching strategy

The most commonly used control technique in converters is Pulse Width Modulation (PWM). The PWM voltage is a pulse train of fixed magnitude and frequency with variable pulse width. The pattern is created by comparing a modulating carrier wave with a reference wave. If the frequency of the carrier wave is increased the switching frequency of the converter also increases. The choice of switching frequency are balance between switching losses in the converter and harmonic losses as well as torque pulsation in the IM, (of course physical limitations of the device must be taken into account). Furthermore, the switching losses also depend on the load type, which in this case is inductive. Typical voltage and current waveforms for turn on and turn off of an inverter leg feeding an inductive load can be seen in figure 1b.

This paper will investigate a discontinuous PWM technique which stops the switching at different time durations during the peak voltage, figures 2a) and b) shows examples of the continuous and discontinuous PWM scheme respectively. However, during continuous PWM sampling, at the so called over modulation, the switching stops for a certain time interval, ie when the voltage reference amplitude is higher than the carrier wave. This occurs at frequencies of approximately 40Hz for the investigated case when constant voltage/frequency ratio is used.

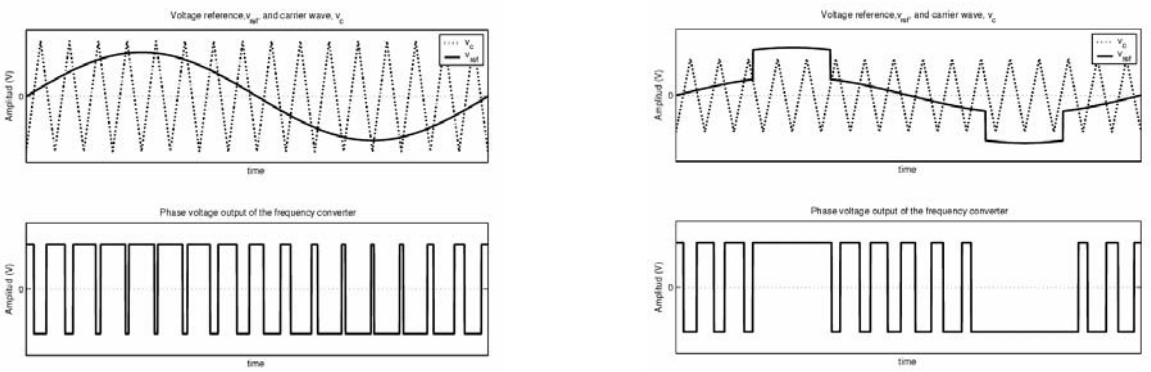


Figure 2a) Continuous PWM b) Discontinuous PWM

Optimal Voltage/frequency control

Improvements in energy efficiency of the IM can be made with different control strategies. A simple control strategy is the constant air-gap flux control which keeps the ratio between voltage and frequency (V/Hz) constant at all loads, (system A and B). However, every loading situation can be achieved with various combinations of voltage amplitude and frequency and it can be shown that there is an optimal frequency and an optimal voltage at each loading point [8,9]. The goal is to control the voltage and the frequency in order to optimize the balance between the copper and iron losses [4]. Different control strategies can be divided into three groups, *Power factor control* [10,11], *model based control* [12-14] and *search method* [15-18]. Evaluation and description of the different methods can be found in [4]. A previous work [4] has shown that the improvements in efficiency has a larger effect at light loads and are therefore suitable for HVAC systems where the power demand varies with the square or the cube of the speed. Furthermore, many HVAC applications, as mentioned in the introduction, can be assumed to operate on reduced load for a long period of time. Furthermore, over dimensioning of HVAC system also contribute to lower efficiency in constant air-gap flux control since the motor now constantly is lightly loaded. Figure 3 shows a simulation of the efficiency using optimal control and constant voltage/frequency control. The applied load is representing a pump/fan.

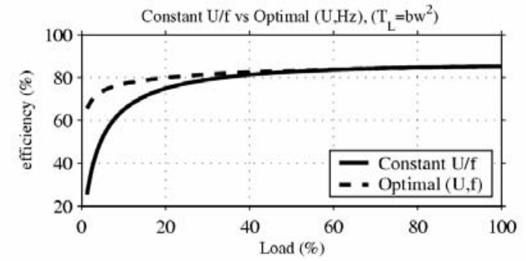


Figure 3 Optimal control and constant voltage/frequency control of an IM. The load is represents a pump/fan

Simulation of inverter switching losses

Calculation of the switching losses were made using Matlab Simulink ®. A state space model of the three phase IM used during the measurement where constructed, fed by a frequency converter using a switching frequency of 18kHz. At each switching instant, current magnitude and the conducting device where detected (i.e. if the current was flowing in a transistor or the freewheeling diode). The losses were then calculated using the voltage and current waveforms shown in Figure 1b using the datasheet of an IGBT type IRGPS40B120UDP.

TESTEQUIPMENT

The measurements were performed on one standard 4kW, 4 pole IM, and three different types of frequency converters A, B and C. The drive system was loaded using a DC machine and the test procedure was equal to all system setups. The various loadings were represented by sweeping the frequency between 10Hz and 60Hz with 5Hz increments. The drive system was operated at the same loads at each frequency, with the exception for the over rated loading points at the lower frequencies.

Table 1 Measurement equipment

Type	**Model**
Torque transducer	Tn 30
Power analyze	Norma 61D2
Power analyze	Yokogawa WT
Digital Oscilloscope	Lecroy 9304 CM
Ohmmeter	CM 1703
Stroboscope	1531 AB
Data aquision card	PC - MIO - 16E -1

MEASUREMENT RESULT AND ANALYSIS

Measurements were performed according to the description found in the previous section. Figure 4 a) and b) shows the different loss components for system C at 50Hz and varying loads. It can be noted that the mechanical and core losses are increasing with increasing load. This is due to the fact that the voltage in converter C is decreased at decreasing load, which differs from system A and B which has a constant core loss component due to the constant V/Hz control (the mechanical losses can be assumed constant in all three systems at a fix frequency). The resistive loss component are naturally increased with increasing load so is the converter loss component due to the increased power transfer.

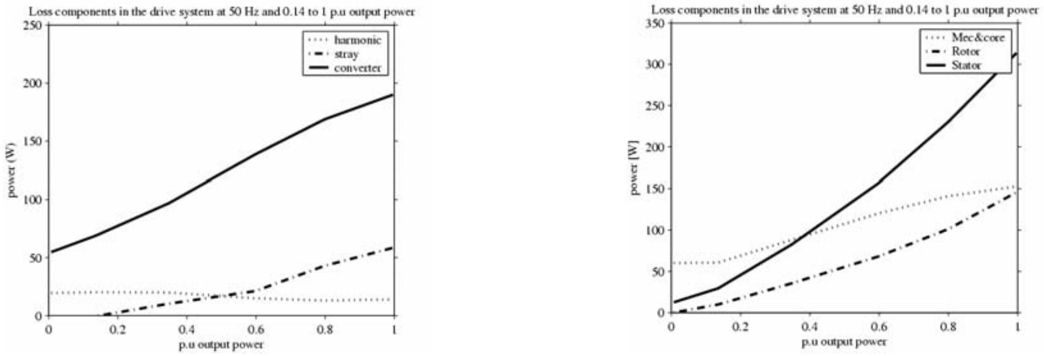


Figure 4a)Measured harmonic, stray and converter losses at 50Hz

b) Measured mechanical+core, rotor and stator losses

Efficiency of the frequency converters

Figure 5a) shows the efficiency of the three converters at two load situations, 0.14 pu and 0.6 pu output power respectively. It can be seen that the difference in the efficiency decreases as the load increases and that converter B has the lowest efficiency while converter A has the highest.

Efficiency of the IM

Figure 5b) shows the efficiency of the IM in the three cases. It can be noted that system A and B has the lowest and the highest efficiency respectively. It can also be noted that the difference is higher at light load. This is due to the field weakening algorithm used by converter C as was explained in the previous section. The converter lowers the output voltage at lower load. As a result, the iron losses are reduced significantly compared to the other systems.

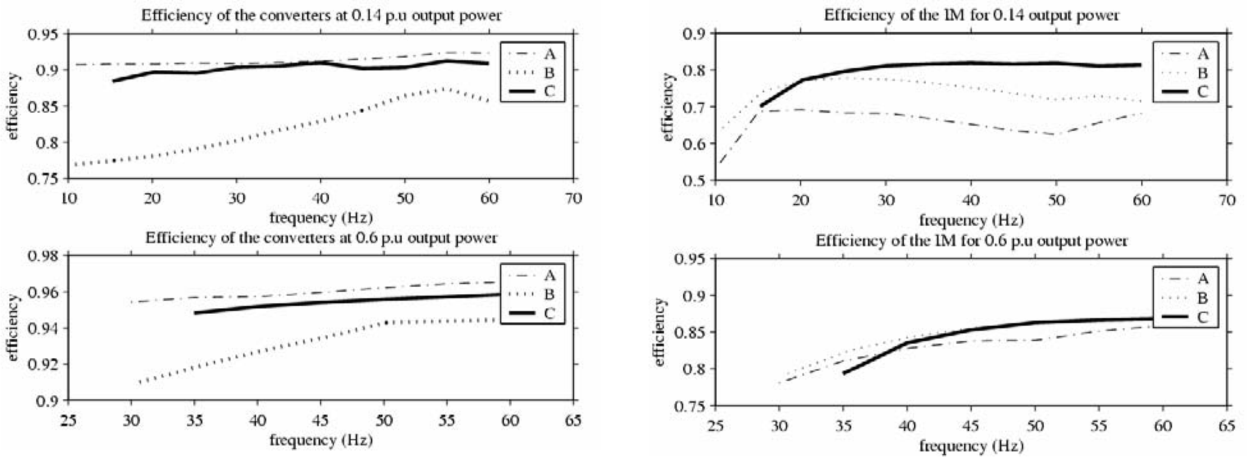
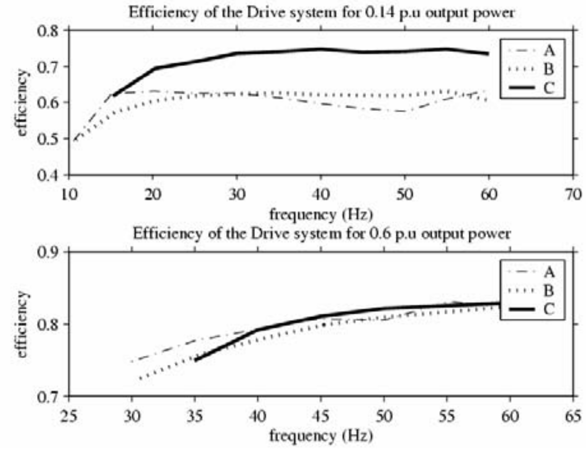


Figure 5a) Calculated efficiency of the converters using measurement data b) Calculated efficiency of the IM



c) Calculated efficiency of the drive system using measurement

Efficiency of the whole drive system

Figure 5c) shows the efficiency of the whole drive system. System C has the highest efficiency due to its field weakening algorithm but also due to its PWM switching scheme.

COMPARIOSON BETWEEN SYSTEM A, B AND C FOR HVAC APPLICATIONS

Figure 6 shows a typical annual load cycle for a variable air volume (VAV) system according to [19]. The operating time is assumed to 8760h (one year). It is further assumed that the system is 25% over dimensioned. The estimated energy consumption using the measurement data is presented in table 2.

Table 2

System	Yearly consumption (kWh)	Difference (kWh)
A	19270	152
B	19368	250
C	19118	0

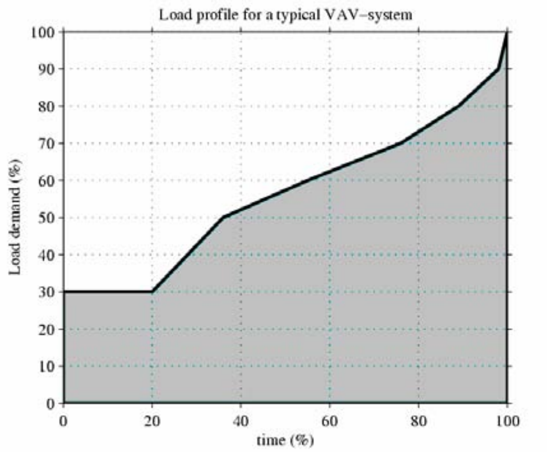


Figure 6 Annual load profile of a VAV-system

Simulation result

The above VAV-system was adopted as the load to the simulation model described in previous section. The switch stop at each half period was set to 0-80 degrees with 20 degrees increments. Figure 7 shows a decrease in the switching losses as the switch stop period increases, as expected. It can also be noted that the losses starts to decrease at certain load points which is due to the natural switch stop at over modulation mentioned earlier.

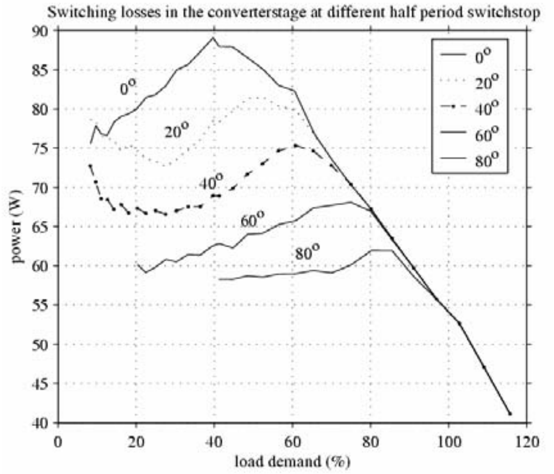


Figure 7 Switching losses in the converter at different half period switch stop. The IM is feeding the fan.

CONCLUTIONS

It was found that it is important to make a complete optimization of the energy efficiency. Using system B, with its special filter, gives higher machine efficiency but a low overall efficiency due to high converter losses. As a general conclusion, it has been shown that system C was the best solution from an efficiency point of view for a typical HVAC application. This is mainly due to the field weakening algorithm. Regarding the switching techniques improvements can be made. However, the relative difference was found small using this type of IGBT and switching frequency, especially at high load due to the over modulation of the converter.

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