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THE IMPACT OF INVERTER LOSSES ON HEAT PUMP PERFORMANCE

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ABSTRACT

Inverter-driven heat pumps have achieved a growing importance. The most commonly used inverter type uses pulse width modulation (PWM). Inverter harmonics and the corresponding distortion currents influence the overall heat pump characteristic. Mechanics and magnitude of these losses are not well-known yet.

For that reason a simple inverter model with three empirical parameters has been developed. The inverter losses can be calculated in relation to the normalised output current and the internal switching frequency. The latter is used, since the frequency dependent losses are caused by the switching losses of the semiconductors used.

State of the art PWM inverters achieve an efficiency between 80% and 96%, provided that the optimal magnetic flux, a function of the voltage/frequency ratio, is established. In addition secondary losses in the range of 4% of the nominal motor losses are produced in the induction drive due to inverter induced harmonics. For switching frequencies higher than 1kHz these losses become negligible.

NOMENCLATURE

\[ \Delta P_0^* \] dimensionless inverter base power consumption
\[ \Delta P_{\text{i}}/P_{\text{i,N}} \] inverter losses related to nominal inverter power
\[ \Delta P_{\text{mot}} \] motor losses
\[ AC \] alternating current
\[ DC \] direct current
\[ C_1 \] constant for inverter switching losses
\[ C_2 \] constant for inverter conduction losses
\[ C_3 \] constant for inverter resistance losses
\[ C_D \] constant for modulation method (distortion current)
\[ C_R \] constant for the influence of skin effect
\[ f_1 \] mains frequency \((= 1/T_1)\)
\[ f_R \] induced rotor frequency
\[ f_S \] fundamental stator frequency
\[ s \] relative rotor slip \((= f_R/f_S)\)
\[ f_{\text{sw}} \] switching frequency
\[ l_1; l_1 \] mains current; RMS value
\[ l_0; l_0 \] distortion current; RMS value
\[ i_S; i_S \] stator current; RMS value
\[ l_S/l_{\text{i,N}} \] actual to nominal inverter output current
\[ L_m \] magnetising inductance
\[ L_R \] rotor inductance
\[ L_S \] stator inductance
\[ m \] number of phases (usually 3)
\[ P_S \] stator power, single phase
\[ R_R \] rotor resistance with skin effect
\[ R_m \] magnetising resistance
\[ R_R \] rotor resistance
\[ R_S \] stator resistance
\[ t \] time
\[ u_1; u_1; u_1 \] mains voltage; RMS value; amplitude
\[ u_D \] distortion voltage
\[ u_S; u_S; u_S \] stator voltage; RMS value; amplitude
\[ u_S; u_S \] fundamental stator voltage
\[ U_{S,N; I_{S,N}} \] nominal stator values
INTRODUCTION

Heat pump / air conditioners with capacity control have become a well established technology over the past years. The capacity control is achieved by varying the compressor speed continuously by means of an inverter, i.e., a static frequency converter that serves as a power supply. Thereby the compressor drive, an induction motor, can be provided with adjustable voltages and frequency. Inverters are mostly of the pulse-width modulating type (PWM Inverter). The settings of the inverter and the harmonics, caused by the principle of PWM, not only change the inverter characteristics but also influence the operating behaviour of the induction motor. Primary losses, i.e., losses within the inverter, and secondary losses, i.e., inverter related losses in the induction motor, are especially relevant for heat pumps, since they influence the coefficient of performance (COP) directly. For that reason the basic electrical fundamentals relevant for the inverter motor characteristic will be summarised. Furthermore, electrical models to take these losses into account are established and described [Afjei 93; Jenni/Wüest 95].

THEORETICAL BACKGROUND

Equivalent Circuit of Inverter and Induction Motor

Speed variation with inverters (or more precisely expressed, AC-AC-converters) became feasible due to the favourable cost development of solid-state electronics. Fig. 1 shows a single phase equivalent circuit of the AC-AC-converter in combination with the induction motor.

\[ u_1 = \hat{u}_1 \sin(2\pi f_1 t) = U_1 \sqrt{2} \sin(2\pi f_1 t) \]  

Principle of Pulse Width Modulation

The AC-AC-converter consists of a rectifier, a DC-voltage link and an inverter. The diode rectifier D rectifies the one or three phase AC-voltage \( u_1 \) of the mains into a DC-voltage. The mains currents created by this simple rectifier are distorted, i.e., they contain harmonic distortions. The DC-link capacitor acts as a filter for this DC-voltage. It decouples the mains from the inverter. The complete inverter, consisting of 6 semiconductors \( Tr \) with turn off capability, generates the three phase stator voltage \( u_S \) for the asynchronous motor. The amplitude \( \hat{u}_S \) and the frequency \( f_s \) of this output voltage can be varied according to the needs of the motor.

The inverter output voltage is a square wave voltage. It consists of pulses with a frequency \( f_{sw} \) higher than the fundamental frequency \( f_s \); typically \( f_{sw} \) is in the range of some kHz. The width of these pulses is generated by means of a pulse width modulation in such a form that its short time average value equals the desired stator voltage \( u_S \) of the motor. By means of a Fourier analysis the stator voltage can be described by a (wanted) fundamental voltage \( u_{S,1} \) with the frequency \( f_s \) and by voltage distortions \( u_o \) with frequencies much higher than \( f_s \) as shown in fig. 2. Undesired harmonics, causing the distortions, can be shifted to higher frequencies by maintaining a high ratio between switching and inverter frequency, i.e., a high carrier ratio \( f_{sw}/f_s \).
Fig. 2: left: stator voltage \( u_s \) and its fundamental wave \( u_{s1} \) for a carrier ratio of 7
right: fourier spectra of the stator voltage \( u_s \) and the distortion current \( i_D \) for a carrier ratio of 15

**Inverter Losses**

The inverter efficiency, a crucial key value for the overall COP of the heat pump, can be calculated with a comparatively simple model. It considers in a general way the most influential electrical effects in PWM inverters contrary to a pure mathematical curve fit, that would only be applicable for a certain inverter type.

In fig. 3 the efficiency and the absolute losses of a PWM inverter are depicted. It can be seen that the efficiency and the absolute losses enlarge with increasing frequency and load (load \( \propto \) inverter output current). Interesting in this context is that the inverter efficiency and the inverter losses are maximal at the highest load and switching frequency. This means that the losses become less significant at higher input performance.

Fig. 3: left: efficiency of a pulse width modulating inverter in dependency of the load and the frequency
right: proportions of absolute inverter losses in relation to the switching frequency and the output current

A closer examination of the functional principle of PWM inverters showed that the absolute inverter losses remain constant as long as the internal switching frequency \( f_{sw} \) and the output current \( i_S \) are fixed. The switching losses in the semiconductors increase proportionally with the switching frequency; there is no direct relation between the inverter losses and the output frequency. Equation 2 shows how the inverter losses, normalised with the nominal power, can be calculated as a function of switching frequency and output current by using three empirical parameters.

\[
\frac{\Delta P}{P_{IN}} = \Delta P_0^* + C_1 \left( \frac{f_{sw}}{f_{SN}} \right) \left( \frac{i_S}{i_{SN}} \right) + C_2 \left( \frac{i_S}{i_{IN}} \right) + C_3 \left( \frac{i_S}{i_{IN}} \right)^2
\]
Phenomena in Induction Motor

The single phase model of the induction motor (cf. with fig. 1) can be divided into three parts: (1) the stator circuit consisting of the stator resistance \( R_S \) and the inductance \( L_S \); (2) the magnetising inductance \( L_m \) together with the resistance \( R_m \) representing the iron losses belonging to the stator and the rotor circuit; (3) the rotor modelled with the inductance \( L_R \) and the rotor resistance with the resistor \( R_R \).

There are two main effects that influence the losses of inverter driven induction drives unfavourably: The skin effect and the current distortions.

The skin effect is an increase of the resistance at higher frequencies. It is significant, because the conductors in the rotor circuit of squirrel cage induction motors consist of big rods yielding higher losses at higher frequencies due to their size. Especially motors designed for a direct start-up at the mains show a marked skin effect. For distortion currents the increase of the resistance can be approximated for a typical size of the rotor conductors.

\[
R^* = R_R \left( 1 + \frac{\sqrt{f_{sw}}}{C_R} \right), \text{ with } C_R = 4 \text{ for standard motors}
\]

The distortion current \( I_0 \) caused by the non sinusoidal PWM inverter output voltage can also be described by an approximation

\[
I_0 = \frac{U_{S,1}}{C_D f_{sw} (L_S + L_R)}, \text{ with } C_D = 135 \text{ for six step control } \left( f_{sw} = f_1 \right)
\]

\[
= 15 \text{ for PWM } \left( f_{sw} > 7f_1 \right)
\]

Moreover other effects such as the torque ripple or the extra noise may have a negative impact on the compressor performance:

The current distortions cause additional motor losses and also a ripple of the torque at the motor shaft having an unfavourable influence on the compressor efficiency. However with a sufficient high switching frequency of the inverter the amplitude of this ripple is very low. Further it is damped by the inertia of the motor and the compressor. The torque ripple can be disturbing when using very low switching rates for the PWM, e.g. six step modulation.

The voltage distortions produce an extra noise with frequencies different than those generated by the fundamental of the stator voltage. This noise and eventually occurring mechanical resonances that are stimulated in the system can be very disturbing.

Losses of Induction Motor

The motor losses are of particular interest in hermetic compressors, since they may have a strong impact on the mass flow efficiency. Depending on their origin the losses of an inverter driven induction motor consist of four main parts:

- copper losses in stator and rotor
- iron losses
- friction or machine losses (here not associated with the motor, but to the compression unit)
- additional losses due to the distortions by the non sinusoidal inverter output voltage

If the motor is supplied with a sinusoidal voltage, i.e., without inverter, the motor losses \( \Delta P_{mot} \) can be determined with \( P_S = U_S I_S \cos(\phi) \) and \( 0.7 < \cos(\phi) < 0.9 \) as

\[
\Delta P_{mot} = m \left( 1 - s \right) \left( R_S I_S^2 + \frac{U_S^2}{R_m} \right) + s P_S
\]

The above equation can be extended to consider also the skin effect and the current distortions

\[
\Delta P'_{mot} = m \left( 1 - s \right) \left( R_S I_S^2 + \frac{U_S^2}{R_m} + R_S I_0^2 \right) + R_R I_0^2 + s P_S
\]
These additional losses depend strongly on the switching frequency used for the PWM as can be seen at the left side in fig. 4. The rotor resistance $R'_R$ increases with the power of 0.5 due to the skin effect. The distortion current $I_D$ decreases with the power of -1. Both counteracting effects yield rotor losses that decrease with the switching frequency. At the right side of fig 4 it is shown that the total motor losses amplify slightly with the inverter output frequency and voltage. There the switching frequency and the torque are fixed ($I_Q$=constant). A fixed torque can be maintained by lifting the voltage/frequency ratio at low stator frequencies to compensate the voltage drop over the stator impedance.

![Fig. 4:](image)

**Fig. 4:** left: distortion current, rotor resistance and rotor losses vs. switching frequency
right: motor losses vs. stator frequency at fixed magnetic flux and switching frequency

To convey an idea of the order of magnitude of the secondary inverter losses, a 7.5 kVA machine is used as an example. Supplied directly from the mains the nominal motor losses are 1013 W. For a six step inverter the additional losses are about 100 W, i.e., 10% of the nominal motor losses. Using PWM with a switching frequency of 1 kHz these losses decrease from 10% to about 4% of the motor losses. This example shows that with increasing switching frequency the secondary inverter losses become negligible.

**EXPERIMENTAL RESULTS**

![Fig. 5:](image)

**Fig. 5:** Comparison between calculated and measured inverter losses as a sample (left: output current fixed at 12 A; right: switching frequency fixed at 1100 Hz)

The actual losses of a PWM inverter (15kW nominal power) have been measured with a precision wattmeter at different operating points and calculated according to equation 2 for the corresponding switching frequency and output current. The values obtained from the measurement and calculation are depicted in fig. 5 over the switching frequency (left) and the output current (right). The resulting deviation between the calculated and the measured inverter efficiency is given at the right hand side of each graph. This deviation, in the average lower than 1%, is in the range of the achievable accuracy of the power measuring equipment.
Optimal Voltage/Frequency Ratio

For each type of induction motor an optimum voltage/frequency ratio exists, where the motor operates under optimum conditions, i.e., minimised electric power consumption. If the voltage frequency ratio is too high magnetising current and the iron losses are excessive. If it is too low the rotor slip rises to an unreasonable level so that the rotor currents and the copper losses are excessive [Murphy 88]. The left side of fig. 6 shows the phenomena taking place if the voltage/frequency ratio deviates from the optimal range. The right side depicts the measured power consumption of a scroll compressor as a function of the voltage amplification setting for different inverter frequencies with the torque (load) held constant. The experimental data show that for the measured compressor the optimal voltage amplification is between 60% and 80%. An unfavourable selection can increase the power consumption of the compressor by up to 10%.

Impact on the Heat Pump Performance

The heating COP of inverter driven heat pumps is mainly affected by the primary inverter losses. With state of the art PWM inverters an average COP reduction between 8% and 15% can be expected. This disadvantage however is compensated by a better adaption of the heating capacity to the system needs. Practical experiences show that an overall improvement in seasonal performance factor (SPF) of 17% and more can be achieved due to reduced storage and cycling losses [Henderson 90].

CONCLUSIONS

The inverter efficiency of commonly used pulse width modulation inverters can be calculated with a simple model using three empirical constants. Experiments show that the efficiency varies between 80 and 96 %, where the maximum occurs at high speed and load. Secondary inverter losses in the induction motor can also be calculated by considering the skin effect and the distortion currents as main dissipation sources. For inverter switching frequencies higher than 1 kHz these additional losses become negligible (<1%). It is crucial to adjust the inverter parameters precisely, such as the voltage/frequency ratio to the motor characteristics. The reduced heat pump COP is compensated by a better system efficiency. Altogether an improvement in SPF of 17% and more can be achieved with inverter driven heat pumps.

REFERENCES

[Afei 93] Scrollverdichter mit Drehzahlvariation, PhD thesis No. 10069, Swiss Federal Institute of Technology Zurich, CH.

[Henderson 90] A Side by Side Test of Variable-Speed and Constant-Speed Air Conditioners, ASHRAE AT-90-29-1 (3378), USA.

[Murphy 88] Power Electronic Control of AC Motors, Pergamon Press, UK.

[Jenni/Wüest 95] Steuerverfahren für selbstgeführte Stromrichter (to be published), Professur für Leistungselektronik, ETHZ, CH.