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DETERMINATION OF THE ENERGY CONVERSION EFFICIENCIES OF INVERTER-FED INDUCTION MACHINES

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Content

Rising cost of energy and diminishing resources have caused the efficiency of electric drives to become increasingly important so as to improve a system's overall energy conversion efficiency. Furthermore, the efficiency affects the economics of machine operation, as any increase in efficiency conversion efficiency translates into energy savings over the entire lifetime of the machine.

The number of inverter-fed induction machines, used for a large variety of drive applications, has been steadily increasing over the recent years. This is due to the many advantages of the inverter supply, notably the large energy saving potential when compared to conventional power adjustment. However, while the energy savings at system level can be significant, mainly because of the added controllability, the inverter operation also increases the losses occurring within the electric machine and thereby reduces the energy conversion efficiency of the latter.

This contribution analyzes the determination of the energy conversion efficiency of inverter operated electric machines according to the standard IEC 60034-2-3 and the possibility to apply the standard IEC 60034-2-1, which defines the efficiency determination for line-operated machines, to inverter operated machines too.

Practical implementation

The efficiencies were analyzed for four off-the-shelf delta-connected four-pole three-phase 50 Hz 400 V squirrel cage induction machines, rated at 3, 7.5, 11 and 15 kW (Fig. 1).

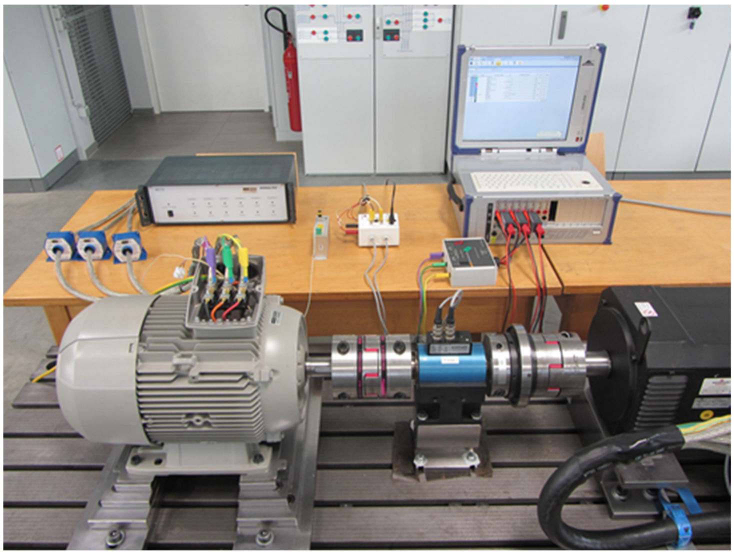

Figure 1: Test setup for efficiency analysis of inverter-fed induction machines

Measurement setup

The test bench comprised a 92 kW synchronous machine used as load, mechanically coupled to the respective induction machine under test. The torque was measured via a torque sensor Kistler 4503A500WA2B1C00. Depending on the test to be carried out, the induction machine was supplied via a variable laboratory voltage (0 – 600) V or via an off-the shelf 400 V industrial inverter.

All measured signals were read and processed with the transient recorder DEWE 5000 at a sampling rate of 500 kHz for PWM inverter operation, and at 100 kHz for sinusoidal supply.

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Efficiency determination according to the standard IEC 60034-2-1

First, the efficiency and the separate losses were determined per indirect measurement, according to the standard IEC 60034-2-1. Even though these standards is only defined for line-operation, it was applied both for sinusoidal as well as for inverter supply. The stator and rotor copper losses P_S and P_R were determined by load tests. The sum of these losses gives the so-called load losses P_L. The constant losses P_c, as the sum of the iron losses P_{fe} and the friction and windage losses P_{fw}, were determined by a no-load test. In the third step, the so-called additional load losses (stray-load losses) P_{LL} were determined by subtracting all the separate losses and the measured output power from the measured input power. From these three loss components, the energy conversion efficiencies were computed, for both supply types.

In addition, the total losses for sinusoidal supply P_{Tsin} were calculated from the individually determined loss components, for use in the efficiency determination at inverter-supply according to the standard IEC-60034-2-3.

Efficiency determination according to the standard IEC 60034-2-3

The efficiency at inverter operation was determined in accordance with the standard IEC 60034-2-3. For this purpose, the additional harmonic motor losses P_{HL} caused by the inverter were determined. The standard divides the additional harmonic losses into a load-dependent part $P_{HL,Load}$ and a load-independent (constant) part $P_{HL,No\text{-}load}$. The load-dependent part of the additional harmonic losses $P_{HL,Load}$ was determined as the difference between the additional load losses of both supply types, measured as described in the previous paragraph. The constant part of the additional harmonic losses $P_{HL,No\text{-}load}$ was calculated as the difference between the constant losses at both supply types, again measured as described in the previous paragraph. The total losses at inverter supply P_{TC} were calculated as the sum of the previously calculated total losses for sinusoidal supply P_{Tsin} and the total additional harmonic motor losses P_{HL}. From this, the efficiency for inverter operation was determined, including the total additional harmonic losses.

Results

The investigations showed a reduction in efficiency of (0.8 – 2) % by the inverter supply, when compared to the sinusoidal supply, due to the harmonic motor losses. The measured results also show that the inverter supply increases the stator and rotor copper losses by the additional inverter harmonics, and, even more significantly, the iron losses. The effect on the additional load losses, however, is relatively small.

It was also observed, that the efficiency for inverter operation calculated with the standard IEC 60034-2-1, which is only defined for sinusoidal supply, is always approximately 1 % larger than the one determined by the IEC 60034-2-3 standard.

Further analysis of the measured values also showed that the directly measured harmonic losses are almost independent of the load. On the other hand, the computed harmonic losses showed a clear load dependency. The constant part of the harmonic losses showed to correspond well to the directly measured harmonic losses. The difference between the calculated and the directly measured harmonic losses is therefore attributed to the load-dependent part of the calculated losses.

	3 kW Motor		7.5 kW Motor		11 kW Motor		15 kW Motor	
Type of supply	SIN	PWM	SIN	PWM	SIN	PWM	SIN	PWM
Efficiency by IEC 60034-2-1 / (%)	82.54	81.45	88.52	87.93	90.14	89.30	91.33	90.77
Efficiency by IEC 60034-2-3 / (%)	-	80.44	-	87.75	-	88.45	-	90.44
Stator copper losses P_S / (W)	219.9	216.9	354.7	361.6	456.7	482.7	535.2	558.4
Rotor copper losses P_R / (W)	125.2	136.9	168.4	173.8	213.2	235.7	274.3	289.6
Iron losses P_{fe} / (W)	114.4	133.4	138.5	157.9	202.4	235.7	242.6	277.7
Additional load losses P_{LL} / (W)	24.2	26.9	99.9	103.9	130.5	136.1	157.7	165.7
Total additional harmonic losses P_{HL} / (W)	-	74.4	-	66.2	-	214.4	-	149.9
Constant part of the additional harmonic losses $P_{H,LNo\text{-}Load}$ / (W)	-	14.7	-	26.89	-	40.09	-	45.8
Measured harmonic losses ΔP_{el} / (W)	-	16.9	-	36.6	-	49	-	67.8

Table 1: Results