Comparison of Efficiency Level for Induction Motor with Dahlander Winding in Direct on Line and via Frequency Converter Drive Connection

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Abstract **- One of the main issues with AC machines i.e. induction motors were speed regulation. In general, speed was mainly possible to regulate by changing number of poles or frequency of supply voltage. Also, smaller speed regulation was possible with changing voltage or load but this worked only for smaller ratio of drives so it will not be described here. Until frequency regulators (converters) reached certain level of development, both technical and economical, speed regulation was possible by changing number of poles. It was mainly done in one of two methods: Dahlander winding or separate windings in stator slots. One of deficiencies is that in Dahlander only combination of pole ratio is 2:1 e.g. 8 pole and 4 poles. Other is that speed is still constant depending on which number of poles you choose while when connected via frequency converter you can choose precisely at which speed i.e. frequency should the motor be rotating. In this paper, accent will be at measuring efficiency of the same motor when connected direct on line on a sine wave with different number of poles and using one pole number but driven via frequency converter and with speed regulation by changing frequency of supply voltage.**

Keywords – Dahlander winding, separate winding, frequency converter, induction motors, frequency converter

I. INTRODUCTION

Shortcomings of AC machines in comparison with DC machines through history was speed control. According to equation (1) we can see that synchronous speed can be altered with change of pole pairs or with change of frequency.

$$n_s = \frac{60f}{p} \qquad (1)$$

where n_s is synchronous speed of rotational magnetic field, f is frequency of supply voltage and p is number of pole pairs.

Pole pair change can be done only in discrete steps e.g. number of pole pairs can be one, two, three etc. while frequency can be changed as practically whatever value is needed. However, changing frequency was not available in common use until electronics i.e. frequency converters was adequately developed in technical and economical way in last 10 or 20 years when modern automatization era began. One of the key elements in automatization of industrial processes is speed control for better productivity and energy savings. Most used machine i.e. motor is AC induction motor with squirrel cage which is estimated to use more than 60% of electric energy worldwide [1], [3].

Before frequency converters became widely used in industrial applications, multi speed induction motors were made with stator winding modification to have different number of poles. One way was to have separate windings, mutually insulated, with different number of pole pairs in same slot and the other method was to use special winding in Dahlander connection with 6 or 9 leads which could be connected via terminals to a varying number of poles. Alteration of pole number in this way is possible in a ratio 2:1. Most commonly used combinations are 8 to 4 poles (8/4) and 4 to 2 poles (4/2) but other combinations are possible as well. To use this combination, it is necessary to have squirrel cage rotor because he can adjust to varying number of poles of stator. Number of poles of stator and rotor has to be the same for proper usage of motor without malfunctions [13]. In this paper conclusion will be made, through measurement on a single induction motor with varying number of poles, is it better to use motor with Dahlander winding or single speed motor driven via frequency converter. Parameter on the which emphasis will be for decision is arbitrarily efficiency of the motor because of constantly growing demand for efficiency in energy using products because of environmental issues [10], [11]. Motor speed control has saving potential of 50 billion kWh/year for EU-25 [14].

II. EQUIPMENT AND MEASUREMENT

A. Equipment

Motor that will be tested is induction motor with 3 speeds i.e. has 3 different pole number configuration that can be achieved with different terminal connection according to connection diagram as shown on figure (1). Number of possible pole numbers are 8, 6 and 4 where 8 and 4 poles are available with Dahlander winding (ratio 2:1) and 6-pole is separate winding in stator slots. In connection diagram n_1 stands for 8-pole configuration, n_2 is for 6-pole and n_3 is for 4-pole configuration. In all of this configurations motor will be connected directly to power

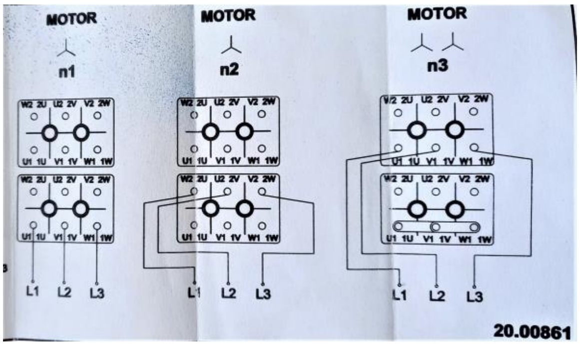

Figure 1. Connection diagram for tested motor

TABLE I. LOADING AND MEASUREMENT EQUIPMENT MOTOR

Tested motor	90S – 8/6/4 0,18 / 0,3 / 0,75 kW
Frequency converter	400 Vac, 8,9 kVA, 0-500 Hz
Load motor	400V, 50 Hz, 11kW
Torque transducers	TM 310/011
Torque and speed display	Model 3411, Magtrol
Data acqusition	NI USB 6212

grid supply voltage of 400 V and 50 Hz. Frequency change will be regulated with commonly used frequency converter of indirect type with DC circuit called voltage source inverters (VSI). Frequency converter provides a pulse width modulation (PWM) for a pseudo sinusoidal voltage and current waveform that allows a fine control of frequency, resulting in an efficient control of speed and torque. Speed regulation via frequency converter will be made only on 4-pole winding of the motor because at that speed torque requirement is highest. Frequency will be regulated to achieve nominal speed of 6-pole and 4-pole winding with corresponding load torque as it is defined on nameplate. Since 4-pole has highest speed, it means that motor will work in constant torque area for 6-pole and 4-pole speed [5]. It means that magnetic flux will also remain constant i.e. frequency converter will be controlled in scalar mode. Well known equation (2) which connects sinusoidal voltage and magnetic flux in electric machines, shows that ratio of voltage and frequency should remain constant in order to keep magnetic flux constant as shown in equation (3).

$$U = 4{,}44 N f \phi f_w \tag{2}$$


Figure 2. Testing station

$$\phi = \frac{U}{f}\frac{1}{4{,}44 N f_w} \tag{3}$$

Where N is number of turns of stator coils and f_w is winding factor.

Torque and speed are measured with torque transducers and signals were connected to the testing station. Loading machine is induction motor controlled with its own frequency converter for fine tuning of speed and torque. Measurement is made with NI DAQ cards and processed with software LabView. Data are also double checked with power analyzer instrument.

B. *Measurement*

Data that will be recorded are: speed, torque, mechanical power, electrical power and efficiency.

First measurement is done so that motor is connected direct on line on sine power supply of 400 V and 50 Hz. Motor is connected in star connection for 8-pole winding. Then 6-pole in star connection and after that 4-pole winding connection in double star connection is made and connected to the same power source. Counter load will be done by another induction motor that will be controlled with its own frequency converter for precise torque adjustment. After all the data are gathered, motor will be connected in 4-pole configuration and driven via frequency converter with three different frequencies corresponding to speed of 6-pole and 8-pole nameplate data. All of the data will be checked against each other before conclusion. Efficiency will be determined in direct method acc.to IEC 60034-2-1 [2] i.e. mechanical power, P_2, will be divided with electrical power, P_1.

$$\eta = \frac{P_2}{P_1} \tag{4}$$

III. INDUCTION MOTOR WITH MULTI SPEED WINDING

Tested motor has two windings in stator slot, one is Dahlander winding for 8 and 4-pole combination, and the other is separate winding for 6-pole configuration so it is obvious that because of three polarities, three nominal speeds are available depending on motor terminals connection to power supply.

Dahlander motor is also known as pole changing motor, dual speed motor or 2 speed motor. Motor works on single frequency. Speed regulated is based on controlling the number of poles i.e. poles can be varied at a ratio of 2:1 and thus the speed can be varied at ratio 1:2 [12]. Most typical connections for Dahlander winding are delta/double star (D/SS) for loads with constant torque such as machine tools, conveyors, hoisting equipment etc., double star/delta (SS/D) for constant power applications and star/double star (S/SS) for loads with variable torque such as fans and pumps when torque increases or decreases as the square of increase or decrease in speed like in figure (3). Tested motor has Dahlander winding for S/SS. Main idea of Dahlander winding, in short, is to divide each phase into two branches. When these two branches are connected in series then smaller number of poles will be formed. When they are connected in parallel, two times bigger number of poles will be formed as shown in figure (4). In order to have 8/4 combination of poles it is necessary to have 4 groups of coils in each phase and stator slot number is determined to fit higher pole number so it means that lower pole number probably will not have optimal stator slot number resulting in lower winding factor and therefore smaller efficiency in comparison with better suitable winding and stator slot combination for single speed motor, e.g. 4-pole single speed motor in this case [12].

When induction motor is operated with frequency change, it basically works in two areas, constant torque up to the nominal speed and constant power area with speeds higher then nominal [5]. As 8 and 6-pole configuration have smaller speed then 4-pole, that means it will work in area of constant torque. If a speed is too low, it should be checked whether the cooling is sufficient if the motor is cooled only with its own fan. Since 4-pole has the highest torque we are sure that motor will not be overheated during measurement acc. to frequency inverter drive chart for IC411 cooling type that most of motor manufacturer give in their catalogues for standard motors [6]. In such diagram it is shown that motor torque should be reduced to 90% of nominal at 40% of nominal frequency i.e. at 20 Hz for nominal 50 Hz to avoid overheating. Torques in our measurements are much lower at frequencies closer to nominal.

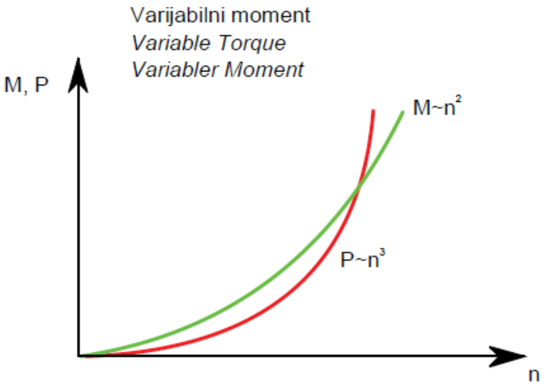

Figure 3. Pump and fan torque and power curve

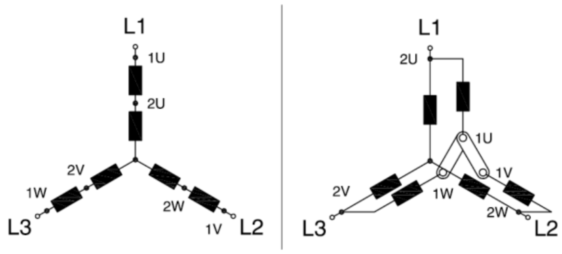

Figure 4. Star and double star configuration

IV. MEASUREMENT AND DATA ANALYSIS

Measurement was made only for nominal static working point without losses during start up taken into an account. Data measured and recorded are shown in table II. Electrical power is measured with data acquisition system from National instruments where measured currents and voltages were used and processed. This parameter was also extra measured with power analyzer Norma D4355 for insurance because it is crucial for efficiency calculation. Mechanical power is calculated by equation (5) with torque T and speed n measured.

$$P_{mech} = T \cdot \frac{n \cdot \pi}{30} \tag{5}$$

Working point was considered stable when torque transducer display showed nominal power because it has accuracy of 0,01 % for speed and 0,02 % of range for torque. All other mechanical and electrical data were written at that moment. After three measurements with different motor pole configurations connected to mains, frequency converter was connected to motor in a way so that grid voltage supply is connected to frequency converter input and its output is connected to motor as shown in figure (5). Motor terminals are arranged for 4-pole configuration i.e. double star connection or n_3 according to figure (1) because this is the most difficult loading point for motor with highest torque value.

Figure 5. Frequency converter and motor

TABLE II. COMPARISON BETWEEN NAMEPLATE AND MEASUREMENTS

MOTOR NAMEPLATE DATA								
POLARITY	FREQUENCY, HZ	CONNECTION AND VOLTAGE	CURRENT, A	SPEED, RPM	P MECH, KW	TORQUE, NM	P EL, KW	EFF, %
8 POLES	50	S 400	1,1	710	0,18	2,4	0,42	42,9
6 POLES	50	S 400	1,5	960	0,3	3	0,6	49,8
4 POLES	50	SS 400	2,6	1440	0,75	5	1,12	67,2
MEASURED DATA WHEN CONNECTED DIRECT ON LINE (SINE VOLTAGE)								
POLARITY	FREQUENCY, HZ	CONNECTION AND VOLTAGE	CURRENT, A	SPEED, RPM	P MECH, KW	TORQUE, NM	P EL, KW	EFF, %
8 POLES	50	S 400	1,19	714	0,18	2,4	0,44	**40,9**
6 POLES	50	S 400	1,59	964	0,3	3	0,63	**47,6**
4 POLES	50	SS 400	2,86	1450	0,75	4,9	1,18	**63,6**
MEASURED DATA WHEN 4-POLE WINDING IS CONNECTED VIA FREQUENCY CONVERTER								
POLARITY	FREQUENCY, HZ	CONNECTION AND VOLTAGE	CURRENT, A	SPEED, RPM	P MECH, KW	TORQUE, NM	P EL, KW	EFF, %
4 POLES	**24**	**SS 195**	1,14	678	0,18	2,5	0,43	**41,9**
4 POLES	**32**	**SS 265**	1,5	923	0,3	3,1	0,61	**49,3**
4 POLES	**50**	**SS 390**	2,65	1444	0,75	5	1,19	**63**

Frequency converter is connected in the simplest plug and play system and driven in scalar mode. No optimization was made such as: compensation of stator resistance and leakage inductance, slip gain, switching frequency increase etc. If some or all of these parameters were adjusted, even higher efficiency when connected via frequency converter can be expected. Switching frequency in parameters is only defined as low noise which is default value. Main goal of this paper is to show whether is better for industrial purpose to have multi speed motor with complex winding or simple and single speed motor driven via frequency converter from the aspect of efficiency i.e. active power consumption. Efficiency difference in observed conditions are also showed graphically with figure (6).

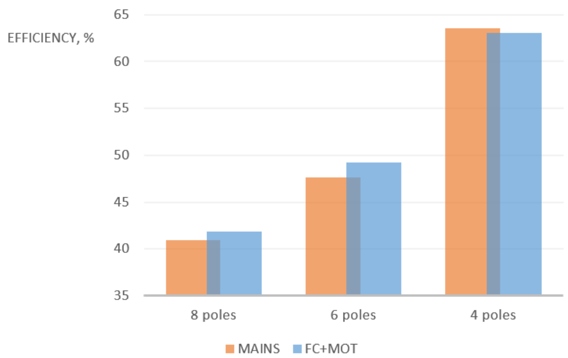

Figure 6. Efficiency levels mains vs frequency converter

V. RESULTS AND DISCUSSION

From efficiency distribution shown in table II and figure (6) it is justified to conclude that motor uses less electrical power in 4-pole configuration driven via frequency converter on different speeds i.e. frequencies corresponding to the speeds of 6-pole and 8-pole winding configuration connected directly to the grid. Exception is for 4-pole configuration because frequency inverter losses increase total losses of the system motor – inverter – load. Efficiency of the system in that way is mostly higher. That leads to assumption that is economically more cost effective to have a single speed motor purchased who is initially cheaper but also have better winding factor because of optimal stator slot and winding distribution for its polarity. Better winding factor leads to better performance in entire spectrum of speeds that could be achieved with motor with multi speed windings, Dahlander or separate winding. Single speed motor has more copper in stator slot because it is entirely used just for one winding what leads to smaller stator winding losses which means smaller heating of motor. Tested motor has 0,75 kW mechanical load capability on 4-pole winding configuration in IEC frame size 90. Single speed 4-pole motors in that same frame size are standardly designed for 1,1 kW, and 0,75 kW is available in IEC frame size 80 [7]. Minimal allowed efficiency for single speed, 4-pole motor connected to 50 Hz at 0,75 kW of mechanical power is 82,5% [1]. It is realistic to assume that such motor even

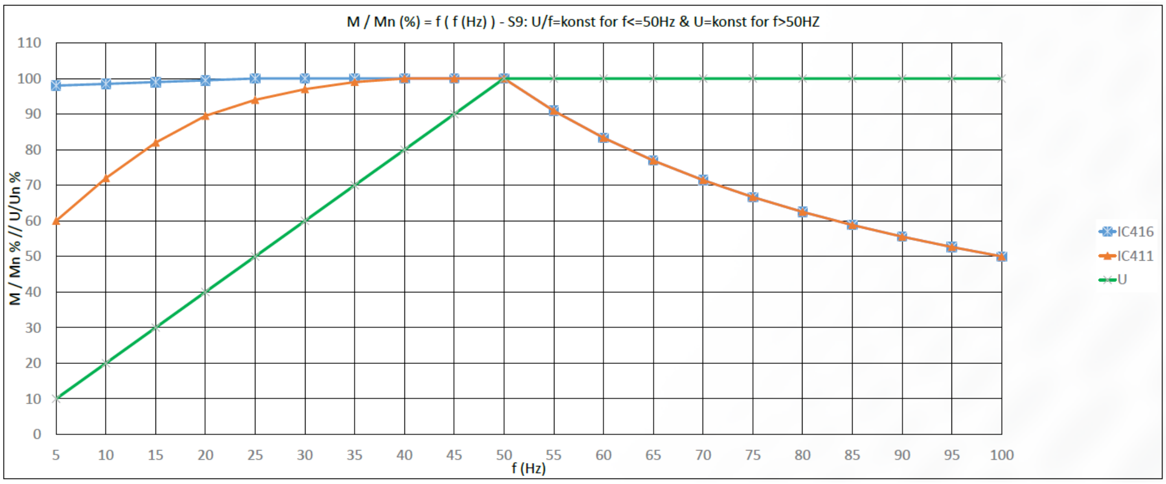

Figure 7. Frequency inverter drive chart [6]

driven with frequency inverter will have higher efficiency than 4-pole Dahlander connected direct on line. It is also worth mentioning lower values of speed and current when driven via frequency converter which indicates lower magnetic saturation in air gap and lower magnetizing current. This makes it obvious that with combination of frequency converter and single speed motor is possible to use higher loads or have less power consumption when applying the same load rating as initially intended for multi speed motors.

VI. CONCLUSION

In this paper are described measurement methods and results for testing multi speed induction motor with two separate windings in stator slots, one of which is in Dahlander configuration, when connected to mains in three different poles i.e. winding configurations. Results are compared when only 4-pole winding of the same motor is connected but with speed regulation via frequency converter for the same three speeds and load torque as in mains. That way measured efficiency was mostly higher so we can conclude that in some applications it is more suitable to use single speed motor and frequency converter than bigger and more complex multi speed motor. Depending on the price of frequency converter it is possible to have even smaller initial costs that way. Through the life span of electric motor that is measured in decades, and considering that price of electricity spent is much higher than initial price of the motor [6], [8], [9]it is realistically to conclude that even in case of more expensive initial costs, this motor and converter combination will have quick return on investment considering electricity prices that will definitely rise in that span.

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