

# Analytical Model of Electrical Machines in Business Software

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**Abstract:** This paper presents a possibility of using enterprise resource planning (ERP) business software for alternative analysis of electrical machines, with SAP ERP as an example of such software. Method presented is valid for all kinds of electrical machines. For the purpose of this paper, induction machine is processed. Analysis started with calculation of all six parameters of equivalent circuit, based on data determined by typical electrical measurements. Completion point is creation of steady-state torque-slip curve. It is important to emphasize that only the standard SAP objects and functions are used for the whole procedure, without any additional programming.

**Keywords:** electrical machines; ERP; induction machine; steady-state characteristics

## 1 INTRODUCTION

Power given by electrical machines is base source of mechanical energy for current industry requirement, so the need for finding a way for some alternative kinds of analysis and design of electrical machines is fully justified. This paper presents the new way of induction machine (IM) analysis done by typical ERP business software.

Dynamic states of electrical machines are described by voltage and mechanical nonlinear differential equations [1]. By solving well known system for AC machines the steady state equivalent circuit of IM, together with formulas for calculation of the values of all six parameters of equivalent circuit can be defined. With further calculation it is easy to determine required expressions for impedance, torque, slip and current [2]. This paper will not cover the process of finding correct formulas, but the process of including all required parameters and formulas in SAP and giving the final results in the form of steady-state characteristics.

The presented procedure has three basic steps:

- calculation of IM parameters in SAP
- preparation of the SAP structure for simulation
- simulation in SAP and determining the needed values for steady-state curves creation.

Proposed solution is based on standard SAP objects (materials, classes, work centres, activity types, cost centres, routings and production orders) and three SAP business modules: Production Planning (PP), Variant Configuration (LO-VC) and Controlling (CO). All needed functionalities covered by these modules are described in detail in [3÷5].

## 2 CALCULATION OF IM PARAMETERS IN SAP

This procedure step has three technical steps in SAP:

- creation of characteristics, classes and dependencies (for measured and calculated data)
- creation of material and configuration profile
- value calculation for all six IM equivalent circuit parameters (Fig. 1).

Symbols  $V_1$  and  $V_2$  stay for stator and rotor phase voltages, respectively. All parameters are defined in Tab. 3.

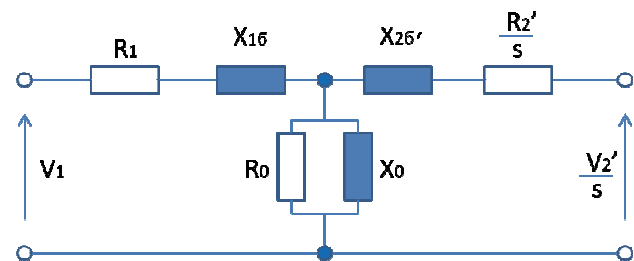


Figure 1 Parameters of IM equivalent circuit

Nominal data of three phase slip-ring IM used in this example are: 1250 kW, 6000 V, 138 A and 1485 r/min [6]. Some measured data were also available and for all of them SAP characteristics are created (Tab. 1). In order to calculate all parameters of equivalent circuit, the standard form of LO-VC functionality is used.

Table 1 Measured data and SAP Characteristics

Parameter	Value	SAP Characteristic
Stator Resistance	0,180 Ω	Z_FER_M01
No-Load Impedance	118,229 Ω	Z_FER_M02
No-Load Current	29,3 A	Z_FER_M03
No-Load Power	28 900 W	Z_FER_M04
No-Load Power factor	0,0951	Z_FER_M05
Short-Circuit Impedance	6,828 Ω	Z_FER_M06
Short-Circuit Current	138,0 A	Z_FER_M07
Short-Circuit Power	44 880 W	Z_FER_M08
Short-Circuit Power factor	0,1151	Z_FER_M09

Based on measured data, three additional parameters should be calculated: Equivalent no-load power, Short circuit resistance and Short circuit reactance. For each of them, both characteristics and dependencies are created (Tab. 2). Technical equations for them are well known [1]. What will be shown is presentation of such equations in SAP, using characteristics and dependencies.

Table 2 IM calculated data

Parameter	SAP Characteristic	SAP Dependency
Equiv. No-Load Power	Z_FER_C03	Z_FER_C03
Short-Circuit Resistance	Z_FER_C04	Z_FER_C04
Short-Circuit Reactance	Z_FER_C05	Z_FER_C05

Dependency for characteristic Equivalent no-load power (Z\_FER\_C03) is shown in Figs. 2a and 2b.

0000 Z_FER_C03	No Load Power Po
• Z_FER_C03	No load eq. Power Po'
• Z_FER_M01	Stator Resistance
• Z_FER_M03	Current Io
• Z_FER_M04	No-Load Power Po

a)

Procedure	Z_FER_C03	No Load Power Po
Source Code		
000010 \$self.Z_FER_C03 = \$self.Z_FER_M04 - 1.5 * \$self.Z_FER_M01 *		
000020 \$self.Z_FER_M03 * \$self.Z_FER_M03		

b)

Figure 2 a) Characteristics used in dependency Z\_FER\_C03, b) Formula in dependency Z\_FER\_C03

Dependency for characteristic short circuit resistance (Z\_FER\_CO4) is shown in Figs. 3a and 3b.

0000 Z_FER_C04	Short-Circuit Resistance Rks
• Z_FER_C04	Resistance short-circuit Rks
• Z_FER_M07	Current Ik
• Z_FER_M08	Power Pk

a)

Procedure	Z_FER_C04	Short-Circuit Resistance Rks
Source Code		
000010 \$self.Z_FER_C04 = Z_FER_M08 / (3*Z_FER_M07*Z_FER_M07)		

b)

Figure 3 a) Characteristics used in dependency Z\_FER\_C04, b) Formula in dependency Z\_FER\_C04

Dependency for characteristic short circuit reactance (Z\_FER\_CO5) is shown in Figs. 4a and 4b.

0000 Z_FER_C05	Short-Circuit Reactance Xks
• Z_FER_C05	Reactance short-circuit Xks
• Z_FER_M06	Impedance Zk
• Z_FER_M09	Cos fi k

a)

Procedure	Z_FER_C05	Short-Circuit Reactance Xks
Source Code		
000010 \$SELF.Z_FER_C05 = \$SELF.Z_FER_M06 * sin(arccos(Z_FER_M09))		

b)

Figure 4 a) Characteristics used in dependency Z\_FER\_C05, b) Formula in dependency Z\_FER\_C05

Next task is calculation of all six equivalent circuit parameters (Tab. 3). They should also be created in SAP as characteristics and their values are given by formulas in dependencies.

Table 3 IM equivalent circuit parameters

Parameter	SAP Characteristic	SAP Dependency
R <sub>1</sub> (Stator phase resistance)	Z_FER_R01	Z_FER_R01
R <sub>2</sub> ' (Eq. rotor phase resistance)	Z_FER_R02	Z_FER_R02
R <sub>0</sub> (Core losses resistance)	Z_FER_R03	Z_FER_R03
X <sub>0</sub> (Magnetizing reactance)	Z_FER_R04	Z_FER_R04
X <sub>1σ</sub> (Stator leakage reactance)	Z_FER_R05	Z_FER_R05
X <sub>2σ</sub> ' (Rotor leakage reactance)	Z_FER_R06	Z_FER_R06

All six dependencies from Tab. 3 are created in the same way as dependencies from Tab. 2. An example for Stator phase resistance (Z\_FER\_R01) is given in Fig. 5.

Procedure	Z_FER_R01	Stator Resistance R1
Source Code		
000010 \$self.Z_FER_R01 = \$self.Z_FER_M01/2		

Figure 5 Dependency for stator phase resistance

After all parameters are connected and dependencies are created, the configuration object (SAP configurable material) should be defined (Fig. 6). After all dependencies are connected to material via configuration profile, configuration simulation can start.

Change Material FER_AM01 (Configurable material)	
Material	FER_AM01
FER - Induction Machine 1.250 kW	

Figure 6 IM as Configurable material FER\_AM01

First step in configuration simulation is to enter measured values from Tab. 1. An easy way to use screen appears with possibility to enter all known values (Fig. 7).

Material	FER_AM01	FER - Induction Machine 1.250 kW
Date	23.12.2015	Quantity
1,000		
Characteristic Value Assignment		
Char. description	Char. Value	I...
Stator Resistance	0,180 Ohm	[i]
Impedance Zo	118,229 Ohm	[i]
Current Io	29,300 A	[i]
No-Load Power Po	28.900,000 W	[i]
Cos fi 0	0,0951	[i]
Impedance Zk	6,828 Ohm	[i]
Current Ik	138,000 A	[i]
Power Pk	44.880,000 W	[i]
Cos fi k	0,1151	[i]

Figure 7 Input of measured values

When all fields are filled, the final values for equivalent circuit parameters appear as calculated (Fig. 8). With values for these parameters, the system for simulation and creation of the steady-state characteristics is prepared. This process can be continued in the same way as calculating values for equivalent circuit parameters (using LO-VC as the only functionality needed), but in order to show different possibilities, some other options are tried out.

Material	FER_AM01	FER - Induction Machine 1.250 kW
Date	24.12.2015	Quantity
1,000		
Characteristic Value Assignment		
Char. description	Char. Value	I...
Stator Phase Resistance R1	0,090 Ohm	[i]
Eq. Rotor Phase Resistance R2'	0,696 Ohm	[i]
Resistance Ro	9,756 Ohm	[i]
Reactance Xo	117,693 Ohm	[i]
Leakage Reactance X1s	3,391 Ohm	[i]
Leakage Reactance X2s'	3,391 Ohm	[i]

Figure 8 Calculated equivalent circuit parameters

So, in the next section one different way of formula processing in SAP is described. Value of parameters

needed for IM steady-state characteristic will be calculated by using two other SAP modules, PP and CO.

### 3 PREPARATION FOR SIMULATION

When using PP and CO modules, preparation for simulation consists of three technical steps in SAP:

- creation of constants and formulas required for defining all parameters of IM equivalent circuit
- creation of activity types, cost centres and work centres in order to collect all constants and formulas
- creation of materials and routings.

#### 3.1 Parameters as Formula Constants

Six parameters of IM equivalent circuit are listed below, with names given in SAP and technical names from Tab. 3:

- K1 = R<sub>1</sub> (stator phase resistance)
- K2 = R<sub>2</sub>' (equivalent rotor phase resistance)
- K3 = R<sub>0</sub> (core loss resistance)
- K4 = X<sub>1σ</sub> (stator leakage reactance)
- K5 = X<sub>2σ</sub>' (rotor leakage reactance)
- K6 = X<sub>0</sub> (magnetizing reactance).

All six parameters will be included in our procedure with the help of Formula constants, which are the basic part of Work centre master data. After all six parameters are defined, they can be used in formulas for electromagnetic torque and rotor / stator current.

What follows is the way for defining parameters and formulas in SAP. Fig. 9 shows the way for defining stator resistance R<sub>1</sub>. Parameter K1 is defined with the origin "Work centre constant":

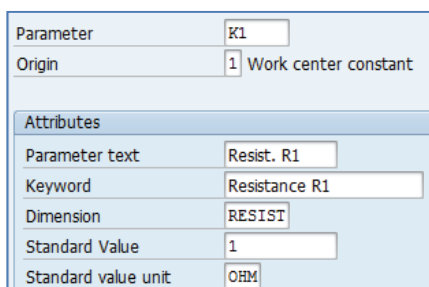


Figure 9 Stator resistance definition

Fig. 10 shows example of grouping all six parameters of IM equivalent circuit.

Param.	Parameter text	Value	Un.
K1	Stator ph.resist. R1	0,090	OHM
K2	Rotor ph.resist. R2'	0,695	OHM
K3	Field resistance Ro	11,176	OHM
K4	Leakage React. X1	3,391	OHM
K5	Leakage React. X2'	3,391	OHM
K6	Field Reactance Xo	117,693	OHM

Figure 10 IM equivalent circuit parameters

After all six parameters are included in SAP, two additional parameters should be created:

- nominal voltage (KP1)
- synchronous speed (KP2).

For both of them User parameters in routings are used. Fig. 11 shows the way for defining synchronous speed as parameter with the origin "User defined field from operation".

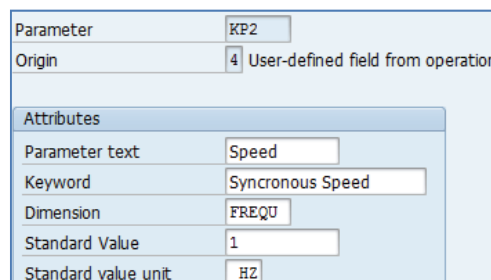


Figure 11 Synchronous speed as SAP parameter

After both user parameters are defined, they should be grouped under User fields key (FER\_01, Fig. 12):

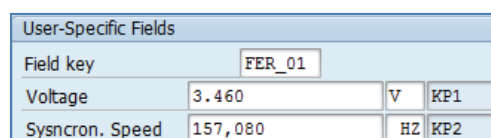


Figure 12 Voltage and synchronous speed as user fields

Slip will be used as main parameter for simulation. This parameter will be defined with the origin "General operational value" (Fig. 13).

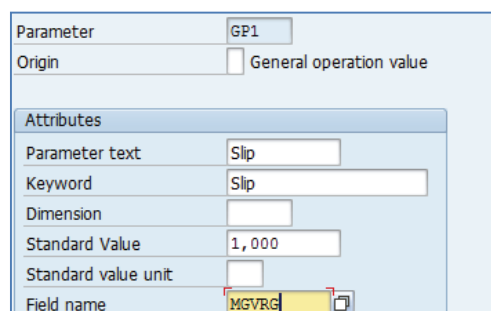


Figure 13 Slip as SAP parameter

In parameter settings, existing connection with SAP field MGVRG (Operation quantity) is visible.

#### 3.2 Formulas for Steady-State Analysis

Formulas from [2] will be used for static analysis. Five new parameters and five formulas for their calculation will be created in SAP.

The first parameter is σ<sub>1</sub>, the dissipation factor. It is defined as follows:

$$\sigma_1 = \frac{X_0 + X_{1\sigma}}{X_0} \tag{1}$$

In order to have the dissipation factor in SAP, a new parameter P01 (Fig. 14) with the origin "Standard value in the operation" and simple formula key F1 (Fig. 15) were created.

For breakdown slip s<sub>max</sub>, described by formula (2), SAP parameter P02 and formula key F2 are created:

$$s_{\max} = \frac{\sigma_1 \cdot R'_2}{\sqrt{R_1^2 + (X_{1\sigma} + \sigma_1 \cdot X'_{2\sigma})^2}} \quad (2)$$

For breakdown torque  $T_{\max}$ , described by formula (3), parameter P03 and formula key F3 are created:

$$T_{\max} = \frac{3V_1^2}{2\omega_s \cdot \sigma_1 \left[ R_1 + \sqrt{R_1^2 + (X_{1\sigma} + \sigma_1 \cdot X'_{2\sigma})^2} \right]} \quad (3)$$

Figure 14 Dissipation factor as SAP parameter

Figure 15 Formula key for dissipation factor in SAP

Formula key F3, as a more complex example, is shown in Fig. 16. It is visible that space provided in SAP for formula definition could sometimes be a problem for complex technical equations.

Figure 16 Formula key for breakdown torque

For electromagnetic torque  $T_{em}$ , described by Eq. (4), parameter P04 and formula key F4 are created:

$$T_{em} = \frac{2T_{\max}}{\frac{s}{s_{\max}} + \frac{s_{\max}}{s}} \quad (4)$$

For rotor current  $I'_2$ , described by formula (5), parameter P05 and formula key F5 are created:

$$I'_2 = \frac{V_1}{\sqrt{\left( R_1 + \sigma_1 \frac{R'_2}{s} \right)^2 + (X_{1\sigma} + \sigma_1 \cdot X'_{2\sigma})^2}} \quad (5)$$

### 3.3 SAP Master Data

In order to include previously created formula keys and parameters in our analysis, three kinds of master data

should be created in SAP: Materials, Work centres and Production routings. They will be simulation carriers.

Figure 17 Slip as material in SAP

The first step is creation of material master data that will later be used for definition of slip value in percentage (Fig. 17). What follows is the inclusion of previously created parameters and formula keys in production work centres.

Figure 18 Simulation parameters as standard value key

For the beginning, the standard value key FER9 is specified, as group of parameters which will be monitored during simulation (Fig. 18). Then the formula keys F1 to F5 should be added to work centre and connect to corresponding parameter P01 to P05 (Fig. 19).

Activities Overview		
Alt. activity descr.	Formula key	Formula description
Dissipation Factor	F1	Dissipation Factor
Breakdown slip	F2	Breakdown slip
Breakdown Torque	F3	Breakdown Torque
Electromagn. Torque	F4	Electromagn. Torque
Rotor Current I2'	F5	Rotor Current

Figure 19 Formulas in Work centre

For existing material master data (slip), a Production routing should be created, as a basic set of master data needed for successful simulation (Work centre FER201 used in this example is one of parameters inside routing, Fig. 20).

After creating all parameters and formulas in SAP, the basic structure is ready for simulation and creation of steady-state characteristics.

Figure 20 Work centre as part of Production routing

## 4 SIMULATION

There are two more things to be done in SAP, in order to have a successful simulation with resulting steady-state characteristics:



- creation of Production order
- several confirmations of Production order with collecting data for each confirmation.

For production order creation (Fig. 21) previously created Production routing is used as a template. Production order should be created for maximum slip value, 100 %.

Figure 21 Production order for simulation

Simulation will be done through business activity named Production order confirmation. Orders will be confirmed for different slip values, from 1 % to 100 %.

Formulas F1 to F3 are slip independent, while formulas F4 and F5 are slip dependent. The last two formulas should be read for each simulation (Production order confirmation) step and given values for electromagnetic torque and rotor current should be collected. At the end, for these two parameters, simulation curves for steady-state model of induction machine can be created.

Quantities			Quantities		
	To Be Confirmed	Unit		To Be Confirmed	Unit
Yield	10,000	\$	Yield	20,000	\$
Scrap			Scrap		
Rework			Rework		
Reason for Var.			Reason for Var.		
Activities			Activities		
	Act. t/b Confirmed	Unit		Act. t/b Confirmed	Unit
Dissipation Factor	1,029	F1	Dissipation Factor	1,029	F1
Breakdown slip	10,392	\$	Breakdown slip	10,392	\$
Breakdown Torque	15.942	NMT	Breakdown Torque	15.942	NMT
Electromagn. Tor...	12.565	NMT	Electromagn. Tor...	15.937	NMT
Rotor Current I2'	346,431	A	Rotor Current I2'	443,869	A

Figure 22 Results for slip = 10 % and 20 %

Fig. 22 shows the SAP screens for production order confirmation for two simulation steps and slip's values of 10 % and 20 %.

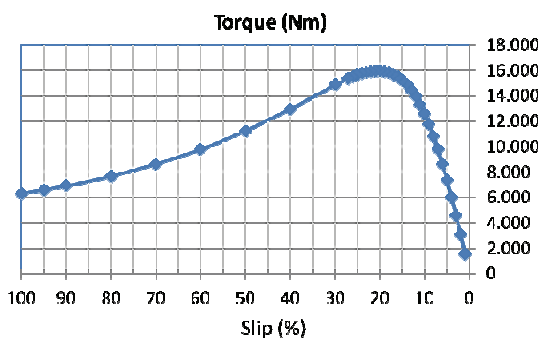


Figure 23 Torque-slip curve

Fig. 23 shows the final curve (created in excel) for steady state torque-slip characteristic.

All dots are calculated by SAP, but curve alone is created in excel. In the same way the curve for current-slip characteristic can be done.

In order to create such simulation curve in SAP, an additional ABAP (programming language used by SAP) program has to be created, because creation of such specific diagrams is not provided by standard SAP ERP software.

## 5 CONCLUSION

The possibility of using business software for analysis of electric machines is still an unknown area whose research requires specific combination of competent knowledge and experience in at least three scientific fields: electrical engineering, business processes and ERP systems.

This paper presents a case with induction machine analysis using SAP ERP as business software. Here, it is described how to calculate the values of equivalent circuit parameters, how to transform technical equations to SAP formula keys and how to get steady-state torque-slip characteristic. Three SAP modules are used, with only standard functionalities, and without any additional programming.

The next and third possible step in using ERP software for electrical machinery analysis is related to the area of business decision making. First research done in this field showed the possibility of helping high-positioned managers (as "natural" users of ERP software) in finding quick answers to critical questions regarding feasibility, costs and scheduling of possible projects. If such option is accepted, then this paper can be viewed as a solid base for the very first step in that direction.

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