Chapter 2
Investigation Methods of Performance Characteristics for Double-Fed Machines with Converter in Rotor Circuit. Summary of Main Investigation Stages of A.C. Machines

This chapter presents investigation methods on operation modes of high-power double-fed machines (DFMs) with frequency converter in rotor circuit. These methods are checked experimentally and are used in modern practice, for example, in production of these machines for operation both in modes of frequency-controlled motors and generators with variable rotation speed.

Main stages of their investigation are noted. Obtained there are equations for calculation of electromagnetic loads of these machines in various operational modes, including equations for calculation of current, voltages and power of rotor winding; they are initial for designing A.C. exciter (exciter EMF frequency is determined by machine slip). Practical examples are given.

As a result of generalization of these stages, it is possible to formulate the main investigation objectives for modern A.C. machines solved in subsequent chapters.

Content of this chapter is development of the methods stated in [14, 20–26].

2.1 Peculiarities of Investigation Methods

Let us consider main peculiarities in investigation methods of performance characteristics for machines of this type; the converter is included into their rotor circuit [21–24].

Summarizing main stages of this investigation, let us also determine basic investigation stages of A.C. machines with squirrel cage rotor windings in nonlinear networks. Investigation methods for these machines modes are more complicated than for DFMs due to the following reasons: rotor winding of DFM is three-phase one. Each phase of such a winding can be considered as the only loop of rotor with lumped parameters: resistance and leakage inductance. Unlike this winding, short-circuited rotor windings of synchronous and induction machines, for example, damper winding of salient-pole machine, squirrel-cage with damaged bars or without damages of induction machine, consist of several loops; these are windings

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with distributed parameters. Only in the simplest case of short-circuited winding, namely the squirrel cage, consisting of N_0 intact bars, in the theory of induction motors it is considered as a polyphase winding with number of phases m_{PH} equal to the number of those bars $(m_{PH} = N_0)$. In general, currents flowing through rotor short-circuited winding loops differ not only in phase, but also in amplitude. It is more difficult to determine these currents than those in a single current loop—either in one of three phases $(m_{PH} = 3)$ of DFM rotor winding or in one of N_0 squirrel cage phases without any damage.

Note another distinction of short-circuited winding in a salient pole machine rotor (damper winding, asymmetrical cage winding) from three-phase rotor winding of DFM: for a machine with short-circuited winding in nonlinear network, each EMF in rotor loops (E_{ROT}) with frequency ω_{ROT} corresponds in stator winding to two EMFs $\left(E_{ST,1}, E_{ST,2}\right)$ with frequencies ω_1 and $\omega_2\, \omega_1 \neq \omega_2$; it also refers, in particular, to the first spatial harmonic of the resulting field in the air gap.

Therefore, mode investigation methods of DFMs are easier. There is no need to investigate the current distribution in rotor short-circuited winding loops taking into consideration those two EMFs in stator winding, etc. However, it is also easy to identify main stages of solving more general problems specific to machines with rotor short-circuited windings and to give their physical interpretation.

Note further that the investigation methods of DFMs described in this chapter are of independent practical interest: It has already been pointed out that such machines are used in engineering practice.

DFMs now become more widely used in various industries including power industry. In motor modes, they are used in controlled electric drives, for example, blast furnace blowers, rolling mill converter units, turbochargers, etc.; their maximum rated power has reached 50–60 MW. In generator modes, they are used in power plants providing constant voltage frequency and amplitude at variable rotation speed of drive motors (diesel, turbine). Depending on type, the DFM maximum power is various: it is 5–8 MW for wind power and small hydroelectric power plants; 400 MW for high voltage transmission line generators; DFMs are also used as condensers (with 60 MVA maximum power) [27–31].

Another application field of such machines has become known recently “variable frequency transformers” [32]. This “variable frequency transformer” with 100 MVA rated power was manufactured by General Electric Co. It is used for connecting two power systems different, for example, in their frequency: its stator winding is connected to one of the systems and rotor winding—to another. Actually, such a “variable frequency transformer” is a device converting energy of one frequency to another. It is necessary to rotate a rotor of this machine to provide slip frequency between two systems. It has vertical design taking into consideration the machine high rated power and, correspondingly, its rotor dimensions. In this case, the air gap can be made smaller than in variant with horizontally-arranged machines. Neither advantages nor disadvantages of this trend are discussed as far as the application of DFMs is not concerned. They are not compared with other technical solutions used in practice [6–9]. It should be noted that the method mentioned below, could also be used for developing such a converter of frequency.

Numerous extensive studies of DFM physical processes, methods of analysis and design, DFM regulation methods for determining optimal power models were launched in 20 s of XX century [10–12]; these were proved by experiments and operation in some European countries and the USA. DFM motor operation mode comprising electric drive (cascades) was considered initially; they differ in their speed regulation principles. DFM quasi steady state and transient processes in generator modes have been researched later. Currently, due to rise of DFM application level and use of frequency converter allowing us to control the rotor winding voltage in amplitude and phase, it is necessary to consider more strictly DFM magnetic circuit saturation, influence of DFM modes on this saturation and flux winding magnitude leakages, to consider the influence of higher time harmonic influence ($Q > 1$) on machine losses and shape of voltage curves [2–4, 6–9, 25].

After these preliminary remarks, let us proceed to investigation methods of performance characteristics for DFMs with frequency converter in rotor circuit. The method is set forth in the equations for two magnetically coupled circuits (stator and rotor); this system takes account of machine magnetic circuit saturation.

2.2 Problem Statement

The calculation methods of DFM modes are shown by examples of the generator mode, so that the original equations would have a univocal form; In references [6–9, 21–23, 25] these generators are sometimes called ASG (asynchronized synchronous generators); This name will be also used in this chapter for short. The equations are written similarly for the motor mode.

There are a number of peculiarities describing the rotational speed variation of DFM rotors:

- the first harmonic voltage at stator winding terminals remains constant in amplitude and frequency: $U_{ST,1} \neq f(n_{REV})$; $f_{ST,1} \neq f(n_{REV})$;
- the first harmonic voltage at rotor winding terminals varies in amplitude and frequency: $U_{ROT,1} = f(n_{REV})$; $f_{ROT,1} = f(n_{REV})$; it is assumed that rotor winding is powered from a frequency converter, for example, via contact rings;
- stator and rotor winding voltage contains a number of higher harmonics: $U_{ST,Q} = f(n_{REV})$; $U_{ROT,Q} = f(n_{REV})$; $f_{ST,Q} = f(n_{REV})$; $f_{ROT,Q} = f(n_{REV})$.

The task is to determine specified relationships.

The assumptions adopted in these equations are standard in A.C. machine theory. They take into account magnetic circuit saturation and higher time harmonic effect. In particular, it is accepted that the resulting flux in ASG air gap is determined according to the Ampere's law [1, 2]. Magnetic circuit saturation is based on considering the first harmonic of this flux in MMF calculations. If necessary, the higher time harmonics can be registered using an iteration method.

2.3 Frequencies and Amplitudes of Voltage and Current First Harmonics in Machine Rotor and Stator Windings

2.3.1 Ratio of Frequencies $f_{ROT,1}$ and $f_{ST,1}$ at $n_{REV} = var$

In rotor speed variation modes ($n_{REV} = \mathrm{var}$) the frequency converter control system should provide:

$$f_{ST,1} \neq f(n_{REV}); \quad f_{ROT,1} = f(n_{REV}).$$

The law of frequency regulation $f_{ROT.1}$ follows from the ratio:

$$f_{ST,1} = \left|\frac{pn_{REV}}{60} + f_{ROT,1}(-1)^{S+1}\right|. \tag{2.1}$$

Here S—sign defining the phase order sequence for the first ($Q_{ROT} = 1$) rotor winding time voltage harmonic or rotor field rotation direction relative to rotor.

Regulation laws of frequency converter are as follows:

- In rotor rotation speed modes at $n_{REV} < 60f_{ST}/p$ a direct phase sequence order (S = 1) should be provided for rotor winding first voltage harmonic; in this case the rotor field rotation direction of the first harmonic ($Q_{ROT} = 1$) and that of rotor coincide;
- In rotor rotation speed modes at $n_{REV} > 60f_{ST}/p$ an opposite phase sequence order (S = 2) should be provided for rotor winding first voltage harmonic; in this case the rotor field rotation direction of the first harmonic ($Q_{ROT} = 1$) and that of the rotor misalign;
- On the practice the modes with $n_{REV} > 60f_{ST}/p$ did not allowed.
- in modes approaching rotor synchronous speed $n_{REV} \approx 60f_{ST}/p$ the frequency of the first voltage harmonic ($Q_{ROT} = 1$) should be $f_{ROT,1} \approx 0$. At the same time, winding overheating in these phases can be different.

2.3.2 Ratio of Voltages $U_{ROT,1}$ and $U_{st,1}$ at n_{REV} = var

In rotor speed variation modes (n_{REV} = var) the frequency converter control system should provide:

$$U_{ST,1} \neq f(n_{REV});\ U_{ROT,1} = f(n_{REV}).$$

The voltage control law $U_{ROT,1}$ follows from the equitation system for magnetically coupled stator and rotor circuits [1, 2, 14, 30, 31]. It is reasonable to present them based on rotating field theory [5, 15, 16] as ASG is a non-salient pole machine. In contrast to the usual equation system of such two circuits, at first, machine magnetic circuit saturation is considered additionally, then influence of higher time harmonics.

In accordance with Kirchhoff's second law, for the first time harmonics of rotor and stator voltage windings we have:

$$I_{ROT,1}\kappa_1 + \Phi_{0,1}\kappa_2 = U_{ROT,1}(-1)^{S+1}, \tag{2.2}$$

$$I_{ST,1}\kappa_4 + \Phi_{0,1}\kappa_3 = U_{ST,1}. \tag{2.3}$$

$$K_1 = Z_{ROT,1} + Z_{F,1(ROT)};\quad Z_{ROT,1} = R_{ROT,1} + j2\pi f_{ROT,1}L_{ROT,1};$$
$$K_2 = j2\pi f_{ROT,1}W_{ROT}K_{W,ROT};\quad K_3 = -\ j2\pi f_{ST,1}W_{ST}K_{W,ST};$$
$$K_4 = -\ Z_{ST,1}\text{-}Z_{F,1(ST)};\quad Z_{ST,1} = R_{ST,1} + j2\pi f_{ST,1}L_{ST,1}.$$

Here $Z_{F,1(ROT)}$, $Z_{F,1(ST)}$—impedance of filter in rotor and stator windings, correspondingly; $Z_{ST,1}$, $Z_{ROT,1}$—impedance of stator winding and rotor correspondingly. In Eqs. (2.2) and (2.3) the impedance values $Z_{F,1(ROT)}$, $Z_{F,1(ST)}$ are calculated at frequencies $f_{ROT,1}$ and $f_{ST,1}$ respectively.

The following is valid for these magnetically coupled circuit windings: $F_{ROT,1} +\ F_{ST,1} = F_{0,1}$ or

$$I_{ROT,1}K_5 +\ I_{ST,1}K_6 +\ F_{0,1}K_7 = 0, \tag{2.4}$$

where

$$K_5 = \frac{m_{ROT}W_{ROT}K_{W,ROT}}{p\pi};\quad K_6 = \frac{m_{ST}W_{ST}K_{W,ST}}{p\pi};\ K_7 = -1;$$
$$F_{0,1} = F_{L,1} + F_{M.C.,1}.$$

Here $F_{ST,1}$, $F_{ROT,1}$—MMF complex amplitudes of stator and rotor respectively, $F_{0,1}$,…, $F_{M.C.,1}$ value—MMF magnetic circuit; $F_{L,1}$—MMF corresponding to $P_{L,1}$ sum of no-load losses and machine additional losses (considering ventilation, mechanical e.g., friction losses and losses in bearings, etc.) [13, 14, 16, 17]:

Table 2.1 Coefficients of the first equation system

$U_{ROT,1}$	$I_{ROT,1}$	$\Phi_{0,1}$	$F_{0,1}$	The right part
$(-1)^{S+1}$	$-K_1$	$-K_2$	0	0
0	0	K_3	0	$U_{ST,1} - I_{ST,1}K_4$
0	K_5	0	K_7	$-I_{ST,1}K_6$
0	0	1	$-E_N$	0

Note: E_N—coefficient (see Sect. 2.5.1)

$$F_{L,1} = I_{L,1}K_6, \text{ where } \left|I_{L,1}\right| \approx \frac{2P_{L,1}}{m_{ST}U_{ST,1}} \tag{2.5}$$

These losses are partially dependent on flux $\Phi_{0,1}$, as well as frequencies $f_{ST,1}$, $f_{ROT,1}$; it is suitable to determine the value $P_{L,1}$ using the iteration method. As an initial approximation, the value $I_{L,1} \approx 0$ can be set; as it has been proved by calculation practice, it is usually sufficient to have three iterations to determine the values $P_{L,1}$ and $I_{L,1}$. The machine magnetic circuit saturation is calculated taking into account the magnetization characteristics according to [13, 16]:

$$\Phi_{0,1} = \Phi\left(F_{M.C.,1}\right). \tag{2.6}$$

Equations (2.1)–(2.6) make up a system for solving the first problem. The followings are set: values $U_{ST,1}$; $I_{ST,1}$; $f_{ST,1}$; $f_{ROT,1}$; impedances $Z_{ST,1}$; $Z_{ROT,1}$; $Z_{F,1(ST)}$; $Z_{F,1(ROT)}$; magnetization characteristic $\Phi_{0,1} = \Phi\left(F_{M.C.,1}\right)$.

There are four unknown values in the system: $U_{ROT,1}$; $I_{ROT,1}$; $\Phi_{0,1}$; $F_{0,1}$. The system coefficients are given in Table 2.1.

It should be noted that in ASG modes at speeds $n_R > 60f_{ST}/p$ rotor winding can correspond to generator mode.

As a result of problem solution given in this paragraph, it is possible to calculate the exciter and frequency converter, thus to determine a series of higher time voltage harmonics in ASG rotor circuit.

2.4 Frequencies and Amplitudes of Voltage and Current Higher Time Harmonics in Machine Rotor and Stator Windings

Amplitude values of higher current harmonics in rotor winding, as well as stator winding voltage and current, are determined by solving the second problem. It allows us to determine a voltage waveform of ASG stator winding, standardized by IEC and GOST (Russian State Standard) [35]; simultaneously the filter options in these windings are determined providing acceptable curve distortion degree.

2.4.1 Ratio of Frequencies $f_{ROT,Q}$ and $f_{ST,Q}$ at $n_{REV} = var$

Now the relation between higher harmonics voltage frequencies ($Q_{ROT} > 1$) in both windings is determined. Similar by to (2.1) we obtain:

$$f_{ST,Q} = \left|\frac{pn_{REV}}{60} + f_{ROT,Q}(-1)^{D+1}\right|, \qquad (2.1')$$

where D—sign defining the phase sequence voltage for rotor winding higher ($Q_{ROT} > 1$) time voltage harmonics or direction of rotor field rotation for this harmonic relative to rotor.

Now, we consider the modes of some practical interest:

In modes at rotor rotation speeds $n_{REV} < 60\frac{f_{ST}}{p}$ (S = 1) the rotor fields of time order $Q_{ROT} = 5, 11, 17, \ldots, 6K–1$ (at K = 1, 2, 3…) and rotor rotate in the opposite direction (D = 2), rotor fields of time order $Q_{ROT} = 7, 13, 19, \ldots, 6K + 1$ (at K = 1, 2, 3,…) and rotor—in the same direction (D = 1).

In modes at rotor rotation speeds $n_{REV} > 60\frac{f_{ST}}{p}$ (S = 2), rotor fields of time order Q_{ROT} = 5,11,17,.., 6 K–1 (at K = 1,2,3 …) and rotor rotate in the same direction (D = 1), rotor fields of time order Q_{ROT} = 7,13,19,.., 6 K + 1 (at K = 1,2,3…) and rotor—in the opposite direction (D = 2).

Example. Frequency of the first voltage harmonic of ASG stator winding with number of poles 2p = 4 is equal to $f_{ST,1}$ = 50 Hz; let us accept the rotor rotation speed equal to n_{REV} = 1150 rpm. As it follows from Eq. (2.1), the frequency of the first voltage harmonic of rotor winding is equal to $f_{ROT,1}$ = 11.67 Hz (S = 1). Then, harmonic of the order Q_{ROT} = 5 ($f_{ROT,5}$ = 58.33 Hz) according to (2.1′) corresponds to the frequency $f_{ST,5}$ = 20 Hz (D = 2), and harmonic of the order Q_{ROT} = 7 ($f_{ROT,7}$ = 81.67 Hz), to the frequency $f_{ST,7}$ = 120 Hz (D = 1).

Note. It is assumed in the example that the number of rotor winding phases is equal to $m_{ROT} = 3$. In this case, it is possible to reduce the voltage harmonic amplitude of frequency $f_{ST,Q}$ by filters in both windings. However, when the number of phases $m_{ROT} = 6$, the time harmonic rotor fields of order $Q_{ROT} = 5$ and $Q_{ROT} = 7$ do not induce any additional voltages in stator winding.

2.4.2 Ratio of Voltages $U_{ROT,Q}; U_{ST,Q}$ at $n_{REV} = var$

In rotor speed variation modes ($n_{REV} = var$) frequencies of voltages of both windings $f_{ROT,Q}$ and $f_{ST,Q}$, and their amplitudes $U_{ROT,Q}$ and $U_{ST,Q}$ change.

In order to determine ratios of these amplitudes, it is advisable to use the rotating field theory [5, 15] for solving this problem, similar to that of the first problem. At the same time, it is also possible to consider magnetic circuit saturation [5, 17].

In accordance with the Kirchhoff's second law the winding voltages of stator and rotor higher time harmonics are as follows:

$$I_{ROT,Q}\kappa_{1,Q} + \Phi_{0,Q}\kappa_{2,Q} = U_{ROT,Q}, \tag{2.2'}$$

$$I_{ST,Q}\kappa_{4,Q} + \Phi_{0,Q}\kappa_{3,Q} = 0, \tag{2.3'}$$

where $K_{1,Q};\ K_{2,Q};\ K_{3,Q};\ K_{4,Q}$—coefficients similar to those $K_1;\ K_2; K_3;\ K_4$ from the first problem, the impedance values $Z_{ST,Q};\ Z_{ROT,Q}; Z_{F,Q(ST)}; Z_{F,Q(ROT)}$, which they contain, are computed for frequencies $f_{ST,Q}$ and $f_{ROT,Q}$, respectively.

For stator winding voltage the following ratio is true: $U_{ST,Q} = I_{ST,Q}Z'_{ST}$; where Z'_{ST} is load impedance, which is external relative to stator winding terminals.

The expression similar to (2.4) is true to magnetically coupled rotor and stator circuits based on Ampere's law:

$$F_{ROT,Q} + F_{ST,Q} = F_{0,Q}$$

or

$$I_{ROT,Q}\kappa_5 + I_{ST,Q}\kappa_6 + F_{0,Q}\kappa_7 = 0, \tag{2.4'}$$

where $F_{0,Q} = F_{1,Q} + F_{MC.,Q}$. Here, $F_{M.C.,Q}$—magnetic circuit MMF depending on mutual flux similar to (2.6) according to the relation:

$$\Phi_{0,Q} = \Phi\left(F_{MC.,Q}\right). \tag{2.5'}$$

$F_{L,Q}$—MMF component corresponding to the sum of machine no-load and additional losses for frequencies $f_{ST,Q}$ and $f_{ROT,Q}$ (without ventilation losses, mechanical losses, for example, friction, in bearings, etc.) [13, 14, 16, 17]:

$$F_{L,Q} = I_{L,Q}K_6, \left|I_{L,Q}\right| \approx \frac{2P_{L,Q}}{m_{ST}U_{ST,Q}} \tag{2.6'}$$

These losses can be calculated using an iteration method.

Equations (2.1′)–(2.6′) make up a system for solving the second problem: where impedances $Z_{ST,Q};\ Z_{ROT,Q};\ Z_{F,Q(ST)}\ Z_{F,Q(ROT)}$; magnetization characteristic $\Phi_{0,Q} = \Phi\left(F_{MC,Q}\right)$.

There are four unknown values in the system: $I_{ROT,Q}$; $I_{ST,Q}$; $\Phi_{0,Q}$; $F_{0,Q}$, and the system coefficients are given in Table 2.2.

It should be noted that voltage and current complex values $\left(U_{ST,1}; I_{ST,1}; U_{ROT,1}; I_{ROT,1}\right)$ in both problems determine the power factor values $\left(\cos\varphi_{ST,1}; \cos\varphi_{ROT,1}\right)$ and, respectively, $\cos\varphi_{ST,Q}$; $\cos\varphi_{ROT,Q}$, as well as values of active and reactive power.

Table 2.2 Coefficients of the second equation system

$I_{ROT,Q}$	$I_{ROT,Q}$	$\Phi_{0,Q}$	$F_{0,Q}$	Right part
$K_{1,Q}$	0	$K_{2,Q}$	0	$U_{ROT,Q}$
0	$K_{4,Q}$	$K_{3,Q}$	0	0
K_5	K_6	0	K_7	0
0	0	1	$-E'_N$	0

Note: $-E'_N$—coefficient (see Sect. 2.5.2)

2.5 Method for Solving Both Problems; Two Systems of Equations

In ASG modes with preset values of power factor and stator current, the first problem can be solved without an iteration method [13, 14, 17]: flux $\Phi_{0,1}$—is determined from Eq. (2.3): $F_{0,1}$ and MMF $F_{M.C.,1}$—from magnetization characteristic (2.6) and from relationship (2.4), herewith, $F_{M.C.,1}$ MMF has the same phase angle as $\Phi_{0,1}$; $I_{ROT,1}$—from (2.4); $U_{ROT,1}$—from (2.2).

However, the given equation systems with their minor modifications remain valid for the calculation of DFM performance characteristics not only in ASG modes, but also in other modes, for example, in frequency controlled motor modes. If the generator power factor (or stator winding current) is not specified, it is also necessary to modify the equations of both systems for ASG.

Let us consider in more detail a method of calculation of DFM modes with account of magnetic circuit saturation for this general case: ASG or motor.

2.5.1 Magnetization Characteristics Presentations $\theta_{0.1} = \theta\left(F_{M.C.,1}\right)$ in Piecewise Linear Function Form

Both systems are nonlinear: they take into account magnetic circuit saturation in accordance with (2.6) and (2.6′). To solve them, it is advisable to introduce the characteristic (2.6) as a piecewise linear function.

In the simplest case, this feature could be presented as a straight line drawn from the origin of coordinates. In this case, the magnetic circuit impedances would not be dependent on the flux.

In a general case, this characteristic can be presented as consisting of S discrete points at the intersections of magnetization curve (2.6) and straight lines drawn from the origin of coordinates.

With account of Table 2.3, the relation between flux $\Phi_N\left(\Phi_N \in \Phi_{0,1}\right)$ in the portion with number N = 1, 2,…, S and MMF $F_{M.C.,N}$ in the same portion takes the form [14] $\Phi_N = E_N \cdot F_{M.C.,N}$.

Table 2.3 Angular coefficient E_N for approximation of elation between flux in portion with number N and MMF in the same portion

N	E_N	Portions Φ_N
1	E_1	$0 \le \Phi_N < \Phi_1$
2	E_2	$\Phi_1 \le \Phi_N < \Phi_2$
⋮	⋮	⋮
N	E_N	$\Phi_{N-1} \le \Phi_N < \Phi_N$
⋮	⋮	⋮
S–1	E_{S-1}	$\Phi_{S-2} \le \Phi_N < \Phi_{S-1}$
S	E_S	$\Phi_{S-1} \le \Phi_N < \Phi_S$

Thus, the only parameter, namely, the angular coefficient E_N corresponds to each straight line drawn from the origin of coordinates. Its value at N = 1 corresponds to unsaturated magnetic circuit.

For this representation of curve, the equation system (2.1)–(2.6) is quasilinear for all values N = 1, 2,…, S. The system can be considered solved provided the calculated values of field in air gap and MMF respond to the value of coefficient E_N in Table 2.3, for which they were determined.

2.5.2 *Peculiarities of Solving Both Systems*

The algorithm for solving the first system $(Q_{ROT} = 1)$ can be represented by the following calculation sequence:

(a) Magnetization characteristic calculation (2.6) as per [5, 17];
(b) This characteristic should be presented as it is shown in Table 2.3. In practical calculations, the portion $0 < \Phi_N < \frac{1}{2}\left[\Phi_{0,1}\right]_{NOM}$ can be represented as a single line with coefficient E_N (for N = 1), where $\left[\Phi_{0,1}\right]_{NOM}$ is the flux approximate value in nominal (rated) mode;
(c) Numerical solution of quasilinear system of Eqs. (2.1)–(2.6) at $E_N (1 \le N \le S)$. Coefficient E_N (for N = 1) is assumed as the initial approximation.
Results of system solution: $U_{ROT,1}; I_{ROT,1}$; $\Phi_{0,1}$; $F_{0,1}$ and $F_{M.C.,1}$;
(d) Analysis of these results: the angular coefficient value E_{N+K} (at $K \ge 0$) is determined according to Table 2.3 for flux $\Phi_{0.1}$. If this value is equal to E_N (K = 0), the results are the desired system solution (the end of the first problem solution);
(e) Otherwise, the following coefficient value E_N (assign $N = N + 1$) should be selected from Table 2.3 and computation of algorithm items: (c), (d), (e) are repeated.

This method can be used for an arbitrary curve form (2.6). The only requirement for this curve is as follows: the first derivative for angular coefficient $E'_N = \frac{\partial \Phi_{0,1}}{\partial F_{M.C.,1}}$ in

Table 2.4 Results of mode calculation for ASG 1250 kW

n_{REV}, rpm	$f_{ROT,1}$, Hz	$U_{ROT,1}$, V	$\cos \varphi_{ROT,1}$
1300	6.67	120	0.635
1350	5.0	94.5	0.65
1400	3.34	63.0	0.68
1450	1.67	35.0	0.755
1550	1.67	19.5	0.36

Note: $f_{ST,1}$ = 50°Hz; $I_{ST,1}$ = 145A $\neq f(n_{REV})$; $I_{ROT,1}A \neq f(n_{REV})$

Table 2.5 Influence of higher order time harmonics Q = 5 and Q = 7

Q	$f_{ST,Q}$, Hz	$f_{ROT,Q}$, Hz	$I_{ST,Q}$, A	$I_{ROT,Q}$, A	$U_{ROT,Q}$, V	$\cos \varphi_{ROT}$
5	20	25	37	181	19.0	0.115
7	80	35	19	93	13.5	0.105

the calculation area of magnetization curve should be continuous. This requirement is always satisfied in practical calculations.

The algorithm of the second system solution in addition should be based on that the saturation degree of machine magnetic circuit is already determined as a result of first problem solution. Mutual induction flux $\Phi_{0,Q}$ and $F_{M.C.,Q}$ MMF in the calculation area can be approximately presented as [18]:

$$\Phi_{0,Q} \approx E'_N F_{M.C.,Q}; \quad \text{here} \quad E'_N = \frac{\partial \Phi_{0,1}}{\partial F_{M.C.,1}} \quad (**).$$

The sign (**) shows that the derivative is taken at the point of machine magnetization characteristic (2.6) corresponding to the flux $\Phi_{0,1}$ determined in the first problem.

Results of mode calculation for ASG 1250 kW, 6.3 kV; 2p = 4 are given in Table 2.4. The effect of higher order time harmonics of EMF and of the rotor currents for Q = 5 and Q = 7 for speed n_{REV} = 1350 rpm is taken into account in Table 2.5.

2.6 Check of Methods

Calculation methods have been tested experimentally by the bench test at « Elektrosila » Work, Stock Company "Power Machines" St.-Petersburg. An induction motor with phase-wound rotor 630 kW, 6 kV, 2p = 12 was used for ASG mode. Excitation was performed with the use of a converter that included a D.C. motor and a synchronous generator [20]. It provided voltage variation in amplitude and frequency. When rotor winding is fed with voltage of higher harmonic order

Q_{ROT} = 5, 11, 17, the reverse phase sequence (A, C, B) was chosen, and for harmonics of order Q_{ROT} = 7, 13, 19—the direct one (A, B, C); thus, rotor rotation speed was $n_R < 500$ rpm. Discrepancy between calculated and tested values of currents in windings did not exceed 6 %.

It should be noted that in practice, when using serial induction motors with phase-wound rotor as ASG, their rated power needs to be lowered by 15–20 % to keep rotor winding overheat at the same level as for motors.

2.7 Excitation System Peculiarities

For DFMs as well as for synchronous machines two exciter versions [3, 4] are possible: brushless or static (with slip rings). In production and operation each of them has advantages and disadvantages. Brushless exciters are traditionally used for synchronous machines. Recently, the works for DFMs have been under way to improve brush assembly operational reliability of brushes and slip rings unit [33, 34] to avoid brushless versions of exciters. Some peculiarities of exciters for DFMs should be noted. Unlike synchronous machine exciters, its dimensions are determined by two apparent power components $P_{TOT,1}$ of rotor winding: $P_{TOT,1} = P_{AC,1} + jP_{R,1}$; the active power $P_{AC,1}$ is determined by machine electromagnetic power and its slip (with account of winding skin effect); reactive power $P_{R,1}$ depends on the rotor winding inductance and slip; that is, on its impedance (also with account of skin effect) [3, 4, 13, 16]. Hence, dimensions of exciter active part and converter in its circuit for DFM are more than for synchronous machine of the same power. The difference is determined by the speed control range in operating conditions.

2.8 Summarizing the Results: Main Stages of A.C. Machine Investigations with Rotor Short Circuited Windings

2.8.1 Stator and Rotor Circuits Frequency Voltage. Rotational Speed of Rotor and Stator Fields in Air Gap

The ratio between the first harmonic voltage circuit frequencies of rotor and stator loops is determined for DFMs in Sect. 2.3.1 with using (2.1), and the ratio between higher time harmonic frequencies at the first spatial harmonics ($|m| = |n| = 1$) is determined using Eq. (2.1′) (see Sect. 2.4.1). These fields cause the resultant field in air gap and torque on machine shaft.

As it follows from equations for a DFM, each time harmonic of frequency EMF ω_{ROT} in rotor loop corresponds to one frequency EMF ω_1 in stator loop, and, therefore, one resulting field in air gap, one torque on machine shaft torques. This is true for spatial harmonics of order $(|m| = |n| \geq 1)$. However, the calculation method mentioned in this chapter takes into account only first spatial harmonic.

Let us designate in this paragraph for short the machines operating in nonlinear networks and with short-circuited loops in rotor in the form of damper winding, squirrel cage with asymmetry as: machines type (*). As it has already been noted, there are some differences in DFMs and machine type (*). In particular, to each EMF harmonic in rotor loops (E_{ROT}) with frequency ω_{ROT} of (*) type machines, in stator winding there correspond to two EMFs $\left(E_{ST,1}, E_{ST,2}\right)$ with frequencies ω_1 and ω_2. Two stator fields and two rotor fields with ω_{ROT} frequency currents correspond to them. These fields produce two resultant fields in air gap different in their amplitudes, rotation direction and speed and two–machine shaft torques. This regularity is true for spatial harmonics of any order $(|m| = |n| \geq 1)$ for (*) type machines. Ratio of EMF frequencies in rotor and stator loops of these machines is given in Chap. 3.

They allow us to determine rotor and stator magnetically coupled circuits of (*) type machines.

2.8.2 Ampere's Law Equations

The ratio between the first time harmonics of MMF stator and rotor windings is determined by Eq. (2.4) for a DFM in Sect. 2.3.2. Both summands of this equation correspond to the fields of the stator and rotor first time harmonics mutually fixed in air gap generating one resulting field. The same is true for fields of each stator and rotor higher time harmonic, their MMFs correspond to Eq. (2.4′) in Sect. 2.4.2; they are also mutually fixed in air gap and generate one resulting field.

Each of these two equations contains expressions for MMF stator and rotor windings. MMF equations are known [3, 4] and given in the above-mentioned paragraphs for multiphase stator windings (usually three-phase, rarely six-phase) and three-phase rotor winding.

However, the problem is more complicated for type (*) machines. It is necessary to investigation preliminarily the current distribution in bars and ring portions of these short-circuited windings in order to write down expressions for MMF of damper winding or squirrel cage with damages. This investigation is an independent problem, and it is solved in subsequent chapters.

2.8.3 Kirchhoff's Second Law Equations for Stator Winding

Ratio between the first time harmonics of EMFs, voltages and stator loop currents is determined in Sect. 2.3.2 for DFMs using Eq. (2.3). Ratio between their time higher harmonics is determined in Sect. 2.4.2 using Eq. (2.3′). Stator winding in these equations is considered as a lumped circuit (with A.C. resistance and leakage inductance), set up in solving the problem. Each of these two equations is based on the assumption that the expression for resultant mutual induction fluxes $\Phi_{0,1}$ and, respectively, $\Phi_{0,Q}$ are determined by Eqs. (2.6) and (2.6′).

However, for (*) type machines, determination of these mutual induction fluxes is connected with a need to find the rotor winding MMF requiring the previous investigation of the distribution of currents in elements of damper winding or squirrel cage with damages. It has already been noted that this investigation makes up a separate problem, and it is solved in the following chapters.

2.8.4 Kirchhoff's Second Law Equations for Rotor Loops. System of Equations

The ratio between the first time harmonics of EMFs, voltages and rotor circuit currents is determined in the same paragraphs for DFMs using Eq. (2.2) and the ratio between their higher harmonics—using Eq. (2.2′). The rotor winding in these equations as well as the stator winding are considered as a lumped circuit (with A. C. resistance and leakage inductance) given in solving the problem.

However, rotor winding unlike stator winding is a circuit with distributed parameters for (*) type machine. It consists of a series of short-circuited loops. Therefore, the system of equations, whose order responds to the number of loops, should be written instead of a single equation as in (2.2) or (2.2′). It should also include the equation of the form (2.3) or (2.3′) for stator in addition to rotor circuit equations according to Kirchhoff's second law. At the same time, EMFs, voltages and currents in stator loops, which differ in frequency [1, 2], should be considered in the system. This numerical solution modification is given in Chap. 5. A system of equations for short-circuited rotor loops is given as a part of this modification. It allows reducing the order for system of equations for magnetically coupled loops.

The above-stated confirms additionally that it is necessary to solve preliminarily the problem of currents distributions in short-circuited rotor winding elements: damper winding or squirrel cage with damages. When solving this problem, it is suitable to use generalized current and MMF characteristics of rotor windings.

Appendix 2.1

A general method of calculating DFM operating characteristics outlined above (in Sects. 2.2–2.7) allows one to calculate the mode characteristics of frequency-controlled motor, condenser, generator and frequency inverter. It is reduced to solving systems of equations of the fourth order in the complex plane. However, in practice, it appears appropriate to develop additionally a DFM calculation method similar to factory methods [13, 17, 19] for calculating non-salient pole machines (turbogenerators, turbomotors and induction machines). It allows the engineer under production conditions to consider the experience of developing traditional designs of these non-salient pole machines. Key elements of this methodology are given below in Sects. A.2.1.1–A.2.1.5 as applied to DFM "overexcitation" in motor, condenser, generator modes.

A.2.1.1 DFM Rotor Current and MMF Under Load

Now, let us use the Ampere's law according to Eq. (2.4). The first summand in the expression for $F_{0,1} = F_{1,1} + F_{M.C.,1}$ can be neglected. Magnetic circuit MMF amplitude $F_{M.C.,1}$ contains two summands [13, 17]:

$$F_{M.C.,1} = F_{M.C.ST,1} + F_{M.C.ROT,1}. \tag{A.2.1.1}$$

First of them $F_{M.C.ST,1} = F_{M.C.GAP,1} + F_{M.C.TOOTH,1} + F_{M.C.YOKE,1}$ contains three components: MMF of air gap, teeth and stator yoke, respectively. These components in (A.2.1.1) are determined by air gap, stator magnetic circuit geometry and mutual induction flux $\Phi_{0,1}$ in air gap [1, 13, 19]:

$$\left|\Phi_{0,1}\right| = \left|\frac{j}{\omega_1 W_{ST} K_{WST}} E_v U_{0,1}\right|, \quad E_v = \sqrt{\cos^2\varphi + \left(X_{ST,1} + \sin\varphi\right)^2}, \tag{A.2.1.2}$$

where ω_1—network angular frequency; E_V—internal EMF [13, 19]; $X_{ST,1}$—stator winding leakage inductance (in per units system, p.u.); we accept that it exceeds A. C. resistance $R_{ST,1}$; $\cos\varphi$—power factor on DFM stator terminals.

The second summand in (A.2.1.1) $F_{M.C.ROT,1} = F''_{M.C.TOOTH,1} + F''_{M.C.YOKE,1}$ contains two components respectively, MMF of rotor teeth and yoke [13, 17, 19]. Both components are determined by the sum $\Phi'_{MI,1}$ of mutual flux $\Phi_{0,1}$ in (A.2.1.2) and rotor slot leakage fluxes $\Phi_{M.C.LEAK,1}$:

$$\left|\Phi'_{MI,1}\right| = \left|\Phi_{0,1}\right| + \left|\Phi_{M.C.LEAK,1}\right|. \tag{A.2.1.3}$$

Here $\Phi_{M.C.LEAK,1} = \left|F_{GEN.EQ,1}\right| \cdot \Lambda_{SLOT.LEAK}$, where $\Lambda_{SLOTLEAK}$,—rotor slot leakage conductivity [13, 17, 19]; $F_{GEN.EQ,1}$—equivalent generator MMF. Based on the calculation method for turbogenerators and turbomotors, let us determine it in the form of sum of two complex amplitudes [19]:

$$F_{GEN.EQ,1} = F_{ST,1} + F_{M.C.ST,1}. \tag{A.2.1.4}$$

where $F_{ST,1}$—MMF of stator winding (phasor).

In practical calculations, it is convenient to calculate complex amplitude module in (A.2.1.4) $F_{GEN.EQ,1}$ in the form:

$$\left|F_{GEN.EQ,1}\right|^2 = \left|F_{ST,1}\right|^2 + \left|F_{M.C.ST,1}\right|^2 + 2\frac{\left|F_{ST,1}\right| \cdot \left|F_{M.C.ST,1}\right|}{\sqrt{1 + \left(\frac{\cos\varphi}{X_{ST,1} + \sin\varphi}\right)}} \tag{A.2.1.5}$$

After determination of $F_{GEN,EQ,1}$ according to (A.2.1.4) or (A.2.1.5), $\Phi'_{MI,1}$ according to (A.2.1.3), we obtain consistently MMF of $F''_{M.C.TOOTH,1}$, $F''_{M.C.YOKE,1}$ and $F_{M.C.ROT,1}$. As a result we obtain the component in (A.2.1.1) $F_{M.C,1}$—MMF of DFM magnetic circuit.

The required complex amplitude of rotor MMF at load $F_{ROT,1}$ is calculated according to (A.2.1.6) and (A.2.1.7).

First, let us determine complex amplitude components in stator coordinates (real axis is aligned with complex phase voltage, and imaginary one makes the angle $+\pi/2$):

$$\begin{aligned} \mathrm{Re}\left(F_{ROT,1}\right) &= -\left|F_{M.C.,1}\right| \cdot \sin\psi - \left|F_{ST,1}\right| \cdot \cos\varphi; \\ \mathrm{Im}\left(F_{ROT,1}\right) &= \left|F_{M.C.,1}\right| \cdot \cos\psi + \left|F_{ST,1}\right| \cdot \sin\varphi. \end{aligned} \tag{A.2.1.6}$$

Here MMF phase angle $F_{M.C.,1}$ is equal to $\psi = \arccos\frac{X_{ST,1}\cdot\sin\varphi + 1}{E_V} + \frac{\pi}{2}$; angle φ—corresponds to DFM power factor. Let us note that according to (A.2.1.6) in the adopted coordinate system, the MMF complex $F_{M.C.,1}$ is positioned so that the angle ψ is within the range: $\frac{\pi}{2} \le \psi < \pi$. In practical calculations, the complex module $F_{ROT,1}$ for check is calculated similarly (A.2.1.5):

$$\begin{aligned} \left|F_{ROT,1}\right|^2 &= \mathrm{Re}^2\left(F_{ROT,1}\right) + \mathrm{Im}^2\left(F_{ROT,1}\right) \\ &= \left|F_{ST,1}\right|^2 + \left|F_{M.C.,1}\right|^2 + 2\frac{\left|F_{ST,1}\right| \cdot \left|F_{M.C.,1}\right|}{\sqrt{1 + \left(\frac{\cos\varphi}{X_{ST,1} + \sin\varphi}\right)^2}} \end{aligned} \tag{A.2.1.7}$$

As it follows from the ratio (A.2.1.7), for DFM: $\left|F_{ROT,1}\right| > \left|F_{ST,1}\right|$.

The rotor current under load $I_{ROT,1}$ is determined according to (A.2.1.7) from the known ratios [13, 17] used for MMF polyphase winding.

A.2.1.2 Phase Angle Defining Complex Amplitudes Position of MMF $\mathbf{F}_{\mathbf{ROT},1}$ *and Current* $\mathbf{I}_{\mathbf{ROT},1}$ *(in Stator Coordinates)*

Using Eq. (A.2.1.6), the following is obtained:

$$\beta = \pi - \operatorname{arctg}\left|\frac{IM(F_{ROT,1})}{RE(F_{ROT,1})}\right|. \tag{A.2.1.8}$$

Let us note that according to (A.2.1.6) in the adopted coordinate system, the MMF complex $F_{ROT,1}$ is positioned, so that the angle β is within the range: $\frac{\pi}{2} < \beta < \pi$.

A.2.1.3 Rotor Winding Voltage, Its Components

Now, the Eq. (2.2) for complex $U_{ROT,1}$ is transformed to find out its real and imaginary components. They determine the phase angle γ in this complex. To do it, the following ratio is preliminarily calculated:

$$Z_{EQ,1} = \Phi_{0,1}\frac{j2\pi f_{ROT,1}\cdot W_{ROT}\cdot K_{W,ROT}}{I_{ROT}} = |Z_{EQ,1}|e^{j\delta} = R_{EQ,1} + jX_{EQ,1}, \tag{A.2.1.9}$$

Taking into account Eq. (A.2.1.9), the following is obtained:

$$\begin{aligned} Re(U_{ROT,1}) &= Re(I_{ROT,1})\cdot(R_{ROT,1}+R_{EQ,1}) - Im(I_{ROT,1})\cdot(X_{ROT,1}+X_{EQ,1}),\\ Im(U_{ROT,1}) &= Re(I_{ROT,1})\cdot(X_{ROT,1}+X_{EQ,1}) + Im(I_{ROT,1})\cdot(R_{ROT,1}+R_{EQ,1}), \end{aligned} \tag{A.2.1.10}$$

where $X_{ROT,1} = j2\pi f_{ROT,1}\cdot L_{ROT,1}; X_{ST,1} = j2\pi f_{ST,1}\cdot L_{ST,1}$. According to (A.2.1.10), the complex amplitude modulus of this phase voltage is equal to:

$$|U_{ROT,1}| = \sqrt{Re^2(U_{ROT,1}) + Im^2(U_{ROT,1})}. \tag{A.2.1.11}$$

In practical calculations, the complex amplitude module $U_{ROT,1}$ is calculated as a check as follows:

$$|U_{ROT,1}| = |I_{ROT,1}R_{ROT,1} + jI_{ROT,1}X_{ROT,1} + j2\pi f_{ROT,1}\Phi_{0,1}W_{ROT}K_{WROT}|. \tag{A.2.1.12}$$

A.2.1.4 Phase Angle Defining Complex Amplitude Position $U_{ROT,1}$

In stator coordinates, the angle defining position of rotor voltage complex $U_{ROT,1}$ is equal to,

$$\gamma = \pi + \mathrm{arctg}\left|\frac{\mathrm{Im}(U_{ROT,1})}{\mathrm{Re}(U_{ROT,1})}\right|. \qquad (A.2.1.13)$$

A.2.1.5 Rotor Winding Power Factor; Active and Reactive Winding Power; Rotor Winding Losses

It is necessary to maintain the rotor winding power factor $\cos\varphi_{ROT,1}$ by means of an exciter (frequency converter) to ensure DFM operational characteristics for operation in network (including its given active and reactive power values, etc.).

It is determined with the help of phase angle values β as per (A.2.1.8) and γ as per (A.2.1.13)

$$\varphi_{ROT,1} = \gamma - \beta. \qquad (A.2.1.14)$$

The angle $\varphi_{ROT,1}$ should be maintained by DFM control system in real time [6–9].

From the obtained expressions for $U_{ROT,1}, \varphi_{ROT,1}$ for rotor windings, we calculate [13, 17] apparent, active and reactive powers of exciter (frequency converter), and also rotor winding losses.

A.2.1.6 DFM Rotor Winding Design Peculiarities

First, let us consider design peculiarities of bar winding [5, 13, 16]. The Field's factor value for DFM high power winding is estimated. The DFM rotor slot height is assumed to be H = 200 mm, the copper height in it is $H_{CU} = 150$ mm, and the Field's coefficient for transposed bars at frequency $f_{50} = 50$ Hz is equal to $K_{F,50} \approx 1.25$. At frequency $f_{ROT,1} = 2.5$ Hz (slip 0.05) we obtain:$K_{F,S} \approx 1.0$. Now this coefficient is determined at first for the same equivalent bar with $f_{ROT,1} = 2.5$ Hz without any transposition. A "reduced height" is to be found for this bar [1, 2] $H_{RED} = K' \cdot H_{CU}$ at industrial frequency (50 Hz):

$$H_{RED,50} = \sqrt{\frac{\omega_{50}\mu_0\Delta}{2\rho_{CU}}} \cdot H_{CU} = 0.085 \cdot H_{CU} = 12.5$$

where μ_0—air magnetic permeability, $\Delta \approx 0.8$—copper width in slot/slot width ratio, ρ_{CU}—specific resistance (at the temperature 75°C); hence, at frequency $f_{ROT,1} = 2.5$ Hz we obtain: $H_{RED,ROT,1} = 2.8$. It is assumed that the ratio of bar slot part to its length is equal to $\lambda \approx 0.75$. Then, for non-transposed bar, the Field's coefficient at $f_{ROT,1} = 2.5$ Hz is equal to $K'_{F,S} \approx 2.1$. This practically eliminates a possibility to use bars without any transposition in the design of bar winding for DFM.

Now, the coil winding design peculiarities are considered [13, 14, 17]. For this winding at H = 200 mm and $f_{ROT,1} = 2.5$ Hz:$K'_{F,S} \approx 1.0$. Hence, the coil winding does not cause any problems with additional losses and in overheating for DFM at slip $S \leq 0.05$.

Appendix 2.2

Generalized current characteristic of three-phase rotor winding of DFM.

As an example of DFMs, let us determine the concept of rotor winding generalized current characteristic [14, 26] in relation to the first time harmonics ($Q_{ROT} = 1$) of current and EMF also to the first spatial harmonic (m = 1) of the resulting field in air gap (mutual induction field); in this winding the resulting field in air gap induces EMF with slip frequency ω_{ROT}.

Let us name the current relation in rotor three-phase winding $I_{ROT,1}$ from Eq. (2.2) to flux density amplitude by m = 1, $Q_{ROT} = 1$ as current generalized characteristic. The flux and the flux density amplitude relation is determined at first as:

$$\Phi_{0,1} = \frac{1}{\pi} T_1 \cdot L \cdot B(m = 1, Q_{ROT} = 1).$$

Then, the EMF induced in winding by this current at the frequency ω_{ROT} is equal to:

$$E_{ROT,1} = -\frac{j\omega_{ROT}}{\pi} T_1 \cdot L_{COR} \cdot W_{ROT} \cdot K_{W,ROT} \cdot B_{0,1}.$$

Here $B_{0,1} = B\,(m = 1,\ Q_{ROT} = 1)$. Generalized characteristic of rotor winding current for the first current time harmonics and EMF and the first resultant field spatial harmonic in air gap can be determined as:

$$I_{ROT,1} = \left[I_{ROT,1}\right] \cdot B_{0,1}.$$

Physically, this generalized current characteristic in rotor three-phase winding at the frequency $\omega_{ROT} =$ idem can be considered as a similarity criterion. It determines in flux density scale $B(m = 1, Q_{ROT} = 1)$ the amplitude and current phase in this winding. In subsequent calculations, a similar concept of generalized MMF winding characteristics is introduced. It will be used to form a system of equitation of magnetically coupled rotor and stator loops.

Brief Conclusions

1. Calculation methods for DFMs allow us to make calculations of the following with account of magnetic circuit saturation: voltages and currents in windings caused by the first time harmonic; voltages and currents of higher time harmonics caused by operation of frequency converter in rotor circuit.
2. Results of mode calculation are initial for further calculations:
   - of exciter in rotor circuit;
   - of filter impedance in stator and rotor windings providing a voltage waveform as per IEC and GOST [35].
3. Generalized characteristic of rotor winding currents is determined by its number of turns and winding factor as well as geometrical dimensions of machine active part.

List of Symbols

$f_{ROT,1}; f_{ST,1}$	Frequencies of the first voltage harmonic of rotor and stator windings
$f_{ROT,Q}; f_{ST,Q}$	Frequencies of higher voltage harmonics of rotor and stator windings
$F_{ROT,1}; F_{ROT,Q}; F_{ST,1}; F_{ST,Q}; F_{M.C.,1}; F_{M.C.,1}$	MMF complex amplitudes (phasors) of rotor, stator windings and machine magnetic circuit
$I_{ROT,1}; I_{ROT,Q}; I_{ST,1}; I_{ST,Q}; I_{M.C.,1}; I_{M.C.,Q}$	Complex amplitudes (phasors) of currents in rotor (stator) windings and magnetization current
$K_{W,ROT}; K_{W,ST}$	Winding factors for rotor and stator windings
L_{COR}	Active core length
$L_{ROT}; L_{ST}$	Leakage inductance of rotor and stator windings
m	Order of stator MMF spatial harmonic
$m_{ROT}; m_{ST}$	Number of phases of rotor and stator windings
n	Order of rotor MMF spatial harmonic
n_{REV}	Rotor rotation speed
P	Power
p	Number of pole pairs
$Q_{ROT}; Q_{ST}$	Orders of time voltage harmonics of rotor and stator windings
$R_{ROT,1}; R_{ROT,Q}; R_{ST,1}; R_{ST,Q}$	A.C. resistance of rotor and stator windings
S	Slip

T_1	Period of the first flux harmonic
$U_{ROT,1}$; $U_{ROT,Q}$; $U_{ST,1}$; $U_{ST,Q}$	Complex amplitudes of phase voltages of rotor and stator windings
W_{ROT}; W_{ST}	Number of turns in phase of rotor and stator windings
$X_{ROT,1}$; $X_{ROT,Q}$; $X_{ST,1}$; $X_{ST,Q}$	Inductive leakage reactances of rotor and stator windings
$\Phi_{0,1}$; $\Phi_{0,Q}$	Complex amplitudes of mutual induction resulting fluxes
$\varphi_{ROT,1}$; $\varphi_{ROT,Q}$; $\varphi_{ST,1}$; $\varphi_{ST,Q}$	Phase angles between voltage and current of rotor (stator) windings

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