Regenerative Test for Multiple Three-Phase Machines with Even Number of Neutral Points

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***Abstract*—Testing the high-power machines in general is not an easy task. One of the standard tests is the full-load test. This test typically requires another machine, of the same or higher power rating, to be coupled to the tested one. For multiphase machines, which are commonly designed for high power applications, this test can be conducted in a different way. In order to simplify full-load test, this paper introduces a new method which is applicable for multiple three-phase machines with even number of neutral points. The method is based on indirect rotor-field oriented control (IRFOC). It enables evaluation of the efficiency and the thermal design in the case of synchronous machines and the segregation of the constant and stator variable losses for induction machines, without the need for coupling another machine as a load. In the presented method the full-load test conditions on the stator are obtained by circulating the rated active power flow in closed loop from one winding set to another. The only power used during the test is to cover machine and converter losses. The proposed control scheme is unique and it is based around *y*-component from the vector space decomposition (VSD) subspace. It is validated through the simulation and experimental results.**

***Index Terms*— Multiphase Machines, Multiple Three-phase Machines, Regenerative Test, Synthetic Loading.**

I. Introduction

MULTIPHASE machines (number of phases $n > 3$) split the power among more than three phases [1]. Therefore, they are getting more and more popular in the high-power applications, such as wind generation. Among multiphase machines, the most popular and also the preferred ones by the industry are those with multiple three-phase winding sets. This is so since they utilise well-established three-phase power electronics technologies [2, 3].

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Development of new machines is always accompanied by numerous tests. The most common one is the full-load test, in which the machine is loaded from zero up to the full load. From this test various characteristics of the machine (e.g. efficiency, temperature rise curve – provided that thermal sensors are built into the machine, etc.) can be obtained before the machine is placed into series production. A common option for performing the full-load test is by coupling the tested machine mechanically with another one, which behaves as a load. During this test, back-to-back configuration of the machines and the converters (used to supply tested and loading machine) is commonly used [4, 5]. Testing the high-power machines in this way is time-consuming and costly, so that alternative methods to perform full-load test have been developed. Several options to perform the test, without the need to couple the tested machine with another one, are available for three-phase machines, including: two-frequency method [6], phantom loading [7] and inverter driven method [8, 9]. From the perspective of the temperature-rise, these methods are equivalent to the back-to-back method and the effective voltage and the stator current are equal to the rated values of the machine [10]. The difference is that the back-to-back configuration has the ability to recirculate the power while these methods cannot (and hence are accompanied by high power losses). In the back-to-back configuration, if the dc-links of the used converters are connected, the only power taken from the supply will be for the losses of the machines and the power electronics converters. However, this way of testing is still very expensive for the electrical machines with high power rating (for example, a few MW wind turbine).

Somewhat different approach for regenerative testing of concentrated winding permanent magnet synchronous machine under the full-load condition, without the need for mechanical coupling, has been introduced in [11, 12]. In this method the power is circulated between the different sections of the machine. The machine had four three-phase sections; hence, two opposite sections were connected in parallel and supplied by two three-phase converters with common dc-link. One converter operated in generation and the other in motoring mode. This system can be also observed as a multiphase system. As the control was done independently for each converter, one can say that it corresponds to multiple *dq* (or multi-stator, MS) control approach of a multiphase machine [2].

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The basic idea of [11, 12] has been further enhanced in [13], where a six-phase permanent magnet machine with sinusoidally distributed windings was considered. While in [11, 12] implementation of the multiple *dq* algorithm was extremely simple due to the machine's construction (three-phase windings are mutually decoupled), that is much more involved in [13]. The control scheme in [13] is also based on the multiple *dq* approach and full coupling compensation (i.e. decoupling) is required since the machine's stator winding is distributed.

In this paper, a novel and different approach to implement the regenerative test for multiple three-phase winding machines with an even number of neutral points is introduced. In contrast to the approach in [11-13], based on the multiple *dq* control algorithm, the method is here based on the VSD modelling. As a consequence, the control requires, at least under ideal conditions, a lower number of the current controllers when compared to the MS approach of [11-13] (in reality, non-ideal drive behaviour necessitates use of the same number of current controllers). The method is based on IRFOC and is implemented by utilising a unique *y*-component of the VSD matrix. It is applied to six-, twelve-, and eighteen-phase machines with symmetrical and asymmetrical configuration.

The testing scenario and the corresponding control algorithm can be used directly for efficiency evaluation of synchronous machines. However, in the case of induction machines, it is only possible to segregate the constant and load-dependent stator losses but not to evaluate the efficiency, for the reasons explained in detail later. This is regarded as the second important contribution of the paper.

The paper is organised as follows. In section II, the regenerative test from [11, 12] is revisited. Section III introduces the regenerative test schemes using the MS (existing) and VSD (novel) approach for multiple three-phase winding machines with an even number of neutral points. The simulation results of the proposed scheme are provided and discussed in section IV, where the differences in the obtainable characteristics for synchronous and induction machines are also addressed. Next, the experimental results of the regenerative test are presented in section V for an asymmetrical six-phase induction machine and the segregation of constant losses from variable stator losses is illustrated. Finally, the conclusions are summarised in section VI.

II. Regenerative Test for High Power Machines with Divided Windings

Regenerative test can be used for testing the machine's full load capabilities. In this way the efficiency and the thermal design (subject to installation of temperature sensors) can be verified. One possible method for performing this test, without the need for coupling another machine to the tested machine, is presented in [11, 12]. Tested machine is a 780 kW, 14 rpm interior permanent-magnet (IPM), three-phase, 136-pole machine and its stator is split, by the construction, into four sections, where each section forms a three-phase machine (Fig. 1). The specific construction of the machine makes those

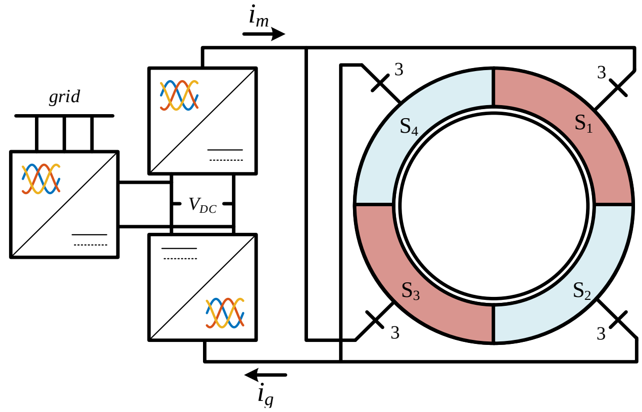

Fig. 1: Regenerative test layout of a machine with divided windings.

three-phase winding sections magnetically mutually decoupled. However, the method is also easily applicable to any other machine with multiple three-phase sections, but, if coupling is present, control becomes much more involved.

For testing this machine, two three-phase sections, which are opposite to each other (S_1–S_3 and S_2–S_4) are connected in parallel to one of the two converters (see Fig. 1). The first set-pair S_1–S_3 operates in motoring, while the second one S_2–S_4 is in generation mode. The set-pairs are controlled in speed and torque mode, respectively. Converter's motoring current i_m is halved between sections S_1 and S_3, while generated current i_g is equally contributed by S_2 and S_4. Used control scheme is a four-quadrant FOC. The machine is accelerated using the first set-pair operating in the speed mode; once it has accelerated and reached the steady state, the rated (negative) torque is applied to the second set-pair. The generation torque and the motoring torque cancel each other within the machine itself. During the test, the phase flux-linkage is also controlled in order to obtain the same voltage fundamental for all four sections (two motoring and two generation sections).

Note that both converters share the same dc-link. Therefore, the power taken by S_1 and S_3 is the re-circulated power generated by S_2 and S_4. The only losses present in the system during the test are the converters' and the machine losses (copper, core and mechanical losses). These power losses are compensated by the power taken from the grid in order to keep the machine running during the test (Fig. 1).

III. Regenerative Test Using MS and VSD Approach

The two main methods for multiple-three phase winding machine modelling are MS and VSD (multi-stator and vector space decomposition) methods. Both are suitable for vector control operation. In the previous works [11-13], related to PM machines, MS approach was used, while here VSD will be employed, as noted already. In order to introduce and explain the newly developed regenerative test, these two modelling approaches and the correlations between them are introduced first. Studied stator winding topologies are shown in Fig. 2.

The correlation between the two approaches represents the starting point for subsequent derivations and formulation of the new regenerative test procedure.

A. Multi-stator (MS) approach

One way to implement the regenerative test for these machines is by using the control based on the multiple *dq* (i.e.

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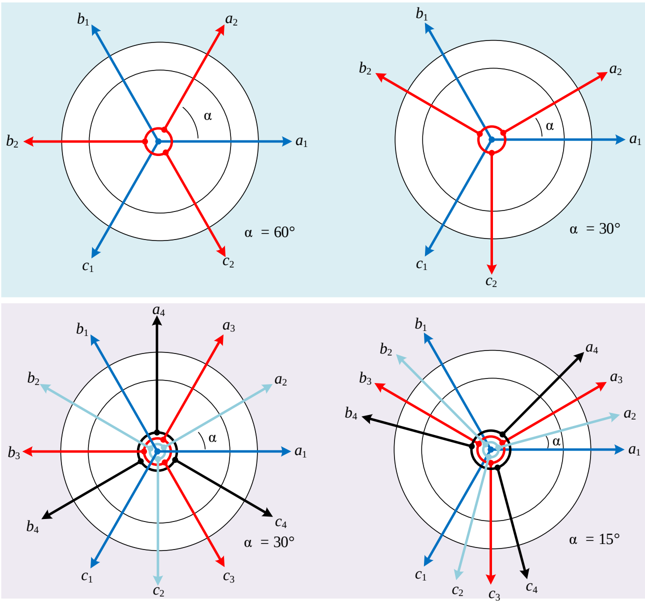

Fig. 2: Magnetic axes of symmetrical and asymmetrical six- and twelve-phase machines with two and four isolated neutral points, respectively.

MS) approach. This technique can be applied to any multiphase machine with multiple three-phase winding sets. MS approach for machine modelling has been introduced in [14] for asymmetrical six-phase induction machine. By using this approach each three-phase winding set can be considered as a separate three-phase machine with different flux and torque current component current controllers (d and q currents); hence, it is also called multi-stator (MS) approach. In [15], the authors utilised the MS approach to control the power flow among different energy sources for a dual three-phase PMSM.

As the same number of sets should operate in the motoring and generation mode, the regenerative test can be easily implemented in the machines with an even number of winding sets, i.e. neutral points. Therefore, the machines considered in this paper are six-, twelve-, eighteen-, etc., phase machines in symmetrical or asymmetrical configuration (see Fig. 2). The regenerative test can be applied using the following steps:

1. For one half of the winding sets FOC scheme has the speed of the machine as the control variable, while the other sets are operated in the torque control mode.
2. During the start-up of the machine, all winding sets are controlled in the speed mode.
3. After reaching the desired speed and establishing a steady-state operating point, half of the winding sets are switched to the torque control mode.
4. The torque reference for these sets is set to a negative value. The total torque reference provided to the generation sets should be set to no more than one half of the rated torque of the machine.

By implementing the pervious steps, half of the machine is set to the motoring mode and the other half is set to the generation mode. In other words, the machine is loaded using its own winding sets.

For a six-phase machine, the equilibrium torque is expressed by the following equation:

$$T_{s1} - T_{s2} = T_{fw} \tag{1}$$

where T_{s1} and T_{s2} stand for the torque developed by the first and the second winding set, respectively, and T_{fw} stands for the friction and windage power losses. However, T_{fw} is usually very small and can be neglected. Thus, equation (1) can be rewritten as follows:

$$T_{s1} = -T_{s2} = T_{ag} \tag{2}$$

where T_{ag} stands for the developed torque in the air-gap of the machine.

The schematic of the regenerative test for a twelve-phase machine using MS control scheme is illustrated in Fig. 3. For the twelve-phase machine, torque balancing equation can be written as follows:

$$T_{s1} + T_{s3} = -\left(T_{s2} + T_{s4}\right) \tag{3}$$

$$T_{s1} = T_{s3} = -T_{s2} = -T_{s4} = T_{ag} \tag{4}$$

Torque balancing equation and MS control scheme are equally applicable to multiple three-phase machines with symmetrical and asymmetrical configuration. The only difference is in the Clarke's (decoupling) transformation that should be applied. Clarke's transformation for each winding set of a multiple three-phase machine is defined as:

$$[\mathrm{C}(\delta)] = \sqrt{\frac{2}{3}} \left[\begin{array}{c|ccc} \alpha_i & \cos(\delta) & \cos(\delta + 2\pi/3) & \cos(\delta + 4\pi/3) \\ \beta_i & \sin(\delta) & \sin(\delta + 2\pi/3) & \sin(\delta + 4\pi/3) \\ o_i & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{array} \right] \tag{5}$$

where δ represents the spatial displacement of the winding set, with respect to the first winding set. If a symmetrical six-phase machine is taken as an example, then δ = 0 for the first winding set and $\delta = 2\pi/6$ for the second winding set. However, for the asymmetrical six-phase machine, $\delta = \pi/6$ for the second winding set. Clarke's transformation presented in (5) can be utilised for a twelve-phase machine as well. For symmetrical configuration δ is equal to 0, $2\pi/12$, $4\pi/12$ and $6\pi/12$ for the first, second, third and fourth winding set, respectively. As far

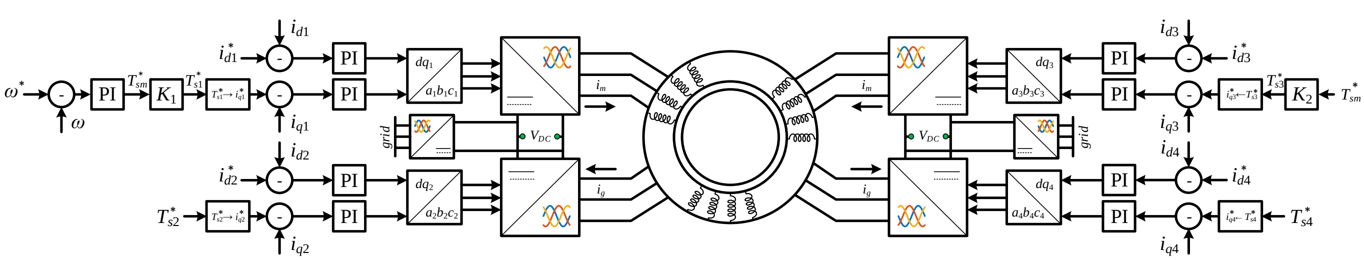

Fig. 3: Regenerative test schematic for twelve-phase machine using MS control scheme.

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as asymmetrical twelve-phase machine is concerned, δ is equal to 0, $\pi/12$, $2\pi/12$ and $3\pi/12$ for the first, second, third and fourth winding set, respectively.

B. VSD approach

Controlling multiple three-phase machines using MS approach is not trivial since there is a heavy coupling between the winding sets [13]. On the other hand, VSD approach decouples a multiphase machine into $n/2$ subspaces. Moreover, there is only one flux/torque producing subspace (α-β subspace), instead of two (six-phase) or four (twelve-phase) when MS approach is used. Therefore, VSD is a preferable way for closed loop control of multiphase machines in general. The remaining subspaces (x-y subspaces) present in VSD approach are the loss-producing subspaces. Theoretically, these subspaces do not need to be controlled, but in practice they are usually controlled in order to eliminate any asymmetries of the machine or of the converter. Sometimes, the auxiliary x-y subspaces are also controlled to non-zero current values, to achieve post-fault operation of a multiphase machine.

VSD transformation for an asymmetrical six-phase machine with two isolated neutral points is given as:

$$\left[\mathrm{VSD}_6\right]=\sqrt{\frac{2}{6}}\begin{bmatrix} \alpha & \cos\left(\left[\theta_{6A}\right]\right) \\ \beta & \sin\left(\left[\theta_{6A}\right]\right) \\ x & \cos\left(5\left[\theta_{6A}\right]\right) \\ y & \sin\left(5\left[\theta_{6A}\right]\right) \\ 0_1 & 1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \\ 0_2 & 0 \quad 0 \quad 0 \quad 1 \quad 1 \quad 1 \end{bmatrix} \tag{6}$$

where $[\theta_{6A}]$ is defined according to the angular position of the phases for the first and the second winding set, as:

$$\left[\theta_{6A}\right]=\pi/6\cdot\left[0 \quad 4 \quad 8 \quad 1 \quad 5 \quad 9\right] \tag{7}$$

For asymmetrical twelve-phase machines, with four neutral points, VSD transformation matrix can be expressed as:

$$\left[\mathrm{VSD}_{12}\right]=\sqrt{\frac{2}{12}}\begin{bmatrix} \alpha & \cos\left(\left[\theta_{12A}\right]\right) \\ \beta & \sin\left(\left[\theta_{12A}\right]\right) \\ x_1 & \cos\left(5\left[\theta_{12A}\right]\right) \\ y_1 & \sin\left(5\left[\theta_{12A}\right]\right) \\ x_2 & \cos\left(7\left[\theta_{12A}\right]\right) \\ y_2 & \sin\left(7\left[\theta_{12A}\right]\right) \\ x_3 & \cos\left(11\left[\theta_{12A}\right]\right) \\ y_3 & \sin\left(11\left[\theta_{12A}\right]\right) \\ 0_1 & \sqrt{2}\ \sqrt{2}\ \sqrt{2}\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\ 0_2 & 0\ 0\ 0\ \sqrt{2}\ \sqrt{2}\ \sqrt{2}\ 0\ 0\ 0\ 0\ 0\ 0 \\ 0_3 & 0\ 0\ 0\ 0\ 0\ 0\ \sqrt{2}\ \sqrt{2}\ \sqrt{2}\ 0\ 0\ 0 \\ 0_4 & 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ \sqrt{2}\ \sqrt{2}\ \sqrt{2} \end{bmatrix} \tag{8}$$

where $[\theta_{12A}]$ is defined as:

$$\left[\theta_{12A}\right]=\pi/12\cdot\left[0 \quad 8 \quad 16 \quad 1 \quad 9 \quad 17 \quad 2 \quad 10 \quad 18 \quad 3 \quad 11 \quad 19\right] \tag{9}$$

Although it is well known that (6)-(9) decouple the machine into $n/2$ subspaces (with only one α-β subspace), the problem is that the information about individual sets is lost now. Therefore, there is no possibility to control the individual winding sets any more directly, without further equation manipulation that is addressed in the next sub-section [16]. Such individual control is an easy task when using MS approach (but, the price to pay was the heavy cross-coupling, [13]). As a consequence, another method, based on links between those two approaches, is developed in order to have the ability to control the winding sets separately.

TABLE I:
MS AND VSD EQUIVALENCE FOR SYMMETRICAL AND ASYMMETRICAL SIX-, TWELVE- AND EIGHTEEN-PHASE MACHINES (X_K-Y_K SUBSPACE).

Six-phase	$i_x=\frac{1}{\sqrt{2}}\left(i_{\alpha1}-i_{\alpha2}\right)$
	$i_y=\frac{1}{\sqrt{2}}\left(-i_{\beta1}+i_{\beta2}\right)$
Twelve-phase	$i_{x3}=\frac{1}{2}\left(i_{\alpha1}-i_{\alpha2}+i_{\alpha3}-i_{\alpha4}\right)$
	$i_{y3}=\frac{1}{2}\left(-i_{\beta1}+i_{\beta2}-i_{\beta3}+i_{\beta4}\right)$
Eighteen-phase	$i_{x5}=\frac{1}{\sqrt{6}}\left(i_{\alpha1}-i_{\alpha2}+i_{\alpha3}-i_{\alpha4}+i_{\alpha5}-i_{\alpha6}\right)$
	$i_{y5}=\frac{1}{\sqrt{6}}\left(-i_{\beta1}+i_{\beta2}-i_{\beta3}+i_{\beta4}-i_{\beta5}+i_{\beta6}\right)$

C. Links between MS and VSD approach

The links between the two approaches have been established first in [17]. The x-y current components from VSD were used there to control the current amplitude of each winding set of a quadruple three-phase machine, i.e. for current sharing. In [18], the authors found the general correlations between the VSD and MS modelling approach for multiphase machines with multiple neutral points. These correlations express the x-y currents in terms of the winding set α_i-β_i currents. This provides the ability to VSD approach to individually control the currents of each winding sets through the control of x-y subspaces. For example, the correlation of asymmetrical six-phase machine VSD and MS approach can be found by multiplying the inverse of (5) ($[\mathrm{C}(\delta)]^{-1}$) for each winding set by the correspondent currents in the stationary reference frame (α_i-β_i-o_i). The result of the multiplication illustrates how the stationary reference frame currents (α_i-β_i-o_i) contribute to the phase currents. By multiplying the obtained correlations by $[\mathrm{VSD}_6]$, defined in (6) for the asymmetrical six-phase machine, the product will define how the VSD currents are related to the individual winding set currents α_i-β_i-o_i. The final result for the highest (the k-th) x-y subspace is illustrated in the first row of Table I. From Table I, one can see that the x and y current components consist purely of either α_i or β_i components. It is interesting to note that repeating the same procedure for a symmetrical six-phase machine will actually produce the same results as for the asymmetrical six-phase machine in Table I.

The correlations between the MS and VSD approach for the twelve-phase machines can be found in the same way (please see Appendix for details). The same can be repeated for the eighteen-phase machines with six neutral points and the results of the highest x-y subspace are included in the third

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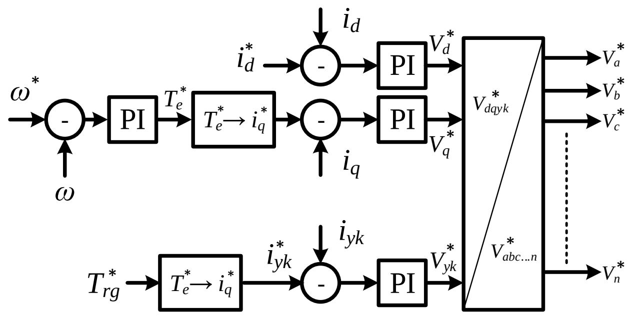

Fig. 4: Regenerative test control scheme for multiple three-phase winding machines with an even number of isolated neutral points.

row of Table I. Once again, regardless of whether the eighteen-phase machine is symmetrical or asymmetrical, the result is the same and is as given in Table I.

D. New VSD-based regenerative test

One can notice from Table I that *y*-current component in the highest order subspace always consists of β_i currents only. Half of the β_i currents are subtracted from the sum of the other half. In case of six-phase machines this is clear from i_y component, for twelve- and eighteen-phase machines this can be seen from i_{y3} and i_{y5}, respectively. Looking back at the regenerative test and MS approach, the idea is to make half of the winding sets to have negative *q* current (generation) while the other sets should provide the same amount of positive *q* current (motoring). Note that, for IRFOC, rotating reference frame control is necessary, which requires use of *d*-*q* variables rather than α-β. In this way, half of the machine winding sets will load the other half.

The regenerative test can be applied to any multiple three-phase winding machine, with an even number of neutral points, by using IRFOC in *d*-*q* subspace and by controlling the last of the *y*-current components. The control schematic of a regenerative test for multiple three-phase winding machines with an even number of neutral points is illustrated in Fig. 4. The regenerative test can be implemented using the following steps:

1. During the initial acceleration, the machine is set to speed control mode, where *d* and *q* currents are regulated using PI controllers.
2. After the machine has reached the reference speed, the desired regenerative torque reference (T_{rg}^*) can be applied using the *y*-axes reference current, i_{yk}^* in the highest-order *x*-*y* subspace (see Fig. 4).
3. Half of the winding sets will be in generation mode (with negative $i_{\beta i}$), while the other half will be in motoring mode (with positive $i_{\beta i}$).

The i_{yk}^* can be found from T_{rg}^* in the same way as the reference i_q^* is obtained from the torque reference T_e^* (output of the speed controller), as shown in Fig. 4. The other *x*-*y* subspace reference currents are set to zero. It should be noted that the Park's rotational transformation for *d*-*q* components is the standard one, leading to the synchronous reference frame; however, for the last x_k-y_k subspace the rotational transformation is implemented in such a way that the values are obtained in the anti-synchronous reference frame. Finally, one can see that the number of PI controllers is significantly reduced. For example, instead of using twelve PI current controllers to implement the regenerative test for eighteen-phase machines using MS approach, only three PI current controllers are required to achieve the same result by utilising the proposed control scheme. Note that the reduction of the number of current controllers is valid in the ideal conditions only (no dead-time and no asymmetries in the machine), while in practice additional controllers are normally necessary.

IV. Simulation Results

No particular attention has been paid so far to the type of the multiphase machine under test. Indeed, the deliberations of sections III are equally applicable to both synchronous and induction machines. The results in Table I are also universally valid, as is the control scheme of Fig. 4. However, the type of the machine leads to very important differences with regard to what can and what cannot be obtained from the regenerative test and this issue is addressed shortly.

The regenerative test utilising the new approach based on VSD and IRFOC for multiple three-phase machines with an even number of neutral points is investigated initially through simulations in Matlab/Simulink. First, to demonstrate the validity of the approach for higher number of phases, simulation results are provided for asymmetrical six-phase and twelve-phase induction machines. However, the experimental results, given in the next section, are collected using the asymmetrical six-phase induction machine, which is the one available in the laboratory.

The traditional speed control IRFOC scheme is implemented for asymmetrical six-phase machine with an extra current controller for i_y by using the general scheme of Fig. 4. Initially, the machine's reference speed is set to 950 rpm (99.5 rad/sec). After the machine has accelerated and reached the reference speed, the regenerative torque reference, T_{rg}^*, is changed from zero to the desired value at 1.7 s. After that moment, the T_{rg}^* is increased every 0.1 s by 2 Nm. The machine parameters are provided in Table II. The obtained simulation results are illustrated in Fig. 5.

From the simulation results shown in Fig. 5, one can see that after applying the regenerative torque at 1.7 s, the phase currents are changing in all winding sets (i_{a1}, i_{a2}) according to the change of T_{rg}^*. However, the i_{dq} currents are constant (i_q = 0, i_d = 0.7$\sqrt{3}$ A). The *x* loss-producing current is equal to zero. However, i_y, which leads to the T_{rg}^* application, changes as the the torque demand T_{rg}^* changes. The phase current peak value corresponds to $\hat{i}_n = \sqrt{\left(i_d^2/3\right)+\left(i_y^2/3\right)}$. The division by $\sqrt{3}$ appears because of the used power invariant version of the VSD transformation.

Active powers consumed by each winding set are shown in the last subplot of Fig. 5. Note that the power converters losses, machine iron core losses and friction losses are neglected in the simulations. The power, and hence the torque (because of the same and constant speed), of the machine are distributed equally among the winding sets. Half of the winding sets are having positive power and torque while the

TABLE II:
SIX- AND TWELVE-PHASE INDUCTION MACHINE PARAMETERS.

f_{sw}	10 kHz	P	3 (pole-pairs)
L_{lr}	25.4 mH	R_r	11.55 Ω
L_{ls}	5.3 mH	R_s	13.75 Ω
L_m	593 mH	V_{dc}	320 V

other half have negative values. From Fig. 5, the total power losses (in this case, the total power consumed from the grid) can be easily obtained. The highest losses are in the last period of the regenerative testing between 1.9 s and 2.0 s. The total losses here are: (379.2 –243.3) = 135.9 W. Table III illustrates the results of the complete analysis of the average input power and stator copper losses of the asymmetrical six-phase machine. The table shows the phase current rms values (I_{rms}) and average input power for each winding set (P_{inSi}, where i is the winding set number), for different values of T^*_{rg}. The copper losses are calculated from the I_{rms} values of the phase currents presented in Fig. 5. The algebraic sum of the P_{inS1} and P_{inS2} is equal to the stator's winding losses (P_{cus}) of the machine since other losses are neglected.

The above given power-related considerations do not mention rotor winding losses. The reason for this is that the rotor currents during the test are zero, since no net torque production is achieved (mechanical losses are neglected). Rotor currents are illustrated in the penultimate plot in Fig. 5 to confirm this observation. This makes the applicability of the test to induction machines very different from the one related to permanent magnet (PM) synchronous machines in [11-13]. In particular, while the test is sufficient to determine the efficiency from no-load to full load operation in the case of PM machines (and to also obtain related temperature rise when appropriate sensors exist), in the case of induction machines this cannot be done. The test only enables obtaining the no-load to full-load sum of constant losses (iron plus mechanical; neglected in simulation) and corresponding stator winding losses. However, since the current is measured, it becomes easy to separate the constant and variable losses, as illustrated shortly.

The twelve-phase machine parameters are the same as for the six-phase machine and are hence as provided in Table II. The simulation results of the asymmetrical twelve-phase machine are illustrated in Fig. 6. Initially, the machine's reference speed is set to 950 rpm. After the machine has accelerated and reached the reference speed, the regenerative torque reference, T^*_{rg}, is changed from zero to the desired value at 1.25 s. The T^*_{rg} is applied using i_{y3} reference current. After that moment, the T^*_{rg} is increased every 0.25 s by 4 Nm. The average power analysis for the twelve-phase machine using simulation results is shown in Table IV. The penultimate subplot in Fig. 6 again illustrates rotor currents and confirms once more that, since they are zero in steady state, rotor winding losses are zero.

The simulation results prove both the validity of the approach and its limitations in conjunction with induction machines. The efficiency and/or thermal design of a synchronous machine can be tested by using suggested simple modification of the FOC, and without the need to mechanically couple another machine, with results expected to be the same as in [11-13]. However, in the case of an induction machine, the approach can only be used to segregate the machine losses (stator copper losses vs. constant – i.e. core (P_{Fe}) and friction and windage losses (P_{fw})).

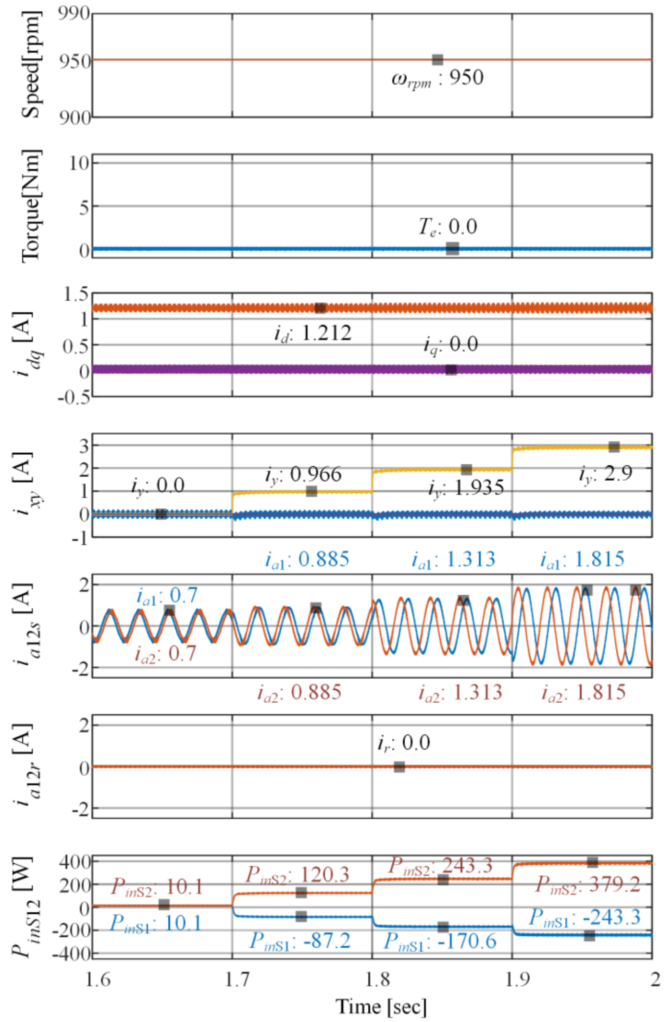

Fig. 5: Regenerative test: simulation results for an asymmetrical six-phase induction machine.

TABLE III:
AVERAGE POWER AND STATOR COPPER LOSSES OF ASYMMETRICAL SIX-PHASE MACHINE – SIMULATION RESULTS.

T_{rg} (Nm)	0	2	4	6
I_{rms} (A)	0.495	0.626	0.928	1.283
$P_{in\ S1}$ (W)	10.1	-87.2	-170.6	-243.3
$P_{in\ S2}$ (W)	10.1	120.3	243.3	379.2
P_{cus} (W)	20.2	32.3	71.1	135.9

Experimental results for the asymmetrical six-phase induction machine are shown next, so that the simulation results and related observations are fully validated.

V. EXPERIMENTAL RESULTS

To examine the regenerative test for multiphase machines with an even number of neutral points, an experimental setup with asymmetrical six-phase induction machine has been used. The machine parameters are the same as those used for the six- and twelve-phase machine, Table II. However, the

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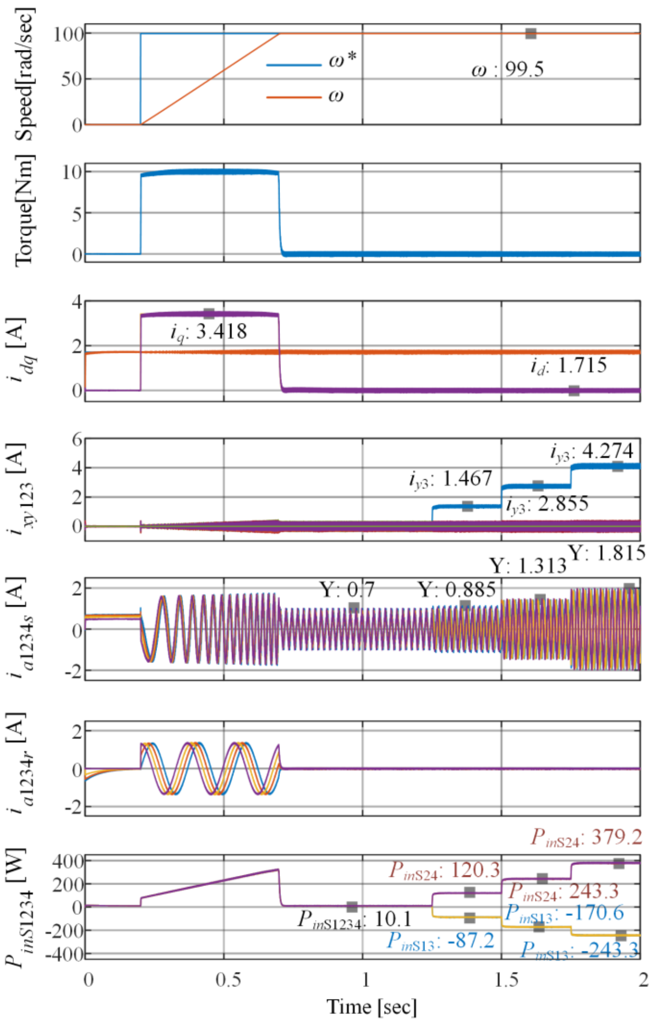

Fig. 6: Regenerative test: simulation results for an asymmetrical twelve-phase induction machine.

TABLE IV:
AVERAGE POWER AND STATOR COPPER LOSSES OF ASYMMETRICAL TWELVE-PHASE MACHINE – SIMULATION RESULTS.

T_{rg} (Nm)	0	4	8	12
I_{rms} (A)	0.495	0.626	0.928	1.283
$P_{in\ S1,\ S3}$ (W)	10.1	-87.2	-170.6	-243.3
$P_{in\ S2,\ S4}$ (W)	10.1	120.3	243.3	379.2
P_{cus} (W)	40.4	64.6	142.2	271.8

switching frequency f_{sw} is 5 kHz. The machine's rated power is 1.1 kW and it is configured with two isolated neutral points.

The experimental setup for the regenerative test for six-phase induction machine is illustrated in Fig. 7. A custom-made six-phase voltage source inverter (VSI) based on Infineon FS50R12KE3 IGBT modules supplies the machine. The VSI has a built-in dead-time of 6 µs. The dc-link voltage is provided by Spitzenberger & Spies four-quadrant operation linear amplifier, PAS2500, which is capable of sourcing and sinking the power. The control is implemented using real-time platform dSPACE ds1006. The phase currents are measured using the VSI internal LEM sensors and the dSpace ADC board dS2004 acquires all the phase current measurements.

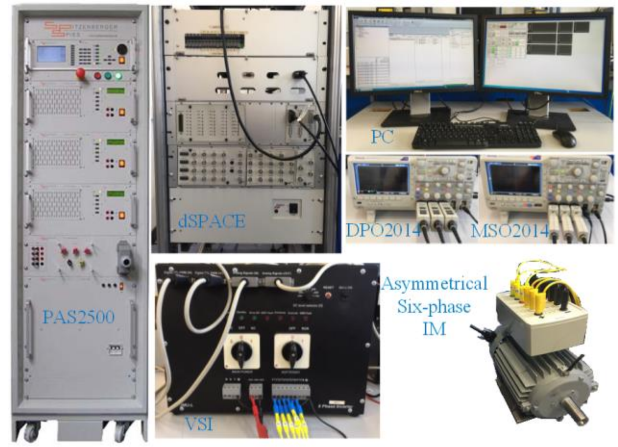

Fig. 7: Experimental setup.

The speed is measured using an optical encoder coupled to the six-phase machine's shaft. Two synchronously triggered Tektronix oscilloscopes (DPO/MSO 2014) are used for ac and dc voltage and current measurements. The measured currents and voltages are multiplied to provide the instantaneous power per winding set. Then, a moving average filter, with a window width equal to the fundamental period, is applied to obtain the average instantaneous power for each winding set.

The regenerative test control schematic illustrated in Fig. 4 is implemented using dSPACE. The flux/torque control is applied in the synchronous reference frame. The auxiliary current (y-current) control is implemented in the anti-synchronous reference frame. Due to the relatively large dead-time of the VSI, the fifth and seventh harmonics are large in the phase currents. Thus, two additional resonant vector PI controllers have been added to the auxiliary (x-y) current PI controllers, since the fifth and seventh harmonic are mapped into this subspace.

Initially, the machine is accelerated using a speed reference of 950 rpm. After the machine has reached the set speed, the regenerative test with different values of the T^*_{rg} is applied. The T^*_{rg} is applied as a sequence with the values 0, 2, 4, 6 Nm. Each value is applied for a duration of 0.1 s. The experimental results of the regenerative test are illustrated in Fig. 8 and Fig. 9. The current values in Fig. 9 are four times the actual currents of Fig. 8, since four turns where used to measure the current. One can notice that during the period from 0 to 0.1 s both windings of the tested six-phase machine are in motoring mode. This is obvious from the positive values of input powers of the winding sets (P_{inSi}), illustrated in Fig. 8. In addition, the i_y current is equal to zero in this period – hence, the regenerative test has not been initiated yet. The regenerative testing starts at 0.1 s. The T^*_{rg} is set to 2 Nm during the interval from 0.1 to 0.2 s. From Fig. 8, one can see that at 0.1 s a step change from 0 to 0.967 A happens in the i_y current. This change corresponds to the change of T^*_{rg}. During this period, the behaviour of the input power of the winding sets is changed. The first winding set power has a negative value, while the second winding set has a positive input power (the last plot in Fig. 8). Of course, the dc-link input power (black trace in the bottom plot of Fig. 8) is still positive. This

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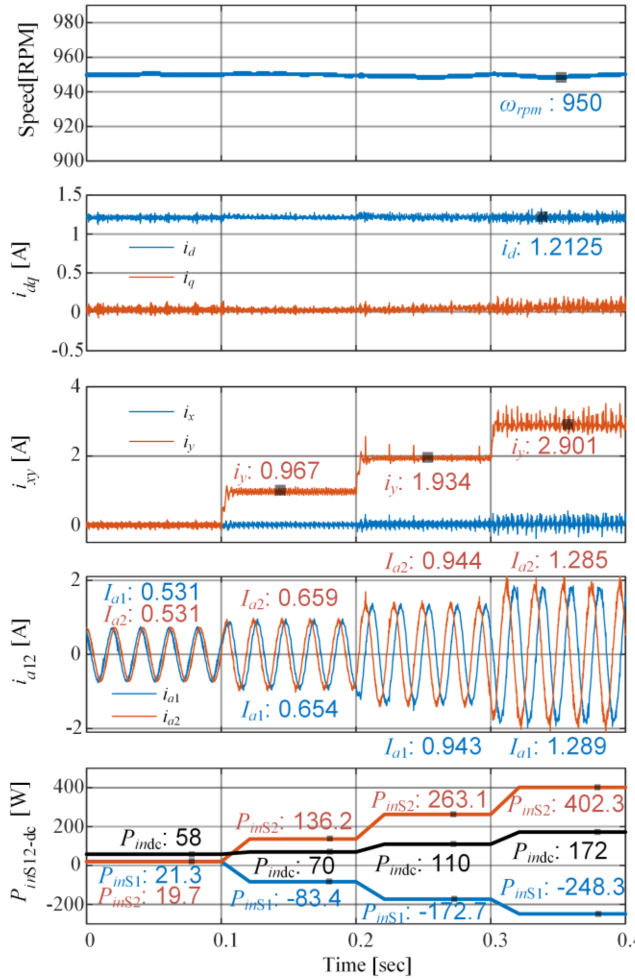

Fig. 8: Experimental results of the regenerative test for the asymmetrical six-phase induction machine (shown phase current values are rms in A).

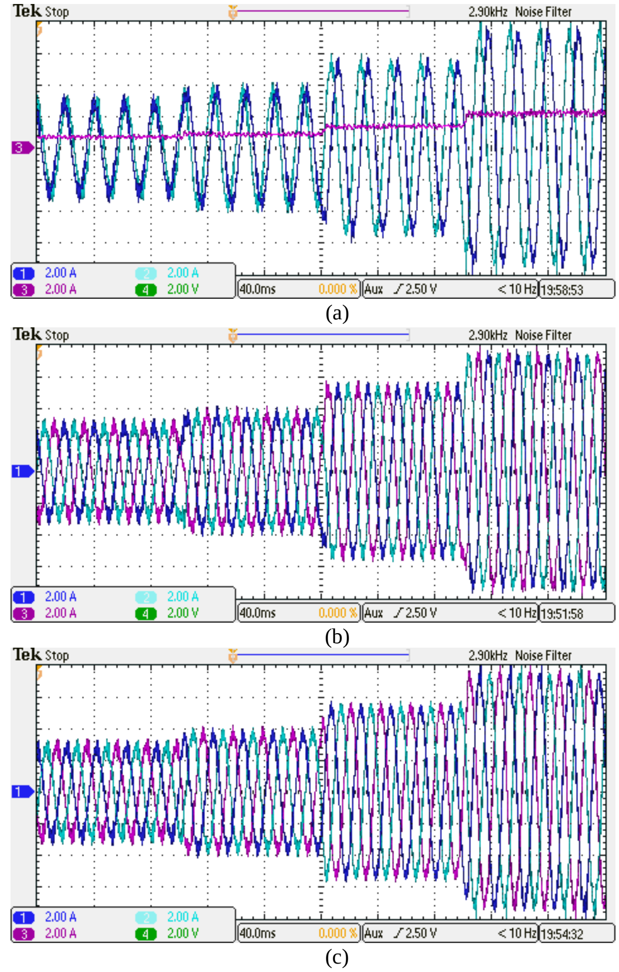

Fig. 9: Experimental results of the regenerative test for asymmetrical six-phase induction machine: (a) Ch1-i_{a1}, Ch2-i_{a2} and Ch3-i_{dc} current, (b) first set currents Ch1-i_{a1}, Ch2-i_{b1}, Ch3-i_{c1} (c) second set currents Ch1-i_{a2}, Ch2-i_{b2} and Ch3-i_{c2}.

is the power that the drive is using to cover the converter and the machine losses. The losses of the system include power electronic converter losses, stator's winding and core losses of the machine, and the friction and windage losses (i.e. variable stator losses and constant losses). During the period between 0.2 – 0.3 s the T^*_{rg} is set to 4 Nm. Finally, the rated stator current conditions of the machine are reached between 0.3 – 0.4 s where the nominal torque and speed are applied.

The current and power values, for different regenerative torques, are summarised in Table V. The machine losses are calculated by adding the input power (P_{inSi}) of the two winding sets. The stator copper losses are calculated from the I_{rms} of the two winding sets and from the knowledge of stator resistance (Table II), [19]. Next, the constant (mechanical and core) losses are calculated by subtracting the stator copper losses from the total machine losses. It is therefore simple to perform separation of constant losses and variable (load-dependent) losses using the test data. Finally, the converter losses are calculated by subtracting the total machine losses (P_{in1}+P_{in2}) out of the input power from the grid ($P_{in\,dc}$).

Comparison of the experimental results in Fig. 8 and the simulation results, given in Fig. 5, shows that the difference appears in the winding set powers, since the core and mechanical losses have been neglected in simulation. Indeed, the total machine losses in Table V exceed the corresponding values in Table III by the amount of the constant losses, which were not included in the simulation.

The calculated stator winding losses, illustrated in Table III, are approximately the same as in Table V, while the stator currents rms values I_{rms} are slightly higher in the experimental results (with the difference reducing as the torque increases, due to the diminishing relative importance of the constant losses).

To verify the accuracy of the constant and load-dependent (stator winding) loss segregation, obtained using the regenerative test, the standard no-load test is performed as well, using the inverter supply and open-loop control. Stator voltage is varied by changing the modulation index of the inverter supply, while the frequency is set the same as for zero load torque in experimental regenerative test results of Table V. The constant machine losses, determined from the no-load test, are shown in Fig. 10, plotted against the fundamental rms voltage squared. Using the fundamental rms voltage of 94.5 V (i.e., its squared value 8,930 V^2), it is possible to read the

TABLE V:
EXPERIMENTAL RESULTS – LOSS ANALYSIS FOR ASYMMETRICAL SIX-PHASE INDUCTION MACHINE.

T_{rg}^{*} (Nm)	0	2	4	6
$I_{rms\ \mathrm{S1}}$ (A)	0.531	0.654	0.943	1.289
$I_{rms\ \mathrm{S2}}$ (A)	0.531	0.659	0.944	1.285
I_{dc} (A)	0.181	0.219	0.344	0.538
$P_{in\ \mathrm{S1}}$ (W)	21.3	-83.4	-172.7	-248.3
$P_{in\ \mathrm{S2}}$ (W)	19.7	136.2	263.1	402.3
$P_{in\ \mathrm{dc}}$ (W)	58	70	110	172
Total Machine Losses (W)	41.0	52.8	90.4	154.0
P_{cus} (W)	23.3	35.6	73.4	136.7
$P_{fw} + P_{Fe}$ (W)	17.7	17.2	17.0	17.3
Converter Losses (W)	17.0	17.2	19.6	18.0

constant loss of the machine as approximately 19.5 W in Fig. 10. This voltage value corresponds to the phase rms fundamental voltage during regenerative test with 0 Nm setting. The value of 19.5 W agrees well with approximately 18 W in Table V, obtained from the regenerative test.

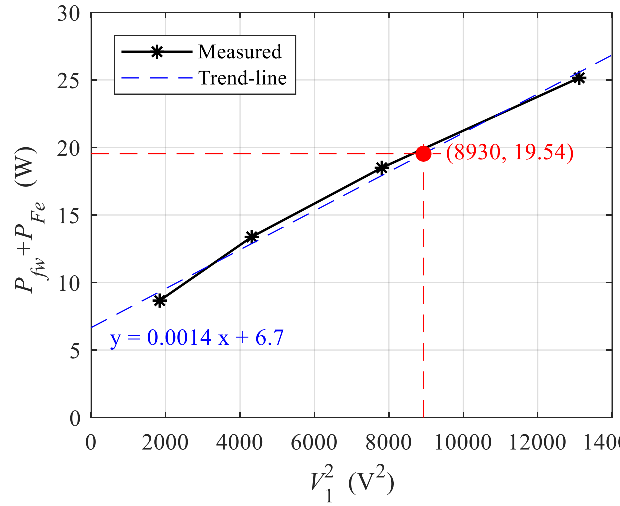

Fig. 10: Results of the standard no-load test of the asymmetrical six-phase induction machine – constant losses against fundamental rms voltage squared.

VI. CONCLUSION

In this paper, a novel approach to the regenerative test for multiple three-phase winding machines with an even number of neutral points has been introduced. In contrast to the existing version, it is based on the VSD modelling method. The regenerative test can be implemented by adding an extra current controller for the y_k-current component, where index k refers to the highest order x-y plane. It is elaborated in general terms for machine phase numbers up to eighteen. Compared to the existing version of the same test, based on the MS approach, control during testing is greatly simplified, since multiple decoupling terms are not required. The testing results are however independent of the control approach used.

The testing principles are the same for both synchronous and induction machines. However, the test outcomes are very different. In the case of a synchronous machine the rated power is circulated among the winding sets, the necessity for mechanical coupling at the shaft of the machine with another machine is eliminated, and the test enables efficiency evaluation and temperature rise measurement. As the test has been used in conjunction with permanent magnet synchronous machine already, the emphasis in the paper is placed on an induction machine. It is shown that, in contrast to synchronous machines, the test cannot be used to yield efficiency evaluation (and temperature rise results). This is so since, during the test, rotor currents are kept at zero, since there is no load attached to the shaft (neglecting mechanical losses). However, the test does enable a simple, straightforward and accurate way of determining the constant (sum of core and mechanical) losses.

The developed control scheme has been examined by simulation of six- and twelve-phase asymmetrical induction machines. Further, it has been validated experimentally using an asymmetrical six-phase induction machine. The results prove the theoretical considerations and show that the machine can operate at the nominal speed with rated stator currents and with zero total torque on the shaft, so that an accurate evaluation of the sum of the stator winding and constant machine losses can be obtained. Subject to the known stator resistance, further segregation of constant losses from the stator load-dependent losses is easily accomplished.

APPENDIX: MS-VSD CORRELATION FOR A 12-PHASE MACHINE

MS approach – Based on (5), for each set of asymmetrical twelve-phase machine, one can write:

$$\left[i_{abc\ i}\right]=\left[C\left(\delta_i\right)\right]^{-1}\cdot\left[i_{\alpha\beta o\ i}\right] \tag{10}$$

where i = 1,2,3,4 denotes the winding set number, and δ_i denotes the winding set angle (δ_i = 0, π/12, 2π/12 and 3π/12). Putting all four equations from (10) together, one can write:

$$\left[i_{ph12}\right]=\begin{bmatrix} i_{abc1} \\ i_{abc2} \\ i_{abc3} \\ i_{abc4} \end{bmatrix}=\begin{bmatrix} \left[C(0)\right]^{-1} & 0 & 0 & 0 \\ 0 & \left[C\left(\frac{\pi}{12}\right)\right]^{-1} & 0 & 0 \\ 0 & 0 & \left[C\left(\frac{2\pi}{12}\right)\right]^{-1} & 0 \\ 0 & 0 & 0 & \left[C\left(\frac{3\pi}{12}\right)\right]^{-1} \end{bmatrix}\cdot\begin{bmatrix} i_{\alpha\beta o1} \\ i_{\alpha\beta o2} \\ i_{\alpha\beta o3} \\ i_{\alpha\beta o4} \end{bmatrix} \tag{11}$$

The zeros in the matrix above are block matrices of size 3×3.

VSD approach – Application of (8) gives:

$$\left[i_{\mathrm{VSD12}}\right]=\left[VSD_{12}\right]\cdot\left[i_{ph12}\right] \tag{12}$$

where $[i_{\mathrm{VSD12}}] = [i_\alpha\ i_\beta\ i_{x1}\ i_{y1}\ i_{x2}\ i_{y2}\ i_{x3}\ i_{y3}\ 0_1\ 0_2\ 0_3\ 0_4]^{\mathrm{T}}$.

The links – If the values of [iph12] from (11) are substituted into (12) one gets:

$$\left[i_{\mathrm{VSD12}}\right]=\left[VSD_{12}\right]\cdot\left[i_{ph12}\right]=\left[VSD_{12}\right]\cdot\left[C_{diag}\right]\cdot\begin{bmatrix} i_{\alpha\beta o1} \\ \vdots \\ i_{\alpha\beta o4} \end{bmatrix} \tag{13}$$

For simplicity, the central matrix of (11) is denoted as $[C_{diag}]$ in (13). After multiplying $[VSD_{12}]$ by $[C_{diag}]$, (13) becomes:

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$$\left[i_{\mathrm{VSD12}}\right]=\begin{bmatrix} i_\alpha \\ i_\beta \\ i_{x1} \\ i_{y1} \\ i_{x2} \\ i_{y2} \\ i_{x3} \\ i_{y3} \end{bmatrix}=\left[\mathrm{VSD}_{12}\right]\cdot\left[i_{ph12}\right]=\begin{bmatrix} \frac{1}{2}\left(i_{\alpha1}+i_{\alpha2}+i_{\alpha3}+i_{\alpha4}\right) \\ \frac{1}{2}\left(i_{\beta1}+i_{\beta2}+i_{\beta3}+i_{\beta4}\right) \\ \frac{1}{2}\left(i_{\alpha1}-i_{\alpha3}+i_{\beta2}-i_{\beta4}\right) \\ \frac{1}{2}\left(i_{\alpha2}-i_{\alpha4}-i_{\beta1}+i_{\beta3}\right) \\ \frac{1}{2}\left(i_{\alpha1}-i_{\alpha3}-i_{\beta2}+i_{\beta4}\right) \\ \frac{1}{2}\left(i_{\alpha2}-i_{\alpha4}+i_{\beta1}-i_{\beta3}\right) \\ \frac{1}{2}\left(i_{\alpha1}-i_{\alpha2}+i_{\alpha3}-i_{\alpha4}\right) \\ \frac{1}{2}\left(-i_{\beta1}+i_{\beta2}-i_{\beta3}+i_{\beta4}\right) \end{bmatrix} \quad (14)$$

Equation (14) gives the links between MS variables ($i_{\alpha1}$, $i_{\beta1}$, …, $i_{\alpha4}$, $i_{\beta4}$) and the VSD variables (i_α, i_β, i_{x1}, i_{y1}, …, i_{x3}, i_{y3}). Zero axes of VSD and MS approach are linked as: $0_1=(1/2)o_1$, $0_2=(1/2)o_2$, $0_3=(1/2)o_3$, $0_4=(1/2)o_4$, and are omitted in (14).

The final links in (14) are actually the same for asymmetrical and symmetrical case.

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