Distributed Current Control for Multi-Three Phase Synchronous Machines in Fault Conditions

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Abstract—Among challenges and requirements of on-going electrification process and future transportation systems there is demand for arrangements with both increased fault tolerance and reliability. Next aerospace, power-train and automotive systems exploiting new technologies are delving for new features and functionalities. Multi-three phase arrangements are one of these novel approaches where future implementation of aforementioned applications will benefit from. This paper presents and analyses distributed current control design for asymmetrical split-phase schemes composed by symmetrical three phase sections with even number of phases. The proposed design within the $dq_0$ reference frame in nominal, open and short circuit condition of one three-phase system is compared with the vector space decomposition technique and further validated by mean of Matlab/Simulink simulations.

Index Terms—Multi-three phase machine, current control, fault tolerance

I. INTRODUCTION

Electrification of future transportation systems is demanding for more reliability and fault tolerance than current fossil fuel solutions are able to guarantee. Nowadays, the multi-three phase machine concept is gaining popularity [1], [2] thanks to the repetition of a very well-known system: a two level voltage source converter controlling a three phase machine with a three phase set of windings (a,b,c) in Fig. 1. The repetition of this unit block (or module, or segment) establishes the multi-three phase machine concept in Fig. 2. The DC/AC converters are connected in parallel rather than in series. Indeed if wired in series, a fault in one converter would affect all the others.

The main advantage of the multi-three phase approach is the reuse of all the know-how regarding different control strategies, fault detection, fault isolation, and winding design for the unit block in Fig. 1. Many different solutions, strategies, and counter measures have been deployed along the years. Some solutions have taken advantages of additional switches or diodes introduction, whereas others simply re-configure the converter control strategy [3]–[5].

II. MACHINE MODELLING

A. Modelling assumptions

The work presented in this paper is based on the assumption that stator inductances are constant. Therefore, it applies to electric machines with negligible saturation effects. In addition it is assumed that:

- all phases are geometrically identical;
- each phase is symmetrical around its magnetic axis;
- the spatial displacement between two whatever phases is an integer multiple of the phase progression $\alpha$ (Fig.3b);
- within the air-gap, only the fundamental component of magneto-motive force is considered.

No restrictive assumption is made, instead, about whether the winding is distributed or concentrated and no leakage flux component is ignored [8], [9], [11].
B. Winding arrangement

Multi-three phase electrical motors are a particular group of split-phase winding machines. Defining $m$ the number of phases per set of windings, in multi-three phase motors $m = 3$ (phases a, b, and c in Fig.1). Therefore, defining $N$ the number of three phase systems (or unit block), the total number of phases is equal to $n = Nm$. The motor modelled in this paper is composed by twelve phases, arranged in four three-phase sets of windings ($m = 3$, $N = 4$, $n = 12$). Considering the case of an asymmetrical split-phase scheme composed of $N$ symmetrical $m$-phase sections with even number of phases $n = Nm$ (Fig.3a), the permutation matrix

$$W_{i,j} = \begin{cases} 1 & \text{if } i - \text{trunc}(\frac{j - 1}{m}) - 2N\text{mod}(j - 1, m) - 1 = 0 \\ -1 & \text{if } |i - \text{trunc}(\frac{j - 1}{m}) - 2N\text{mod}(j - 1, m) - 1| = mN \\ 0 & \text{otherwise} \end{cases}$$

maps the scheme in Fig.3a into the asymmetrical $n$-phase scheme (or standard equivalent scheme) with sequentially-distributed phases in Fig.3b (where $\text{trunc}(x)$ is the largest integer less than or equal to $x$, $\text{mod}(x, y)$ is the remainder on dividing $x$ by $y$, and $i, j$ are row and column identifiers.) [9]. The phase progression in asymmetrical $n$-phase schemes is $\alpha = \pi/n$. In Fig.3, for graphical simplicity’s sake $n = 6$ ($m = 3$, $N = 2$, $\alpha = \pi/6$) but in this work $n = 12$. The stator inductance matrix of the standard (denoted with subscript std) winding scheme in Fig.3b has the structure shown in the following $nxn$ matrix:

$$L_{std} = \begin{bmatrix} 
\lambda_0 & \lambda_1 & \lambda_2 & \cdots & -\lambda_2 & -\lambda_1 \\
\lambda_1 & \lambda_0 & \lambda_1 & \cdots & -\lambda_3 & -\lambda_2 \\
\lambda_2 & \lambda_1 & \lambda_0 & \cdots & -\lambda_4 & -\lambda_3 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
\lambda_2 & \lambda_3 & \lambda_4 & \cdots & -\lambda_0 & -\lambda_1 \\
\lambda_1 & \lambda_2 & \lambda_3 & \cdots & -\lambda_1 & -\lambda_0 
\end{bmatrix} = WL_{abc}W^T$$

The above relates the vector $\phi_{std}$ of the $n$ phase flux linkages to the vector $i_{std}$ of the $n$ phase currents ($\phi_{std} = L_{std}i_{std}$). The $L_{std}$ matrix values will allow to verify the results presented in Sec.III and can be easily computed from the stator inductance matrix $L_{abc}$ by (1) and (2).

C. Analytical model in Park’s coordinates

Distributed current control is achieved within the rotor-attached orthogonal $dq0$ reference frame thanks to the Park’s transformation relating machine stator variables (denoted with subscript $abc$) to the $dq0$ ones (denoted with subscript $dq$). In distributed current control, there is one controller per three phase set and only the local three currents are provided as feedback. Since the machine is made by multiple three phase systems, the global $nxn$ Park’s transformation matrix is given by Eq. 3, where $O_3$ is a $3x3$ null matrix, and $\theta$ is the rotor position.

$$T = \begin{bmatrix} 
T_1 & \cdots & 0_3 \\
\vdots & \ddots & \vdots \\
0_3 & \cdots & T_N 
\end{bmatrix}_{nxn}$$

$$T_h = \sqrt{\frac{2}{3}} \begin{bmatrix} 
\cos[\theta - (h - 1)\alpha] & \sin[\theta - (h - 1)\alpha] & 0 \\
-\sin[\theta - (h - 1)\alpha] & \cos[\theta - (h - 1)\alpha] & 0 \\
0 & 0 & 1 
\end{bmatrix}$$

$$W = \begin{bmatrix} 
v_{dq1} & \cdots & v_{dqN} 
\end{bmatrix}^T, \quad i_{dq1} = [i_{dq1} \cdots i_{dqN}]^T, \quad e_{dq1} = [e_{dq1} \cdots e_{dqN}]^T$$

$$v_{dq} = R_{dq}i_{dq} + \omega J_{dq}i_{dq} + L_{dq} \frac{di_{dq}}{dt} + e_{dq}$$

$$i_{dq} = [i_{dq1} \cdots i_{dqN}]^T; \quad e_{dq} = [e_{dq1} \cdots e_{dqN}]^T$$

where $v_{dq} = [v_{dh} \ v_{qh} \ v_{0h}]^T; \quad i_{dq} = [i_{dh} \ i_{qh} \ i_{0h}]^T; \quad e_{dq} = [e_{dh} \ e_{qh} \ e_{0h}]^T$$

$$\phi_{dq} = \frac{vdq}{\omega dt}$$

The whole set of machine variables can be thus transformed into the $dq0$ reference frame. The machine voltage equation in the new coordinate system is:

$$v_{dq} = R_{dq}i_{dq} + \omega J_{dq}i_{dq} + L_{dq} \frac{di_{dq}}{dt} + e_{dq}$$

$$v_{dq} = \begin{bmatrix} v_{dh} \\ v_{qh} \\ v_{0h} \end{bmatrix}^T, i_{dq} = \begin{bmatrix} i_{dq1} & \cdots & i_{dqN} \end{bmatrix}^T, e_{dq} = \begin{bmatrix} e_{dq1} & \cdots & e_{dqN} \end{bmatrix}^T$$

$$v_{dq} = R_{dq}i_{dq} + \omega J_{dq}i_{dq} + \frac{\omega d\phi_{dq}}{dt}$$

$$J = \begin{bmatrix} J_1 & \cdots & 0_3 \\
\vdots & \ddots & \vdots 
\end{bmatrix}; \quad J_h = \frac{dT_h}{dt} = \begin{bmatrix} 0 & -1 & 0 \\
1 & 0 & 0 \\
0 & 0 & 0 \end{bmatrix}$$

$$J = \begin{bmatrix} J_1 & \cdots & 0_3 \\
\vdots & \ddots & \vdots 
\end{bmatrix}; \quad J_h = \frac{dT_h}{dt} = \begin{bmatrix} 0 & -1 & 0 \\
1 & 0 & 0 \\
0 & 0 & 0 \end{bmatrix}$$

More precisely, $R_{abc} = R_{dq} = r_s I_{(nxn)}$ where $r_s$ is the stator phase resistance, whereas

$$L_{dq} = \begin{bmatrix} 
L_{dq(1,1)} & \cdots & L_{dq(1,N)} \\
\vdots & \ddots & \vdots 
L_{dq(N,1)} & \cdots & L_{dq(N,N)} 
\end{bmatrix}$$

with $L_{dq(i,j)} = T_{h(i,j)}L_{abc(i,j)}T_h^T$
where $L_{md}$ and $L_{mq}$ are $d$, $q$ magnetizing inductances. Parameters $M_k$, $X_k$, $H_k$ are the stator leakage inductances expressed in the rotor $dy0$ reference frame. Their physical meaning is schematically shown in Fig. 4 (where $i$ and $j$ are the stator set identifiers $1..N$) and they can be calculated with finite element analysis or analytic formulation [12], [13]. In particular, it can be seen that the mutual leakage inductance $X_{i-j}$ couples the $d$-axis circuit corresponding to the $i$-th set with the $q$-axis circuit corresponding to the $j$-th set of windings. It is worth to notice that $d$-$q$ cross coupling depends on leakage fluxes alone and may occur only between $d$ and $q$ circuits representing different stator sets (i.e. only if $i \neq j$, hence $X_{0-0} = 0$).

**D. Leakage inductances**

The stator leakage inductances in of the electric motor under investigation are reported in Table I. They are expressed in p.u. using as base value of the impedance $V_n/\sqrt{3}I_n N$, where $V_n$ and $I_n$ are respectively nominal voltage and nominal current. Since $X_{0-1} = 0$, there are no $d$-$q$ interactions between different sets of windings. In the next section, for simplicity’s sake, whenever the current dynamic is the same in all the segments, only data regarding the first unit-block will be plotted. Actually, since in this particular case $L_{md} = L_{mq}$, only data regarding the $q$ axis of the first module will be shown.

**III. CURRENT CONTROL DESIGN IN NOMINAL CONDITIONS**

In order to simplify the design of the distributed current controllers, this Section aims at finding a transfer function linking each element of the current vector only to the corresponding element of the voltage vector, with no other input acting as a disturbance. Unfortunately this is not possible by the analytical model in $dq$ coordinates since the inductance matrix $L_{dq}$ is not diagonal. In order to diagonalize the inductance matrix the vector space decomposition is used, as it will be explained in the following.

Since much faster than the rotor dynamic, the current control loop design based on the voltage stator equation (5) has been computed in blocked rotor condition. Therefore, the speed ($\omega$) is zero, and (5) becomes:

$$v_{dq} = R_{dq}i_{dq} + L_{dq} \frac{di_{dq}}{dt}$$

In state space model form, (8) becomes:

$$\dot{x}_{dq} = A_{dq}x_{dq} + B_{dq}u_{dq}$$
$$y_{dq} = C_{x}x_{dq} + D_{u}u_{dq}$$

where $x_{dq}$ is the current state vector, $u_{dq}$ is the applied voltage input vector, $y_{dq}$ is the output current vector, $A_{dq} = -L_{dq}^{-1}R_{dq}$, $B_{dq} = L_{dq}^{-1}$, $C$ and $D$ are respectively identity and null matrices n.x.n. Since $L_{dq}$ is not diagonal, it is not possible to get the decoupled transfer functions between the $i$-th input and $j$-th output with the following equation:

$$G_{dq} = C(sI - A_{dq})^{-1}B_{dq} + D = Y_{dq}/U_{dq}$$

where $I$ is identity matrix and $s$ is the Laplace operator. Indeed $G_{dq}$ is not diagonal. In order to find the first harmonic inductor value for designing the current controller in nominal condition, the matrix of inductances can be diagonalized thanks to the vector space decomposition (VSD) technique. The transformation matrix $T_{vsd}$ maps the orthonormal coordinates $dq0$ into the so called $vsd$ orthonormal space. Therefore

$$L_{vsd} = T_{vsd}^{T}L_{dq}T_{vsd}$$

whereas $R_{vsd} = R_{dq}$, since $R_{dq}$ is diagonal. The new input, output and state space vectors in (12), respectively $u_{vsd}$, $y_{vsd}$ and $x_{vsd}$, are the odd harmonic values of applied voltages, output currents and state space values up to the $2\nu + 1$-th harmonic (with $\nu = \text{trunc}((n - 1)/2)$), on both $d$ and $q$ axes.

$$u_{vsd} = [u_{d1} u_{q1} u_{d3} u_{q3} \cdots u_{d(2\nu+1)} u_{q(2\nu+1)}]^T$$
$$y_{vsd} = [y_{d1} y_{q1} y_{d3} y_{q3} \cdots y_{d(2\nu+1)} y_{q(2\nu+1)}]^T$$
$$x_{vsd} = [x_{d1} x_{q1} x_{d3} x_{q3} \cdots x_{d(2\nu+1)} x_{q(2\nu+1)}]^T$$

Therefore, defining the new state space matrices $A_{vsd} = -L_{vsd}^{-1}R_{vsd}$ and $B_{vsd} = L_{vsd}^{-1}$, the decoupled transfer functions have been computed in the $vsd$ space thanks to the following equation:

$$G_{vsd} = C(sI - A_{vsd})^{-1}B_{vsd} + D = Y_{vsd}/U_{vsd}$$

The matrix $G_{vsd}$ is diagonal and it describes the odd harmonic values of the currents up to the $2\nu + 1$-th harmonic, on both

**TABLE I
STATOR LEAKAGE INDUCTANCES IN dq0**

<table>
<thead>
<tr>
<th>$i-j$</th>
<th>0-0</th>
<th>0-1</th>
<th>0-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ [p.u.]</td>
<td>0.1</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>$H$ [p.u.]</td>
<td>0.1</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>$X$ [p.u.]</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Phase (deg)

-90
-45
0
Phase (deg)

-90

-20

0

20

40

60

Magnitude (dB)

10^{-1} 100 10^{1} 10^{2} 10^{3}

Frequency (rad/s)

System: G_{vsdNC}(2,2)

Frequency (rad/s): 2.15

Magnitude (dB): 39.8

3dB

Fig. 5. Bode diagram comparing the transfer functions in both vsd and dq state space models.

d and q axes. From this point, nominal, open and short circuit condition will be denoted respectively with subscript \( NC \), \( OC \) and \( SC \).

The \( G_{vsd} \) and \( G_{dq} \) transfer function \( nxn \) matrices link input and output of two equivalent orthonormal spaces. Since the \( vsd \) space is related to the equivalent poly-phase winding arrangement in Fig.3b, characterized by a symmetrical circulant structure inductance matrix like the one in (2), the \( G_{vsd} \) matrix is diagonal. In Fig.5 it is shown the equivalence of the following transfer functions: \( G_{AdqNC} = \sum_{k=1}^{N} G_{dqNC(k,2)} \) and \( G_{vsdNC(2,2)} \). \( G_{AdqNC} \) (in red asterisks) relates all the \( dq0 \) inputs with the \( q \) output current of the first set of windings \( x_{dq(2,1)} \) in (9). \( G_{vsdNC(2,2)} \) (in blue circles) relates the first harmonic \( q \) input voltage with the first harmonic \( q \) output current, \( x_q1 \) in (12). In order to highlight that the mutual leakage inductance \( X_0-1 \) in Fig. 4 is zero, in green triangles it is shown the transfer function \( G_{BdqNC} = \sum_{k=1}^{N} G_{dqNC(k,1-2)} \) describing just the \( q \) output current of the first set of windings taking into account only the \( q \) input voltages \( (u_{dq(2,1)}, u_{dq(0,1)}, u_{dq(5,1)}, u_{dq(8,1)}, u_{dq(11,1)}) \). The match between \( G_{AdqNC} \) and \( G_{BdqNC} \) confirms that there are no interactions among different axes of different sets of windings.

The \( G_{vsdNC(2,2)} \) transfer function pulsation in Fig.5 is

\[
\omega_{NC} = r_s / d_{NC1}
\]

where \( d_{NC1} \) is the first harmonic inductance in nominal condition. Since \( r_s \) can be easily measured and \( \omega_{NC} \) can be extrapolated from Fig.5, \( d_{NC1} \) computation is trivial. However, in order to plot Fig.5, \( G_{dq} \) in (10) or \( T_{vsd} \) in (11) and \( G_{vsd} \) in (13) must be numerically computed. Exactly the same \( d_{NC1} \) value and \( L_{vsd} \) diagonal matrix could have been obtained analytically thanks to the vector space decomposition with the following equations [8], [9]:

\[
d_j = \sum_{k=1}^{n} \lambda_{k-1} \cos \alpha k (k-1)
\]

(where \( \lambda_k \) are the matrix values in (2)) keeping just the odd elements up to \( j \) equal to \( 2\nu + 1 \) like in the following:

\[
L_{vsd} = \begin{pmatrix}
d_1 & 0 & 0 & \cdots & 0 & 0 \\
0 & d_1 & 0 & \cdots & 0 & 0 \\
0 & 0 & d_3 & \cdots & 0 & 0 \\
0 & 0 & 0 & \cdots & d_{2\nu+1} & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
0 & 0 & 0 & 0 & 0 & d_{2\nu+1}
\end{pmatrix}
\]

Since the first harmonic inductance \( d_1 \) describes the dominant pole of the current dynamic on both \( d \) and \( q \) axes, once \( d_1 \) is computed in nominal condition with one of the two presented methods, \( q \) and \( d \) current proportional integral controllers (PI) in Fig.6 can be computed considering the plant in (17).

\[
G_{vsdNC(2,2)} = \frac{1}{s d_{NC1} + r_s} = \sum_{k=1}^{n_{NC}} G_{dqNC(k,2)}
\]

In the next section open and short circuit conditions are detailed, and it will be shown that (15) is not valid for the short circuit condition.

IV. CURRENT CONTROL DESIGN IN FAULTY CONDITIONS

In a real case scenario, in a system like the one in Fig. 2, both on machine and inverter side, many different faults can occur. In this paper, for brevity, only the two following faulty conditions have been modelled: a) last set open (Fig. 7a), b) last set short circuited (Fig. 7b). In this work, it is assumed that after a generic fault, the system is able to configure itself in one of these two configurations.

A. Open circuit

In order to calculate the first harmonic inductance under open circuit condition (Fig.7a), the state space model in (9) must be re-written. If the model order in healthy condition is equal to the phase number \( n_{NC} = N_{NC} \cdot m \), the new model...
order in open circuit condition is equal to \( n_{OC} = n_{NC} - 3 = N_{OC} - N_{NC} = 9 - 3 = 6 \), being \( N_{OC} = 3 \) instead of four. Therefore, the new state space model in \( dq0 \) coordinates will be built without considering the last three rows and the last three columns of the state space model in nominal condition:

\[
X_{dqOC} = X_{dqNC}(1:n_{NC}-1), \quad u_{dqOC} = u_{dqNC}(1:n_{NC}-1)
\]

\[
y_{dqOC} = y_{dqNC}(1:n_{NC}-1), \quad L_{dqOC} = L_{dqNC}(1:n_{NC}-1)
\]

\[
R_{dqOC} = R_{dqNC}(1:n_{NC}-1)
\]

\[
C_{dqOC} = I_{(n_{OC}-n_{NC})}, \quad D_{dqOC} = 0_{(n_{OC}-n_{NC})}
\]

Similarly to what has been done for the nominal condition in the previous section, computing \( A_{dqOC}, B_{dqOC}, \) (10), (11), (13) with the new variables defined in (18), the diagonalised sub-state space model leads to a new transfer function \( G_{vsdOC(2,2)} \). In Fig.8, the bode diagrams of the dominant transfer function in nominal (black line) and faulty conditions, both from \( vsd \) (yellow right triangles) and \( dq0 \) (magenta diamonds) state, have been reported. From the diagrams it is possible to appreciate the match between the two different coordinate systems and the difference between faulty and healthy state. The \( G_{vsdOC(2,2)} \) differs from (17) only for the inductance \( d_{1OC} \) value that can be used for the design of the current controller under open circuit condition. Like in nominal condition, the \( d_{1OC} \) value can be computed by (15) (with \( k \) ranging from 1 to \( n_{OC} \)) or it can be extrapolated from Fig. 8.

B. Short circuit

The model describing the system in Fig.7b, with the last three phase set of windings in short circuit, is obtained imposing zero voltage on the fourth phase set (\( v_{d4} = v_{q4} = v_{o4} = 0V \)). The state space model order will be the same of the one in nominal condition (\( n_{SC} = n_{NC} \)) and for this reason (15) is not valid. Short circuit currents presence in the faulty set affects the current dynamic of healthy sets. According to the spatial disposition of the healthy three phase sets with respect to the faulty one (the fourth one), current dynamics of the first and third three phase sets are identical, but they are different from that of the second three phase set. Transfer functions relating healthy \( q \) input voltages (\( u_{dq(1,1)}, u_{dq(5,1)}, u_{dq(8,1)} \)) with healthy \( q \) output currents (\( x_{dq(1,1)}, x_{dq(5,1)}, x_{dq(8,1)} \)) are plotted in Fig.9. From the diagrams it is possible to appreciate the difference between the second (red asterisks) set versus the first (blue circles) and the third one (magenta triangles). Since at high frequency all the sets of windings differ from nominal condition (black line), the proportional gains of the PI controllers must be updated in order to match the healthy system closed loop transfer function in Fig.6. It will be latter shown that determining the three high frequency magnitude differences between nominal and faulty condition transfer functions in Fig.9 (\( K_{SC1} = K_{SC3}, \) and \( K_{SC2} \)) and updating the PIs as indicated in Table II, it is possible to compensate the fourth set short circuit fault.

![Fig. 8. Bode diagram comparing the dominant pole in nominal condition \( G_{vsdNC(2,2)} \) versus the open circuit condition \( G_{vsdOC(2,2)} \) versus the open circuit condition \( G_{vsdOC(2,2)} \).](image)

**V. SIMULATION RESULTS**

The system has been simulated in all the conditions presented above: nominal, open and short circuit condition. The \( q \) currents \( i_{q1}, i_{q2}, i_{q3}, i_{q4} \) of the four sets of windings are respectively the 2-nd, 5-th, 8-th and 11-th element of the state space vector \( x_{dq} \) in (9). The stator leakage inductances in \( p.u. \) are reported in Table I, the magnetizing inductances and stator phase resistor are respectively \( L_{mq} = L_{md} = 1.62H \) and \( r_s = 0.0072\Omega \). In nominal condition, the resulting first harmonic inductance \( d_{1NC} \) has been computed by (15) equal to 0.0033\( H \) and further verified thanks to (14) and Fig.5. In all the simulations the current PI controllers have been set
up with current bandwidth \( \omega_c = 600[\text{rad/sec}] \) and phase margin \( \varphi_c = 60^\circ \). In order to highlight how stability margins are affected by faulty conditions, second order current filter and microprocessor actuation delay \( e^{-s1.5T_s} \) have been introduced as shown by the block diagram of Fig.11. The delay has been set as \( T_s = 2\pi/(25\omega_c) [\text{sec}] \) and the current filter cut-off frequency as \( \omega_f = 66 \cdot 10^3 [\text{rad/sec}] \). The PI parameters

\[
\begin{align*}
\omega_f^2 &= \sqrt{2}\omega_f s + \omega_f^2 \\
\end{align*}
\]

Fig. 11. Actuation delay and current filter have been introduced in order to highlight stability margin variations while keeping constant the PI gains in faulty conditions.

computation in nominal condition has led to \( K_{pNC} = 2.12 \) and \( K_{iNC} = 197 \).

A. Nominal condition

The output current in nominal condition of the control diagram in Fig.11 has been compared with the four \( i_q \) output currents of a Simulink simulation with the four PI controllers regulating the whole \( dq0 \) machine model. In Fig.10a, it is possible to appreciate the match between the desired dynamic from the control diagram in Fig.11 and the four Simulink output currents with the same PI parameters \( K_{pNC} \) and \( K_{iNC} \).

B. Stability margins in faulty conditions

In Figs.10b and 10c, stability margins of loop gain transfer functions in open and short circuit condition are shown. It is clear that without updating the controllers in open circuit the system is stable, whereas in short circuit the phase margin is very small.

C. Open circuit condition

In Fig.12a, the Simulink output currents with the last set of windings in open circuit condition \( (i_q = 0) \) are reported. In this situation the new first harmonic inductance \( d_{1OC} \) has been computed with (15) equal to 0.0025\( H \) and further verified with (14) thanks to Fig.8. Since the PI parameters have not been updated, the resulting current dynamic do not match the desired one. In order to guarantee the nominal dynamic performance, the PI parameters must be re-calculated taking into account the new first harmonic inductance \( d_{1OC} = 0.0025H \) \( (K_{pOC} = 1.59 \) and \( K_{iOC} = 149) \).

D. Short circuit condition

In Fig. 12b, system’s stability margins in SC with updated regulators are shown. Looking at Fig.10c, the phase margin improvement is clear. As detailed in Sec.IV-B in Table II, in short circuit condition the PI controllers must be divided by the \( K_{SCj} \) factors which take into account the set displacement within the stator. The calculations of the compensating factors in this particular case lead to the following values: \( K_{SC2} = K_{SC8} = 23.13 \) and \( K_{SC5} = 14.07 \). The current dynamic under short circuit condition with updated parameters is depicted in Fig.12c. Enhancement is highlighted comparing \( i_q \) with nominal regulator under SC condition (dash-dot line).

VI. CONCLUSION

This paper presents a distributed current control for multi-three phase synchronous machines with even number of phases under healthy and faulty conditions, e.g., one three-phase set of windings in open circuit, one set in short circuit. The plant for designing the current controller in healthy condition was numerically obtained diagonalising the state space model in the \( dq0 \) reference frame. The results were successfully compared against the ones analytically obtained thanks to the vector space decomposition. Furthermore, the same analysis and comparison was conducted with one three phase set of windings in open circuit condition. Finally, current control design in all the three conditions, respectively healthy, open, and short circuit were validated by mean of Matlab/Simulink simulations. Stability margin analysis highlighted system degradation under short circuit condition with nominal current regulators. However, the on-line current controller update did not rise any particular issue contrasting multi-three phase machine adoption in critical applications where higher fault tolerance is demanded.
REFERENCES


