Features of Segment Winded PMSM for a Low Voltage Supply System

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Abstract— **This paper presents a symmetric winded PMSM which is connected by all in part coil to a supply system at low voltage of 48-100 V DC, developed by Research Center of Vehicle Industry in Szechenyi University. It has several benefits of this winding system its separate supply. The motor construction is slightly different from the general constructions; its running and control are different but on the whole offers new availabilities and prosperous solutions as well as electrical motor features. The paper presents some results of investigations mainly in the control for this divided kind of PMSM which was patented in 2014.**

Key words: divided coils; control; flux weakening; Matlab; PMSM

I. Introduction

The conception is based on the idea that the multiphase motors winding parts of the electric drive are maybe supplied separately from each other by getting the electric input power for produce rating in the electrical motor. In this composition may be realized the several supplied motor parts, motor-segment by supplying units pro segment so that their voltages will be not added into a higher voltage in the motor and in supply system. The several power supplies could have a low voltage of 48~100V.

The point of the conception is the dividing of the whole electrical drive system into lower voltage part units and building it up from these parts. This division concern to the electrical motor, the power supply units such as the driving inverters of motors as for a totally independent driving unit.

The realization of this conception effects a segment drive system which includes optional *n* No. supply units at low voltage of 48-100 V therefore it is safer in a special usage and not life threatening.

There are also in the drive system an *n* number motor drive inverters at low voltage which insure in their connection the drive of the segment winding parts by the controlling unit signals. The several inverter input points are separated and connected to the supply system units, mainly to the batteries or DC electric line. The segment system of this conception is useful in field weakening also for expanding the frequency range. For achieving this it is changed separately all inverter's currents in their phase and amplitudes. A special benefit is that any of the supplying of the several 3ph windings could be failed in any cases.

The other benefit of the conception is can divided of the electrical motor not only radially but axially also. It means in praxis that the mechanical connection of the segment motor units can arrangement axially each other. This variant is advantages where a longer electrical motor is can be placed. For example, there is an electrical motor of 600 V for trolley-buses in 2 axial units, divided into 3 which means that instead of the usual supply only a power supply of 100 V application is needed only.

In any unusual event such as an accident, at isolation damage is practically safer touch-save-parts at a voltage of no more than 100 V DC available.

The Fig. 1 shows a three part winding in other words the third of winding supplied variant. By using the 48 V voltage systems it's possible to touch the segments by hand without getting an electric shock hereby avoiding the insecure run of the electrical vehicles and other electrical systems because of voltage in this system is reduced. This safety raising can make a possibility to reduce feeling of danger by electric shocks of using electrical vehicles.

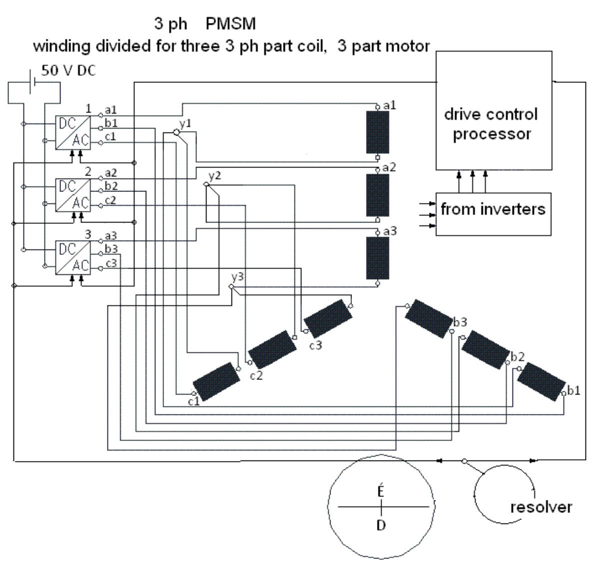

Fig.1. The tierce voltage supplied 3ph divided-winded PMSM with y_1, y_2 and y_3 star-points

II. THE POSSIBLE VARIANT OF A DRIVE SYSTEM OF LOW VOLTAGE OF USE

The inverter scheme is in principle the standard and its control system does not require any new special function. There was needed one angle position sensor for our first investigations. Fig. 1 shows all three winding of one motor side should get the same voltage, frequency and torque angles. By an unsymmetrical supply of the motor will be the current in windings also not symmetrical.

All inverter and control systems are currently adjusted to equivalent position, which will get signals about the relevant speed or torque from the torque angle code as well as from the vehicle or from the computer of the drive system and they can so operate the three phase part motor.

The 1st and 2nd motor sides are in fact two axial connected half-motors or a "twin motor" in Fig. 2.

Fig. 3 shows all leading out of the segment-winded stator our PMSM. Here all of the 18 ends of 9 part-coils are leaded out for measurements. Next time the y-connections will be made in the winding and the places of leading-out being choired optimised.

The maximum amplitudes on plotting by rated speed and at 60% rated torque are in Fig. 4. The torque ripple is of 0.987 Nm, therefore 1.23%.

The cost of inverters and leadings is increases but the cost for a unit of inverter is lower because of lower voltages. This solution is little more complex and therefore expensive also, but the advantages of a lower voltage-system maybe meaningful.

III. MAIN FEATURES OF THE SYSTEM

According to the conception the number turns of each motor phase-coil are as much that the proposed voltage is sufficient to the rated voltage of 50 V DC supplied segment part-coil.

The proposed value on the whole winding will be given in the motor by the excitations through the wind parts in line, meanwhile the voltage supply of the system is from

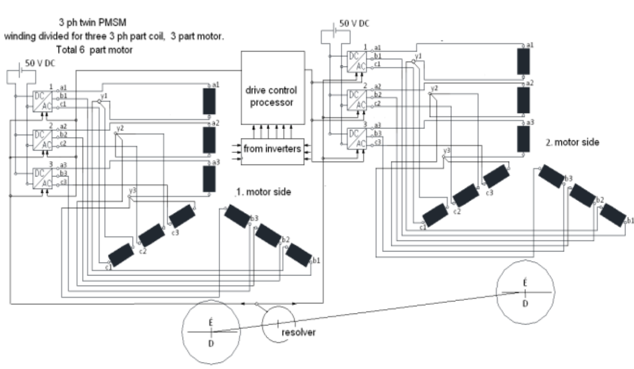

Fig. 2. Variant of the tierce low voltage supplied winding in „twin-motor" type 3ph part-winding system with star-connection.The 1st and 2nd motor sides are in fact two.

Fig. 3. The photo demonstrates the 1st version of divided coiled stator.

from units of only 50 V DC. As they are not in series connected, the highest DC voltage is lower than 50 V in the system. The winding of the divided coils in the slots will be modified so that in each slot will be placed third of the rated number of turns. The two motor sides operate in this connection with inverters of 3-3 pieces and 50 V DC pro phases which means this setting is pro phase coil of 50 V. This solution is equivalent a star connected motor of 150 V DC.

The two motor sides in the centerline which are practically two half-power sides of the rated power motor, have it's coils and the whole motor designed for a needed voltage supply of the coils whose voltage is therefore only of 50-50 V DC a piece. The effect of the complete winding and the two motor- sides are equivalent with the effect of a 2*150= 300 V DC PMSM driven by one inverter. Our system needs here only 50 V DC from in six parallel coupled supply units of 50 V DC.

Each part-coil means a third coil of original. The a, b, c coils models in the field with its offset of 120 grad a regular three- phase winding whose **y** star point is the own part of the third-sized part-coil system. These parts-coil systems we can call sub-motors, part-motors.

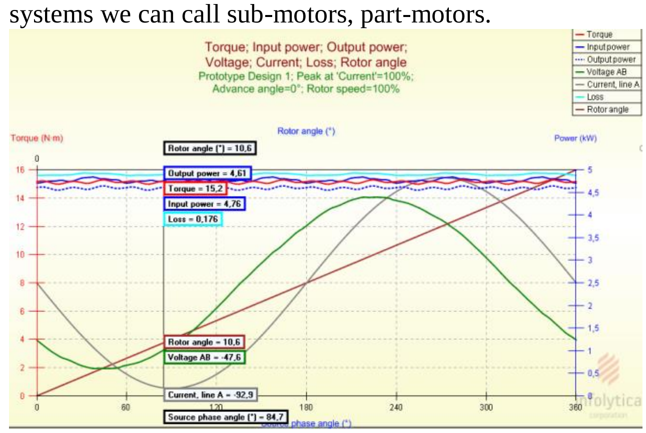

Fig. 4. Measurement on maximum torque ripple amplitude

They are operated by its three phase inverter-units. Their controlling and running mean the same operation which is realized by the inverters for regular motors. Their connecting to the part-coils of the galvanic separate sub-motors, part-motors become electrically independent.

There is a possibility for a rated capacity of the two other inverter units as well as the two part motors by an inverter failure. This solution for a 3phase motor effects an unidentified operation safety increase.

The useable field weakening in a higher speed range enables a further speed increase without increasing the voltage supply in this motor also.

IV. CURRENTS, FLUXES AND VOLTAGES OF DIVIDED MOTOR

In case of a dividing into 3 parts is a rated current, voltage and *the* same torque angle needed to realize rated values in each 1/3 number of turns of part coils.

At the same time there is a possibility to get diverse currents and torque angles of the separate part coils if the torque shape and angle position of the resultant current needs it for some reason by reducing the torque ripple.

The stator flux is caused in each phase by the part coils currents' resultant excitation which is to be calculated by not only the motor current but by the vector sum of the singular part coils currents. It is explained by the controlling of the inverter currents injected into the part-coil at the same frequency but even intentionally diverse amplitude and torque angle. The stator flux

$$\boldsymbol{\varphi}_{s,abc}=L_{abc}\boldsymbol{i}_{abc}, \qquad (1)$$

and

$$\boldsymbol{i}_{abc}=[\boldsymbol{i}_a,\ \boldsymbol{i}_b,\ \boldsymbol{i}_c]^T. \qquad (2)$$

With part-coils currents

$$\boldsymbol{i}_a=[\boldsymbol{i}_{a1},\ \boldsymbol{i}_{a2},..\ \boldsymbol{i}_{an}]^T,$$

$$\boldsymbol{i}_b=[\boldsymbol{i}_{b1},\ \boldsymbol{i}_{b2},..\ \boldsymbol{i}_{bn}]^T,$$

$$\boldsymbol{i}_c=[\boldsymbol{i}_{c1},\ \boldsymbol{i}_{c2},..\ \boldsymbol{i}_{cn}]^T, \qquad (3)$$

where $\boldsymbol{i}_{a1}$, $\boldsymbol{i}_{a2}$,.. $\boldsymbol{i}_{an}$ mark the *a* phase a_1, a_2, ..a_n part-coils' current vectors which can be of the equal values but not needed as well as that of the torque angles. By dividing in to 3 parts $n = 3$.

The flux in airgap is the sum of the stator flux and rotor flux:

$$\boldsymbol{\varphi}_{abc}=\boldsymbol{\varphi}_{s,abc}+\boldsymbol{\varphi}_{r,abc}=L_{abc}\, i_{abc}+\boldsymbol{\varphi}_{r,abc}=$$

$$=\begin{bmatrix} L_{s,aa}(\theta e) & L_{m,ab}(\theta e) & L_{m,ac}(\theta e) \\ L_{m,ba}(\theta e) & L_{s,bb}(\theta e) & L_{m,bc}(\theta e) \\ L_{m,ca}(\theta e) & L_{m,cb}(\theta e) & L_{s,cc}(\theta e) \end{bmatrix}\begin{bmatrix} \boldsymbol{i}_a \\ \boldsymbol{i}_b \\ \boldsymbol{i}_c \end{bmatrix}+\begin{bmatrix} \boldsymbol{\varphi}_{ra}(\theta e) \\ \boldsymbol{\varphi}_{rb}(\theta e) \\ \boldsymbol{\varphi}_{rc}(\theta e) \end{bmatrix} \qquad (4)$$

Here the L_{abc} matrix is of self-inductions and mutual inductions which can be released to the connection of part coils inductions. The $\boldsymbol{\varphi}_a$, $\boldsymbol{\varphi}_b$, $\boldsymbol{\varphi}_c$ components of the rotor flux vector are based on the value of the three phase coil directions.

The $\boldsymbol{v}_{abc}$ phase voltage because of the $\boldsymbol{i}_{abc}$ current components will be resulted by vector sum; therefore will be regard the voltage of the singular part coil separately.

With a_1, a_2, ..a_n, b_1, b_2, ..b_n, and c_1, c_2, ..c_n, part-coils voltages

$$v_a=[v_{a1},\ v_{a2},..\ v_{an}]^T,$$

$$v_b=[v_{b1},\ v_{b2},\ ..v_{bn}]^T,$$

$$v_c=[v_{c1},\ v_{c2},..\ v_{cn}]^T, \qquad (5)$$

and

$$v_{abc}=R_{abc}\, i_{abc}+\boldsymbol{\varphi}_{abc}=R_{abc}\, i_{abc}+(\boldsymbol{\varphi}_{s,abc}+\boldsymbol{\varphi}_{r,abc}), \qquad (6)$$

where

$$\boldsymbol{v}_{abc}=[v_a,\ v_b,\ v_c]^T$$

represents the phase voltage. Here

$$R_{abc}=\begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}. \qquad (7)$$

The resistances of phase coils imply the part-coils resistances. The R_s value by part coils dividing will be an approximate rate of number turns but the 2nd member of the (6) equation will be changed in function of number turns. The voltage calculated from flux will be met the rate number of turns of the part coils as well as the currents from inverters. We realized all this calculation with FE method by sufficient approximation.

The system in Fig. 2 at case of a simple control means to prescribe of the same current and torque angle for all part- motor but the drive construction can make other possible conception also.

V. CHANGE IN FEATURES OF MOTOR CONTROL

The system in Fig. 1 at case of a simple control means to prescribe of the same current and torque angle for all part motor but the drive construction make other possible conception also.

Each 3 phased part-motor can built with independent inverter-control which their input signals arrive from an upper system control unit. This setting in order to make offer opportunity to realize some newer driving possibilities for example reducing the torque ripple by current-shape and vector angle modifications and so on by separate supplied part coils.

At this case the system behavior will be describable by a multi degree of freedom and multiple inputs–single or multiple output type control scheme. This region will be one of our research fields in next time. If each part-motor has own inverter the centre control unit can give their reference signal as shown in Fig. 1 and Fig. 2.

The control unit of part-motors runs with the same feedback signal from speed and rotor position. The Fig. 5 shows the extension of speed-control for three part-motors. In these cases the control of motor will be more complicated because of mutual linkages of part-windings and the alter behavior of each individual control unit.
At simplest case each control unit receive the same torque angle or current reference signal depend on actual aim of control. In that case the behavior of complete motor will be not same compared to usual PMSM regarding to fact that the behavior of three control units will be independent, own setting and the little alterations of part-windings. For achieve an identical behavior it would be needed one control circle only and a same IGBT control for all inverter of that motor which will not be a supportable solution in a part-motor construction because of several reason, mainly of safety aspects. Fig.7 shows the torque control scheme for divided winding PMSM based on three independent inverter.

The equation (8) shows that i_d and i_q currents are coupled, meaning control difficulties.

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q,$$
$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \psi_m. \qquad (8)$$

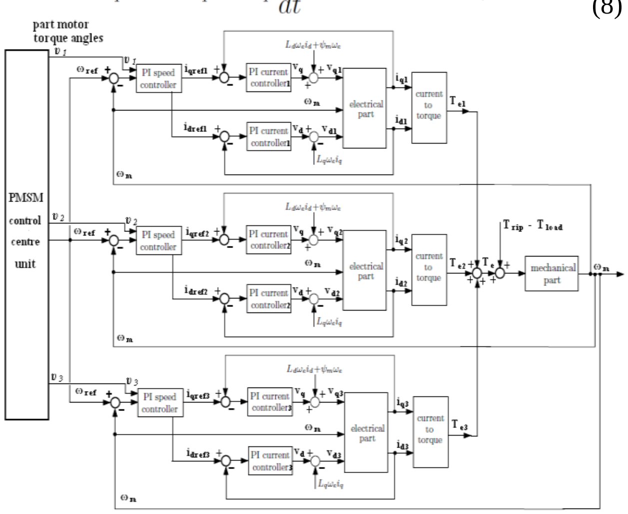

Fig. 5. Speed control scheme for three-parts divided winding PMSM with torque angle input, based three independent inverter

The Fig. 6 shows these couplings for a divided PMSM regarding influence of L_1, L_2, L_3 inductances of part coils and i_{q1}, i_{q2}, i_{q3} together with i_{d1}, i_{d2}, i_{d3} part-currents.

The electromagnetic torque expression is

$$T_e(\theta_m) = n_p \left(\frac{1}{2} i_{abc}^T \frac{dL_{abc}}{d\theta_e} i_{abc} + i_{abc}^T \frac{d\psi_{r,abc}}{d\theta_e} \right) \qquad (9)$$

where

$\theta_e = n_p\theta_m$, and θ_m is the mechanical angular position of the rotor.

It can be seen that the T_e electromagnetic torque is function of

$$\boldsymbol{i}_{abc} = [\boldsymbol{i}_a, \ \boldsymbol{i}_b, \ \boldsymbol{i}_c]^T,$$

where

$$\boldsymbol{i}_a = [i_{a1}, i_{a2}, .. \ i_{an}]^T,$$

$$\boldsymbol{i}_b = [i_{b1}, i_{b2}, .. \ i_{bn}]^T,$$

$$\boldsymbol{i}_c = [i_{c1}, i_{c2}, .. \ i_{cn}]^T$$

are the part-coils' current vectors in c_1, c_2, c_3 part-coils as in (2) and (3).

Some curves from Matlab simulation for investigate the speed and torque control accordance with Fig. 6 and 7 are shown in next figures. The used data issued from design process of PMSM computed by Infolytica-softwer are shown in Fig. 8. In running of simulations the value of i_d vector firstly was set to zero. The use of varied vector angle and i_d values of control process in flux-weakening operation will be made in next time. Next parameters were changed in simulations:

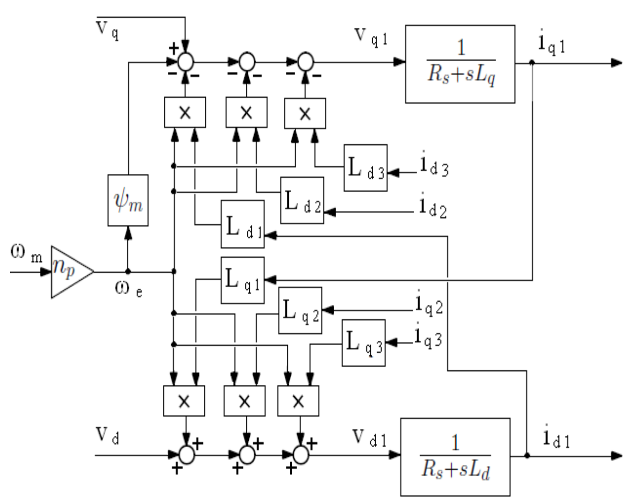

Fig. 6. The inductive linkages of 1st part-motor's coils ycleped electrical part in Figure 6. Here n_p is the number of pole pair

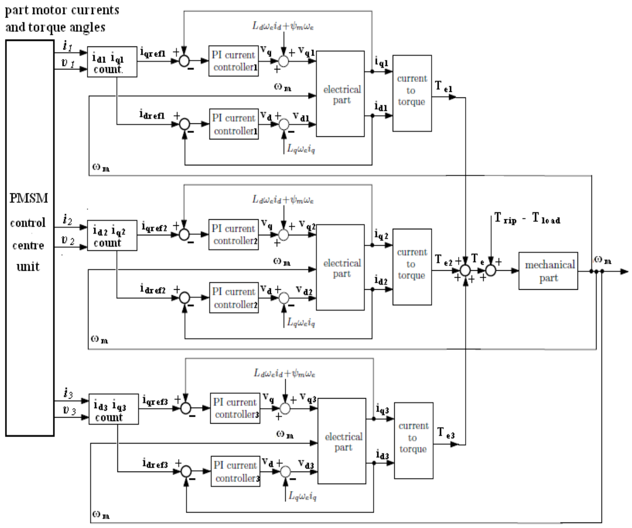

Fig. 7. Torque control scheme for divided winding PMSM based on three independent inverter

- the number turn of coil by of 20 % considered the fact that in case of produce an one-turn coil can bring about a relative large inaccuracy;
- the resistances regarding to number turn of coil;
- the inductances, similarly, and the time constants which influence also the behavior of control;
- the Kt torque-constant rated to number turn of coil;
- the P proportional gain in the three speed controls were set by of 10 % alterations. In the internal current control circles the value of P gain were set the same for all three part-motors.

If all parameters of part-motors and its inverter's Kp, proportional gains are same the runoff of investigated attributes are the same also as can be shown in Fig. 9 in which the T_{e1}, T_{e2} and T_{e3} torque curves are same, in case a load vaulting done by step function.

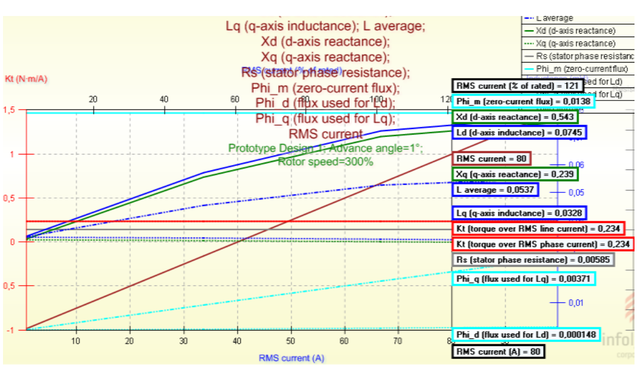

Fig .8 The main electromagnetic characteristics (inductances, reactances and fluxes) of divided winding PMSM for using them in Matlab-modelling

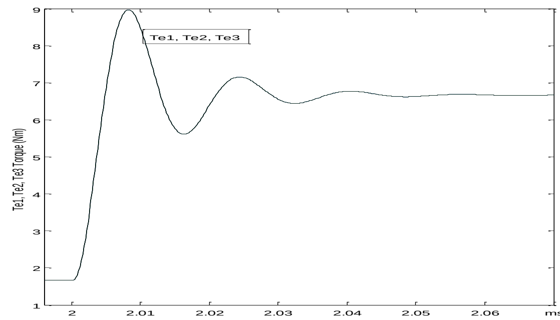

Fig. 9. Course of T_{e1}, T_{e2} and T_{e3} same torque curves with same set for a load vaulting by step function

In Fig.10 all mantioned parameters are changed. Influences of mutually induced voltage alterations are significant. Behavior of v_{ind1}-$v_{ind\,3}$ induced voltages issued mutually joint part-coils at case as in previous figure shown in Figure 11.

By applied all changes in above specification appear the influence of mutual inductances and the deviations the time-constants and torque constants, so in the three torque curves appear the components of higher frequency and increase the settling time. The behavior of mutually induced voltages in part-coils can show significant voltage and current waves.

Fig.12 shows current curves in at acceleration case. The settling time increased but in a slower system this is acceptable. In Fig.13 and Fig.14 it can show for torque control the Nyquist-curves without and with mentioned alterations causing behavior of mutually induced voltages. Mainly the phase margin decreased, here by about 30 %.

Regarding that length of time in these transients are less than 0.1ms, so it can estimated that in a slower control process with this feature will not cause significant control difficulties. In driving of vehicle by divided PMSM the usual control methods maybe adequate.

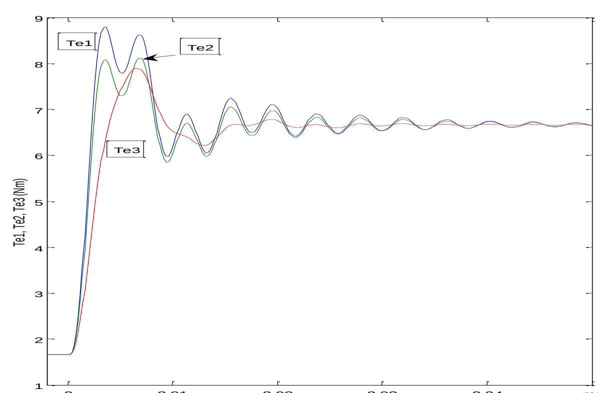

Fig.10. Torque curves for step-up loading at all parameter changed

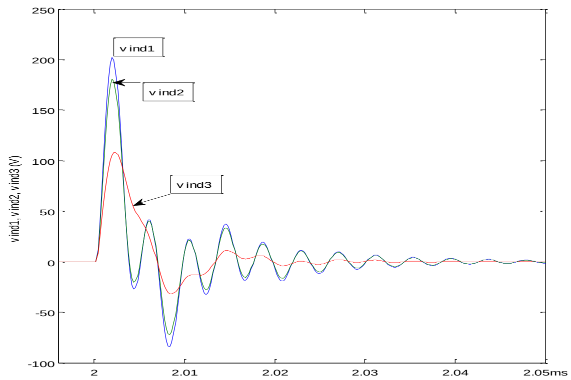

Fig.11. Behavior of v_{ind1}-v_{ind3} induced voltages issued mutually joint part-coils at case as in previous figure

CONCLUSIONS

The developed and presented segment winded PMSM has more good attributions. One of them of its supply possibility is the unusual low voltage, which can offer diverse benefits. Such for behavior of control because of mutual inductances are maybe significant between part-coils. In this field it is need investigate for cases flux-weakening operation when the angle of current vector changed and the value of i_d component alters from zero. This can spoil the control features also and it will be needed investigated.

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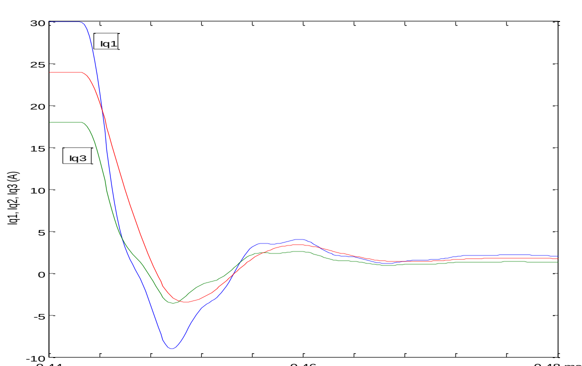

Fig.12. Current curves in at acceleration case

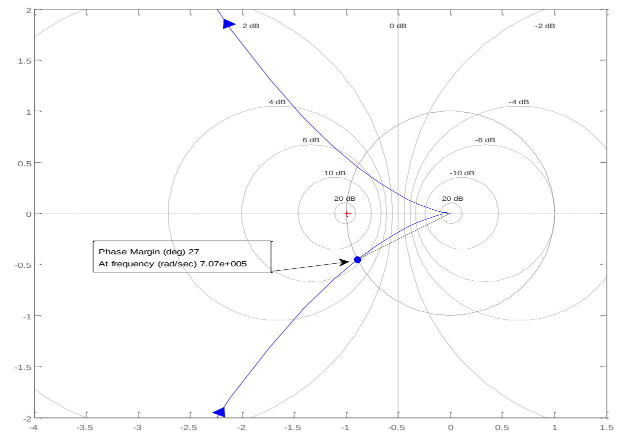

Fig.13. Without alterations in torque control the phase margin is 27 degrees

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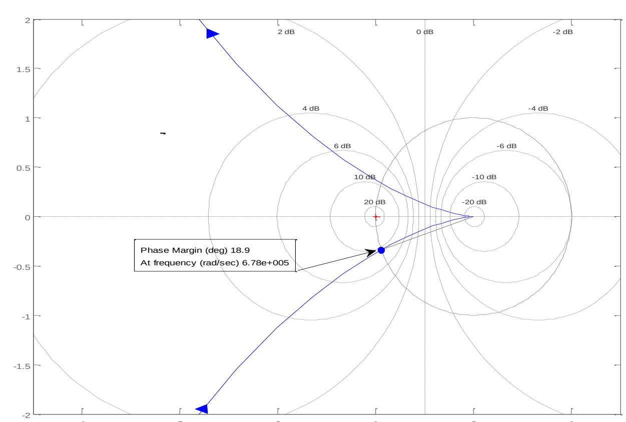

Fig.14. With mentioned alterations phase margin decreased to 18.9 degrees