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Performances of Asynchronous Motor within Variable Frequency Drive with Additional Power Source Plugged via Combined Converter

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***Abstract* — The paper deals with analysis of induction motor operation when it is fed by two sources – one is the frequency converter, the second is a low voltage DC source like photovoltaic panel or fuel cell connected in a special manner via the neutral point of the motor. In this special schematic solution, the switches of frequency converter are controlled by proper algorithm that allows transmitting the energy to the DC link. In the article, the effect of the additional current components on the motor's performances is estimated. Detailed mathematical description of the motor within such combined converter is given, simulation results are shown. Recommendations regarding the values of components providing the best operation are given as well.**

Keywords* — *induction motor, variable frequency drive, DC source, power electronic converter, torque ripples

I. Introduction

It is often appropriate to have two power sources instead of one. The second power source may be needed in order to provide uninterruptable power supply, in such cases the extra source plays the role of "backup" power. In other cases, power sources of different nature may be employed for various applications. Typical applications are so-called "hybrid" systems, like hybrid electric vehicle with gasoline-fed internal combustion engine and electric battery and electric motor, or wind-solar power stations [1,2]. In hybrid systems, the drawbacks of one power source are mitigated by the advantages of the other and vice versa. For example, some sources are good in providing peak power, while others, like fuel cells 'prefer' steady operation.

In this paper, we will examine an electromechanical system with induction motor fed from two sources. One may be lithium battery, the other – photovoltaic source or fuel cell, i.e. generally low-voltage and relatively low power DC source. A special schematic solution is examined, when the extra source is connected to the neutral point of the motor. Special switching algorithm of the inverter's transistors allows transferring energy from the DC source to the DC link, thus reducing power consumption from the primary source.

However, in order to use this solution in practice, it is necessary to understand the behavior of the motor with additional current components (those from the extra DC source) and quantify the effect of those components.

The available mathematical apparatus of space vector cannot be used in this case, since due to additional current components the sum of instantaneous values of currents in motor's windings is not zero.

Thus, the goal of this article is to give the detailed mathematical description of the processes in induction motors with currents of arbitrary waveforms and calculate the torque ripples caused by the components of current from extra DC source.

II. Architectures of Systems with Several Power Sources

In order to provide simultaneous operation of the two sources onto one load, different schematic solutions may be applied. The most common approach may be called "common DC bus" solution [3,4]. It implies using rectifiers and/or DC-DC converters connected into DC link; from there, the energy is transferred to the load via the inverter (Fig. 1).

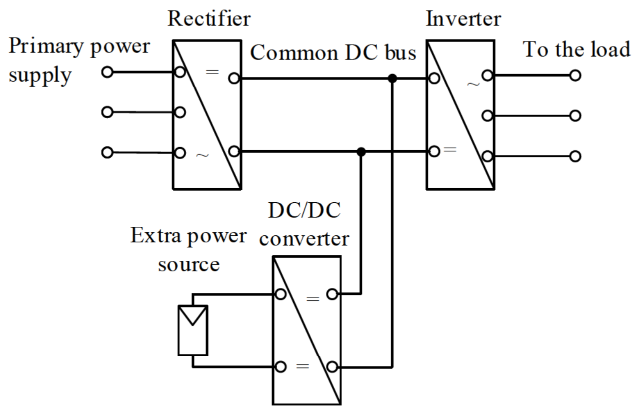

Fig. 1. Common DC bus schematic solution – traditional approach for systems with two or several sources

The substantial advantage of such a traditional approach is that power sources do not depend on each other and, having individual power converters, they can be maintained at points of highest possible efficiency. Besides, several power sources can be connected to common DC bus by this approach. DC sources of different voltage level can be connected to the common DC link using "boost" or "buck" DC-DC converters [5], or both.

On the other hand, the need for individual power converters obviously increase system cost and volume. It also reduces the reliability of the overall system, since the more elements, the more there is a room for fault.

Neuburger et al. [6] have suggested using one inverter for utilization of energy from two sources. To do that, special connection diagram is needed (Fig. 2).

In this scheme, the additional power source is connected to the neutral point of induction motor via the choke and the diode; the other terminal is connected to the negative pole of DC link. Particularly, such a solution was offered for the electric vehicle [6]. Photovoltaic panel mounted on the vehicle body was used as an extra power source, giving some 3 kW of power.

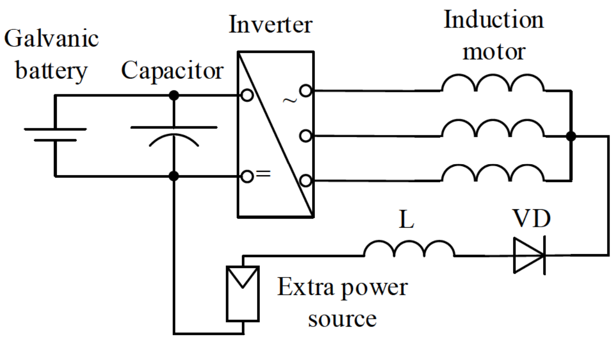

Fig. 2. Connection of the extra power source to the neutral point of induction motor ("combined converter scheme")

Such an approach allows utilizing the energy of two sources by using only one inverter, which simultaneously acts as a DC-DC converter. However to do that, more sophisticated valve-switching algorithm is needed, which is described in detail in [8,9]. The operating sequence of transistors switching has so called "zero combinations", i.e. situations when all the transistors in either positive or negative leg of inverter are opened. The current from the extra source starts to flow, accumulating the energy in the choke. When the transistors close, the induced self-EMF in the choke "injects" the current to the DC link via the motor's windings. The current components flowing through the windings supposedly do not affect to the rotating field in the induction motor, since the voltage drops across the windings are symmetrical.

The viability of this approach has already been demonstrated and simulation has been carried out [10]. However, the biggest question is whether the additional components of currents will not hamper the performances of induction motor while it operates. It is hard to estimate using the commonly accepted space vector equations, as they are true only when a sum of the currents in the windings is zero (in case of combined power converter, it is not).

Hence, let us make mathematical description of the motor with additional current components from the extra DC source and investigate the dependencies between the signals in the system.

III. Mathematical Description of the Signals in the System with Combined Power Source

Obviously, the energy from the additional DC source plugged into the neutral point can flow to the AC side only when the diode VD opens. It happens when the anode voltage is bigger than the cathode's, i.e.

$$V_0 \geq V_{10} \quad (1)$$

In order to control the induction motor, the inverter produces rotating magnetic field, described by the voltage vector $\overline{V_1} = |\overline{V_1}|e^{j\omega_1 t}$, where ω_1 is the angular frequency, $|\overline{V_1}|$ is the amplitude of the voltage vector $\overline{V_1}$. Thus, voltage V_{10} is the sum of the voltages across one or two motor's windings, connected in parallel to the negative terminal of the inverter. In this case $V_{10,min} = E_1/3$; $V_{10,max} = 2E_1/3$ (E_1 is the EMF of the AC source).

Hence, the VD diode opening condition can be rewritten as $V_0 \geq E_1/3$ or $V_0 \geq 2E_1/3$.

Anyway, in this approach when the switche are controlled according to the law, which is presented in [9]. When the diode is opened, the current from the EMF source E_0 starts flowing simultaneously through all three phases; the directions and values of the currents is different in each phase of the motor. These components superimpose the three-phase voltages from E_1 source, resulting in a vector that rotates at the same angular speed ω_1 but with variable amplitude. The $\overline{V_1'}$ vector's end point makes a curved trajectory in the stationary (α, β) frame, as it is shown in Fig. 3.

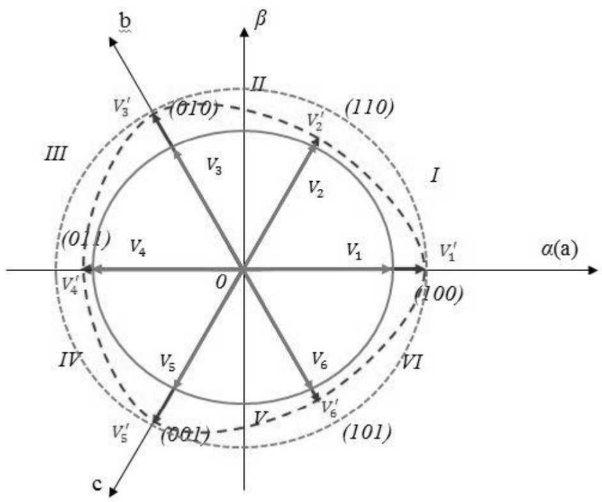

Fig. 3. The locus of the resulting vector under combined power supply

It can be seen that the locus has irregular (not round) shape, which means that the equivalent amplitude of the voltage will pulsate. Moreover, motor torque should pulsate then, too.

In [9] there are the formulas describing the variation of the $\overline{V_1'}$ amplitude:

$$|\overline{V_1'}| = |\overline{V_1}| + \Delta V_1(\theta), \quad (2)$$

$$\Delta V_1(\theta) = \Delta V_0 + \Delta V_{01}|\cos(3\theta/2)| \quad (3)$$

where ΔV_0 is the constant increment of the vector's amplitude, which doesn't depend on the vector angle (the circle of $|\overline{V_1}| + \Delta V_0$ radius in Fig. 3);

ΔV_{01} is the amplitude of the vector $\overline{V_1}$ increment;

$\theta = \omega_1 t$ vector $\overline{V_1'}$ rotational angle.

In the stationary frame (α, β) the following equation can be written

$$\bar{V}'_{1(\alpha,\beta)} = |\overline{V_1'}|e^{j\theta} \quad (4)$$

Substituting (2) into (4) we have

$$\bar{V}'_{1(\alpha,\beta)} = (|\overline{V_1}| + \Delta V_1(\theta))e^{j\theta} =$$

$$= |\bar{V}_1'|e^{j\theta} + \Delta V_1(\theta)e^{j\theta} =$$

$$= \bar{V}_{1(\alpha,\beta)} + \Delta V_1(\theta)e^{j\theta} \quad (5)$$

In (x,y) frame, rotating at arbitrary speed $\omega_к$ we have

$$\bar{V}'_{1(x,y)} = \bar{V}'_{1(x,y)}e^{-j\theta_к} =$$

$$= \bar{V}_{1(\alpha,\beta)}e^{-j\theta_к} + \Delta V_1(\theta)e^{j(\theta-\theta_к)} =$$

$$= \bar{V}_{1(x,y)} + \Delta V_1(\theta)e^{j(\theta-\theta_к)} \quad (6)$$

where $\theta_к = \omega_к t$

Since now we have the rotating vector with variable amplitude, we can expect that the induction motor fed in such a way will have the torque ripples.

Let us examine the system of vector equations describing the electromagnetic transients in the induction motor. The equations written in the (x,y) frame are

$$\bar{V}'_{1(x,y)} = R_1\bar{I}_{1(x,y)} + \frac{d\bar{\Psi}_{1(x,y)}}{dt} + j\omega_к\bar{\Psi}_{1(x,y)} \quad (7)$$

$$O = R_2\bar{I}_{2(x,y)} + \frac{d\bar{\Psi}_{2(x,y)}}{dt} + j(\omega_к - \omega)\bar{\Psi}_{2(x,y)} \quad (8)$$

$$\bar{\Psi}_{1(x,y)} = L_1\bar{I}_{1(x,y)} + L_2\bar{I}_{2(x,y)} \quad (9)$$

$$\bar{\Psi}_{2(x,y)} = L_2\bar{I}_{2(x,y)} + L_{12}\bar{I}_{1(x,y)} \quad (10)$$

Let us assume that the electromagnetic transients have ceased so the motor operates in steady state. The (x,y) frame rotates at speed $\omega_к = \omega_1$ and the (x) axis is directed along the rotor flux vector $\bar{\Psi}_{2(x,y)}$. Then

$$\bar{\Psi}_{2(x,y)} = \Psi_{2x} + jO = \Psi_{2m} \quad (11)$$

where Ψ_{2m} is the amplitude of $\bar{\Psi}_{2(x,y)}$ vector.

Then equations (7)-(10) relative to the projections in (x) and (y) axes will look as

$$V'_{1x} = R_1 I_{1x} - \omega_1\Psi_{1y} \quad (12)$$

$$V'_{1y} = R_1 I_{1y} + \omega_1\Psi_{1x} \quad (13)$$

$$O = R_2 I_{2x} \text{ or } I_{2x} = 0 \quad (14)$$

$$O = R_2 I_{2y} = +(\omega_1 - \omega)\Psi_{2m} \quad (15)$$

$$\Psi_{1x} = L_1 I_{1x} \quad (16)$$

$$\Psi_{1y} = L_1 I_{1y} + L_{12} I_{2y} \quad (17)$$

$$\Psi_{2x} = \Psi_{2m} = L_{12} I_{1x} \quad (18)$$

$$\Psi_{2y} = 0 = L_2 I_{2y} + L_{12} I_{1y} \quad (19)$$

Since the motor's torque is the vector product of vector $\bar{\Psi}_{1(x,y)}$ and the adjoint vector $\bar{\Psi}_{2(x,y)}$ assuming the taken designations of $\bar{\Psi}_{2(x,y)}$ in (x, y) frame we have

$$M = K(\Psi_{1y} \cdot \Psi_{2m}) \quad (20)$$

where K is the proportional factor.

Expressing the currents via the fluxes from equations (12)-(19) we derive that

$$V'_{1x} = \frac{\Psi_{1x}}{T_1}(1 - \omega_1 T_1) \quad (21)$$

$$V'_{1y} = \frac{\Psi_{1y}}{T_{1в}}(1 + \omega_1 T_{1в}) \quad (22)$$

where: $T_1 = {L_1}/{R_1}; T_{1в} = {L_{1в}}/{R_1}; L_{1в} = L_1 - \frac{L_{12}^2}{L_2}$

.

So the torque is

$$M = K\Psi_{2m} I_{1x} \quad (23)$$

When $\omega_к = \omega_1$ from the equation (6) it follows that:

$$V'_{1x} = V_{1x} + \Delta V_{1x} \quad (24)$$

$$V'_{1y} = V_{1y} + \Delta V_{1y} \quad (25)$$

where:

$\Delta V_{1x} = \Delta V_1(\theta)cos\theta_v; \Delta V_{1y} = \Delta V_1(\theta)sin\theta_v;$

θ_v is the angle between the vectors of flux $\overline{\Psi}_{2(x,y)}$ and voltage $\overline{V}_{1(x,y)}$.

The angle θ_v depends on the load torque, in the steady state it is constant. The (24) and (25) equations written relative to the increments taking into account equations (12)-(19) and (23) give

$$\Delta M = KL_{1в}(\Psi_{2m}\Delta I_{1y} + \Delta\Psi_{2m} I_{1y}) \quad (28)$$

$$\Psi_{2m} = \frac{L_{12}}{L_1}\left(\frac{T_1}{1 - \omega_1 T_1}\right)V_{1x} \quad (29)$$

$$\Psi_{2m} = \frac{L_{12}}{L_1}\left(\frac{T_1}{1 - \omega_1 T_1}\right)\Delta V_{1x} \quad (30)$$

$$I_{1y} = \frac{M_c - K\Psi_{2m}\Delta I_{1y}}{(\Psi_{2m} + \Delta\Psi_{2m})KL_{1в}} \quad (31)$$

$$\Delta I_{1y} = \frac{\Delta V_{1y}}{L_{1в}}\left(\frac{T_{1в}}{1 + \omega_1 T_{1в}}\right) \quad (32)$$

$$V_{1x} = V_{1m} cos\theta_v \quad (33)$$

$$V_{1y} = V_{1m} sin\theta_v \quad (34)$$

$$\Delta V_{1x} = \Delta V_1(\theta)cos\theta_v \quad (35)$$

$$\Delta V_{1y} = \Delta V_1(\theta)sin\theta_v \quad (36)$$

where V_{1m} is the amplitude of the voltage from source E_1.

The current I_{1y} can be calculated from (31), which, in turn, is derived from the condition of torque's equality $M + \Delta M = M_{load}$ written for the steady sate.

The system of equations obtained allows to estimate the torque ripples resulting from the voltage variations with precision to the third digit. The curves of transients under the ramp voltage and steady-state signals in the model of induction motor, described by equations (7)-(10) are shown in Fig. 4. The torque ripple value, obtained by the simulation, coincide with the estimates derived from (12)-(20). The torque ripples are shown in the zoomed fragment of the transients in Fig. 4.

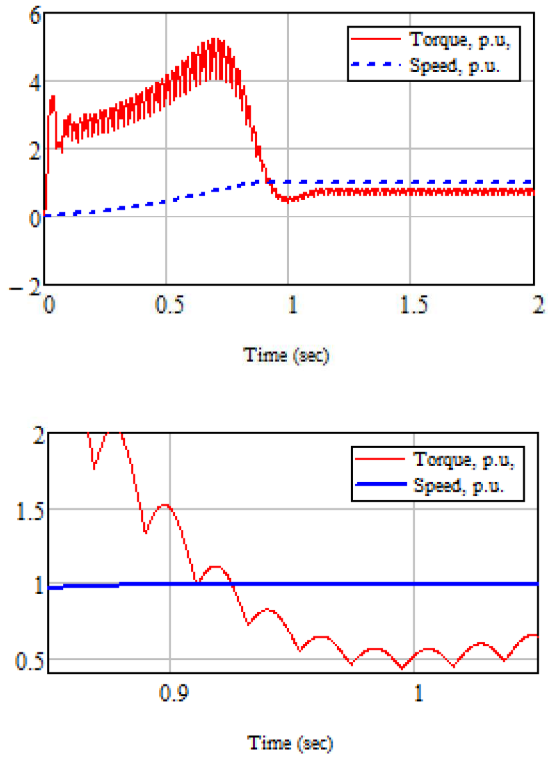

Fig. 4. The transients in the induction motor fed by two sources under ramp voltage with the zoomed fragment of torque ripples

Given the motor parameters, the equations (12)-(20) can be used to calculate the dependencies of the average toque increment M_{ave} and maximal torque ripple amplitude from the DC component ΔV_0 and alternating component ΔV_{01} of the supply voltage vector $\bar{V}_1$ (Fig. 5).

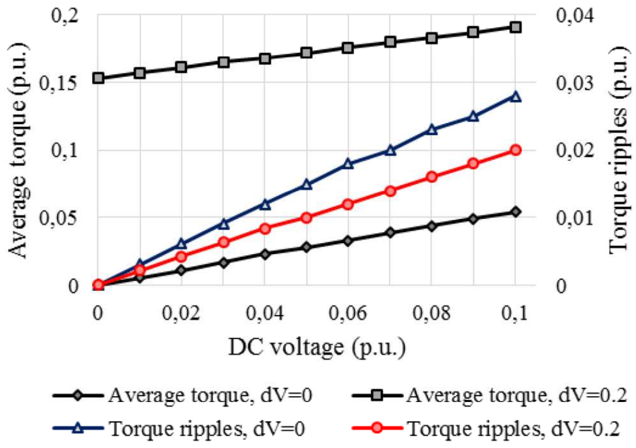

Fig. 5. Dependencies of the torque ripples from DC and AC supply voltages

The dependencies obtained allow making the following conclusions:

- The increment of DC component ΔV_0 obviously leads to the increase of the motor torque. However, the torque increases more slowly than the ΔV_0 value. For example, the increase of ΔV_0 from zero to 20% of the phase voltage value makes additional 15% of the torque under the 70% rated load of the induction motor. Since there is no variable (alternating) component of the voltage in this case, there are no torque ripples.
- When voltage vector ΔV_{01} has alternating component only, the torque increases as well. However, this leads to variable torque component (torque ripples). For example, the increase of ΔV_{01} from zero to 10% relative to the phase voltage under the same 70% rated load increases the torque by 5.4% and makes 2.8% ripples.
- The growth of the DC component of $\bar{V}_1$ voltage vector together with the increase of the average torque leads to the decrease of the torque ripples (given the constant voltage variation amplitude). For example, when the amplitude of voltage $\bar{V}_1$ is constant, its increase by 20% increases the torque by 15%. Adding the variable component of the voltage vector with amplitude of 10% of phase voltage increases the torque only by 3.8%.

Conclusions

Connection of extra DC source into the motor's neural point allows to transfer the energy to the DC link using one semiconductor converter instead of two, thus reducing the cost of the system.

In this paper, the equations describing the currents and voltages in the motor fed from two sources were derived. Analytical expressions allow to calculate the components resulting from conducting the energy from the extra source to the DC link, as well as torque ripples occurring from these components.

The new schematic solution leads to the following:

- Apart from the increase of DC voltage component, the scheme leads to appearance of the alternating component in the motor's windings, which produces the torque ripples;
- The highest efficiency of the combined power supply is provided when the DC component is utilized for torque production while the extra alternating components are suppressed.

As for the latter, this can be done by 1) providing special control algorithm for the inverter's switches that suppresses the voltage pulsations; 2) by making special control system for the electric drive that damps the torque ripples.

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