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INFLUENCE OF TRANSVERSE BRANCH PARAMETERS OF CAPACITOR DC BRUSHLESS MOTOR ON ITS OPERATIONAL PROPERTIES

ABSTRACT *Work conducted at the Silesian University of Technology on the drive systems of brushless motors which could be operated at speeds higher than the basic speed led to creation of a new design, which was called the capacitor type, brushless, dc motor . This design is characterised by a not complicated scheme of connections and simple control system (Fig.1). The stator winding is made as a divided three-phase one and capacitors connected in delta are connected between the common points of coils of each phase of the winding.*

When loaded by a not high torque, the motor rotates with a speed near the double basic speed. At the instants when the inverter transistors are being commutated, the capacitors are recharged by current pulses. The pulses, flowing through half of the two armature

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phases produce a pulse type drive torque which accelerates the rotating masses. Increase in load decreases the rotating speed and causes that the current pulses flowing through the phase halves become higher and higher and produce higher and higher torque. When the rotor slows down to a speed lower than the basic one, the current begins to flow through the whole winding. From that instant the motor begins to behave like a classical brushless dc motor.

Figure 2 shows the mechanical characteristic of the presented drive system supplied by a PWM wave shape with the filling factor near unity.

Mechanical characteristics of the same motor are shown in the same diagram, when it operates in the classical system with full winding and with a half of the rotor coils. It can be seen that with changing load the characteristic of the drive approaches the one or the other characteristic of the motor operating in the classical system.

The paper also discusses the effect of changes in capacitance and resistance of the transversal branch on the operation properties of the whole drive system (Figs.5, 6, 7). Increased capacitance of the capacitors used causes the rotational speed to be increased in the range of medium loads but at the same time the input motor current rises. The capacitance of the capacitors, if selected properly, permits easy speed control, without exceeding the maximum motor current. Increased resistance in the transversal branch decreases the value of the current pulses which recharge the capacitors and by doing this decreases the motor rotation speed in the range of medium loads.

1. INTRODUCTION

In the conventional supply system, the synchronous permanent magnet (PM) motors and dc brushless motors operate in the so-called “constant torque range”, i.e. while changing the supply voltage the excitation flux remains constant (this flux is due to permanent magnets). These systems make possible the variation in speed from null up to the “base speed” (motor’s speed at rated voltage and rated excitation flux). However, sometimes there arises a need to increase the speed above base speed level, even if the motor’s torque should at the same time decrease. This in particular applies to traction drives. That is why the drive design can utilise cost-effective inverters.

There are two possible solutions of this issue utilising motors excited with permanent magnets fixed to the rotor. The first method is to control the valves in such a way, that demagnetising component of the armature reaction weakens the PM field. The second method is to use switchable stator windings (switch from wye to delta or switching the coils from series to parallel circuit connection). Both methods are applied to PM synchronous motors.

In popular dc brushless motors excited with permanent motors the change in excitation flux is not possible. In typical speed control circuits of these drives the first range of speed variation is utilised ("constant torque" range), i.e. change of speed from null up to base speed is achieved by increasing the supply voltage. The research conducted in Silesian University of Technology on brushless motor drives, which could operate at speeds greater than base speed has led to the development of new motor design. This design has been named condenser dc brushless motor [1, 2, 3, 4]. It is characterised by simple connection diagram and uncomplicated control circuit.

2. DESIGN AND PRINCIPLE OF OPERATION OF CONDENSER DC BRUSHLESS MOTOR

The schematic diagram of drive using condenser dc brushless motor is shown in Fig.1. The stator winding consists of three phases ($m = 3$, the consecutive phases are marked as 1,2,3) and each phase in turn is divided into two parts (A and B). In this way, phase one consists of coils $A1$ and $B1$ connected in series, phase two of coils $A2$ and $B2$ and phase three of coils $A3$ and $B3$. Into the common points of A and B coils of each phase (i.e. phase winding's midpoint) the delta-connected condensers are connected (these are marked as $C1$, $C2$ and $C3$). The condenser branches will hereafter be called the transverse branches of condenser dc brushless motor.

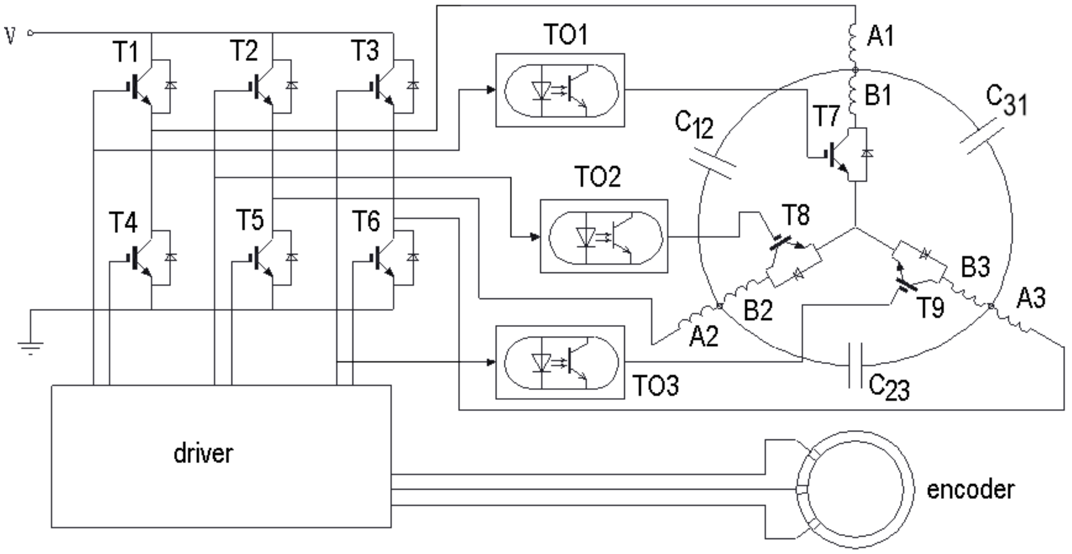

Fig.1. Schematic diagram of condenser dc brushless motor

The winding is supplied with dc voltage V via three-phase inverter consisting of $T1$ to $T6$ valves (switches). The phase windings are wye-connected with the help of $T7$, $T8$ and $T9$ switches. The switches are composed of diodes and transistors connected in the push-pull manner. The separation of gates controlling the switches $T7$, $T8$, $T9$ from gates belonging to $T1$ –$T6$ switches is ensured by transoptors $TO1$, $TO2$, $TO3$. The control circuit of switches $T1$-$T6$ (inverters) and $T7$-$T9$ (wye connection) is common to both transistor groups. The transistors are controlled by signals from electronic control units in accordance with encoder signals, which determine the current position of rotor vs. stator in the way similar to that accomplished in conventional control of dc brushless motor.

The circuit operation will be presented for inverter's time interval, when $T1$ and $T6$ transistors are conducting current and so does transistor $T7$. Let us assume (Fig.1) that machine's three phases are denoted by symbols 1,2,3 respectively and that each phase consists of two coils connected in series: part A which will be called "upper" part and part B, which will be called "lower" part of the winding.

When transistors $T1$ and $T6$ start to conduct, the current pulse flows in he "upper" part of the armature's first phase ($A1$), charging the capacitor C_{31} and capacitors C_{12} and C_{23} connected in series and flows back through "upper" part of armature's third phase ($A3$). The value of this pulse depends on the difference in the voltage supplying the inverter and total of rotational EMFs induced in both halves of the phases. Assuming that the rotor operates at double the base speed, the sum of rotational EMFs induced on the upper halves of the rotor's phases is equal to approximately the supply voltage. Considering Kirchhoff's voltage law, it is obvious that the capacitor's voltage is then very small – equals several volts. The phase current flowing through "upper" parts of armature's phases ($A1$ and $A3$) generates pulse driving torque, which accelerates rotating masses.

Similarly, in the lower halves of the windings rotational EMF will be induced and its value will be equal to about half the supply voltage. Closing the voltage loop through the lower halves of the phases (Bx) and the capacitor, it is obvious that the current cannot flow through these parts of the windings, since the resultant voltage is directed against the diode barrier. It is worth noting that after recharging the capacitor the current will decay, since inside the loop containing lower and upper halves of the phases, even though the sum of voltages is greater than the supply voltage, the diodes of $T8$ and $T9$ transistors are polarised reversely and will not allow the braking current to flow.

At the time instant when transistor $T6$ ceases to conduct current, transistor $T5$ starts to conduct. The capacitors' connections change: condenser C_{12} is discharged, condensers C_{31} and C_{23} are connected in series and each is being charged with half the voltage. That is why in the upper halves of the windings the current pulses start to appear again. Eventually the electromagnetic torque due to the current pulse will resemble the torque pulse that occurred before.

During the remaining four sections of the period the situation repeats itself with successive transistors coming in. Ultimately the electromagnetic torque consists of six pulses over the time period.

If the motor operates and becomes loaded, its speed decreases a little. The fall in speed will cause decrease of EMF induced in the windings' halves and increase the condenser's maximum voltage. In such a case, the subsequent condensers' recharging require transmitting higher charges, therefore current pulses flowing through upper halves of the windings generate greater electromagnetic torque balancing the load torque. The torque balance occurs at lower rotational speed.

The situation described above occurs every time when the load increases as long as the rotor decelerates down to speed lower than base speed. At that instant the resultant rotational EMF induced in all four halves of the phases is smaller than the supply voltage and the current flows through lower halves of the phases. Since then the current flows all the time and not exclusively when current pulses recharge and discharge the condensers. The motor behaves as the typical dc brushless motor and it can be further loaded up to the rated torque.

It must be noted that in the circuit under consideration both encoder and control circuit are identical to those present in the conventional dc brushless control circuit, while the process of speed change from null up to the "constant torque" range and "condenser control" range occurs automatically, similarly as in the dc series motor with electromagnetic excitation.

The switches ($T7$, $T8$, $T9$) are controlled by the identical impulses as the upper switches ($T1$, $T2$, $T3$) of the inverter. Their objective is to prevent the situation when current flowing through lower halves of the coils might change its direction and brake the rotor's rotation.

To summarise, at high loads the motor behaves in the same way as conventional dc brushless motor, while with the decrease of loading torque the rotational speed increases quickly and this part of torque-speed characteristic resembles that of dc series motor. Fig.2 shows torque-speed characteristic of the discussed drive system, measured for dc brushless motor rated at $P_N = 1$ kW and $U_N = 110$V, operating with delta-connected three condensers of $C = 293$μF each, connected to the windings' midpoints (heavy-line curve). In order to understand the reasoning better, the same diagram shows the torque-speed characteristics of the identical motor operating in the standard (conventional) circuit with undivided windings at half the armature winding turns.

It is clear that as the load changes, the drive characteristic comes close to either one or the other characteristic curve of the motor operating in the standard way.

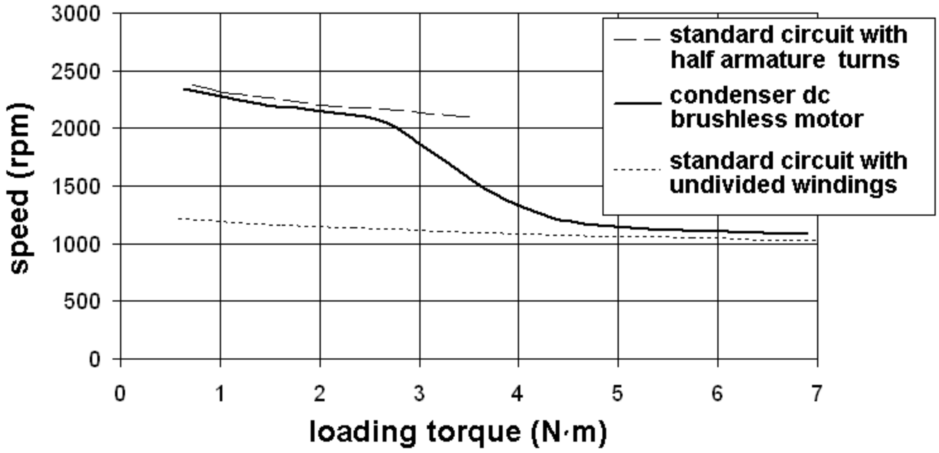

Fig.2. Torque-speed characteristic of condenser motor P_N = 1 kW, U_N = 110 V, C = 293 µF

All three curves shown in Fig.2 were measured with PWM waveform pulse-duty factor approximately equal to one, this is equivalent to armature current flowing continuously. Under such conditions, the typical shape of torque-speed characteristic of dc brushless motor is a slightly dropping straight line, typical of dc motor with PM excitation (shunt motor characteristic). If the pulse-duty factor is less, the torque-speed characteristic changes: at small and very small loads the motor speeds are high, similar to those attained at continuous voltage supply. Moreover, when the load increases from small to medium, the current becomes pulsing and the torque-speed characteristic sharply drops down. When the continuous current boundary is reached, the slope of the characteristic decreases and starts to resemble the slope measured, when PWM waveform pulse-duty factor was close to one.

3.THE INFLUENCE OF THE TRANSVERSE BRANCH PARAMETERS OF THE CONDENSER DC BRUSHLESS MOTOR PROPERTIES

All the measurements presented in the following chapters of the paper have been conducted for dc brushless motor rated at P_N= 1 kW, U_N = 110V, I_N = 10,7 A, n_N = 1000 rpm, M_N = 9,3 N·m, number of poles $2p_b$ = 6, number of armature phases m = 3, and each phase consisted of two identical coils connected in series. Due to the printing limitations, the discussion has been confined to considering the influence of capacitance and resistance of the transverse branch on the condenser dc brushless motor's properties, when the inverter supply voltage changes, while the PWM waveform pulse-duty factor is approximately equal to 1.

It is logical that capacitance value influences the motor's properties most of all. Small capacitance condensers will change the shape of motor characteristics at high voltages and very small loads only. High capacitance condensers will raise the characteristic curves at relatively high loads, which can lead to overloading and in consequence, motor failure.

Figure 3. shows three families of motor curves, measured for three different supply voltages and three different capacitances connected to windings' mid-points. It is clearly seen that at small supply voltages and low rotational speeds (line marked with crosses for very low voltage) the impact of the capacitances is negligible and can be observed only if the machine is running idle. After supplying the motor with higher voltage (characteristic curves marked with round points) the capacitances' influence is distinct at load torques smaller than 0,4 M_N and it depends on the condensers' capacitance. In general, increasing the condensers' capacitance causes the shift in the speed increase range towards higher loads.

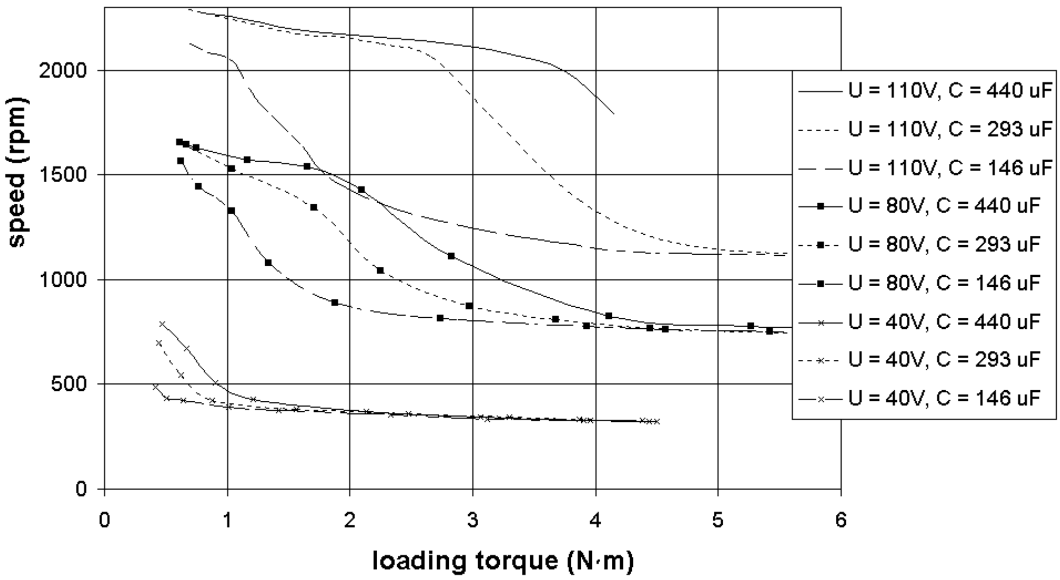

Fig.3. Torque-speed characteristics of condenser motor at different capacitances

In the case of motor supplied with rated voltage (characteristic curves drawn with no markers) the influence of the capacitances is very obvious. The range of speeds higher than base ones starts to include half the motor's operation range. The measurements of uppermost characteristic curve, taken at U = 110 V and C = 440 μF had to be interrupted at half the rated load, since the current started to exceed its rated value.

On the basis of characteristic curves shown in Fig.3 the following conclusions may be drawn:

- motor under consideration behaves as anticipated, i.e. at high loads its characteristics are similar to characteristics of conventional motor; if the load is lifted, motor's speed doubles,
- condensers' capacitance should not be too low, since the motor could attain speeds higher than base speed practically running idle only, while relatively small load will cause a dramatic decrease in rotational speed,
- condensers' capacitance should not be too high, since it may result in exceeding the rated current (and overheating motor windings) at loads equal to approximately half the rated load.

This latest conclusion means that the selection criterion for the capacitance can be formulated thus: at the highest possible supply voltage, the shift in operation mode from half the number of winding turns to full number of winding turns should take place at loads smaller than half the rated load value. This reasoning is explained by the current curves vs. load torques, depicted in Fig.4.

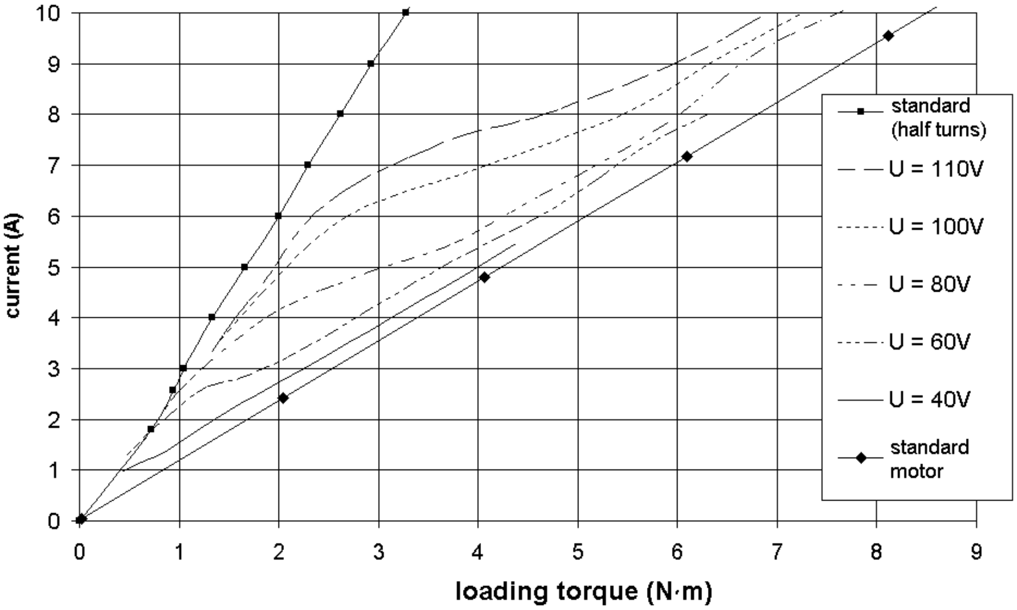

Fig.4. The dependence between the current and load torque of the motor for C = 293,3 μF

The straight lines depicted in Fig.4 show the dependence between the current and load torque of the motor, measured in the standard circuit for motor with full number of the turns and for motor with number of turns cut by half. The non-linear relationships between current and load torque for condenser motor have been shown in the same drawing. It can be seen that at lower loads these characteristics approach the characteristic of the motor with half the turns, while after loading the motor higher they bend and asymptotically come close to the characteristic of the motor with full number of turns. This smooth change in the characteristic curve results in motor's decrease in speed when the load increases, while the motor's current increases more slowly than in the standard circuit and does not exceed its rated value.

Increasing the capacitance connected into the transverse branch results in shifting the motor's characteristics along the line relative to half the number of turns before they start to bend towards the line relative to full number of turns. For instance, at full supply voltage and condenser capacitances of 440 μF, the current exceeds its rated value at load torque equal to 4 N·m only. Therefore the condensers' capacitance should not be overly high.

The resistance of the motor's transverse branch also influences the speed of the drive. Increasing the resistance decreases the value of current pulses flowing through upper half of the winding during discharging and recharging the condensers, decreasing at the same time the rotational speed attained under these particular load conditions. Therefore increasing the transverse branch resistance has similar effects to decreasing the condensers' capacitances. Comparison of torque-speed characteristics of the drive with and without additional resistance in the transverse branch, measured for different supply voltages, is shown in Fig.5.

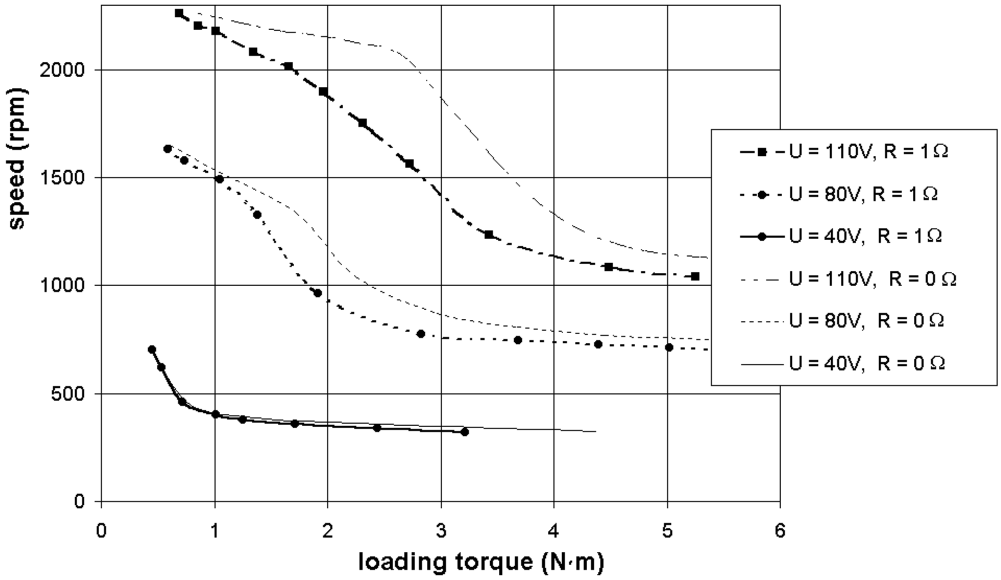

Fig.5. The influence of transverse branch resistance on torque-speed characteristics of the drive (*C*=293 μF)

4. CONCLUSIONS

The lab tests of condenser dc brushless motor have confirmed its previously anticipated properties. At small loads and rated supply voltage the motor attained double base speed, while at higher loads it operated as conventional condenser dc brushless motor. The full range speed control (from null to double the base speed) is possible by changing the inverter's supply voltage, or by changing the PWM waveform pulse-duty factor. The increase of condensers capacitances used causes an increase in speeds in medium load range, while at the same time the motor's input current increases. The adequately selected capacitance makes possible convenient speed control without exceeding the motor's maximum current. The increase in the transverse branch resistance decreases the value of pulse currents recharging the condensers, which in turn leads to the decrease in rotor's rotational speed in the medium load range. This effect suggests possibility of controlling the speed by changing the inverter's current cut-off. Both the encoder and control circuits are identical as in the conventional dc brushless motor, and the process of speed control from null up through "constant torque" range and "condenser control" range occurs automatically.

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WPŁYW PARAMETRÓW GAŁĘZI POPRZECZNEJ KONDENSATOROWEGO SILNIKA BEZSZCZOTKOWEGO PRĄDU STAŁEGO NA JEGO WŁAŚCIWOŚCI RUCHOWE

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STRESZCZENIE *Prace prowadzone na Politechnice Śląskiej nad układami napędowymi silników bezszczotkowych, które mogłyby pracować przy prędkościach większych niż prędkość bazowa, doprowadziły do powstania nowej konstrukcji, która została nazwana kondensatorowym, bezszczotkowym silnikiem prądu stałego. Konstrukcja ta charakteryzuje się nieskomplikowanym układem połączeń i prostotą układu sterowania (rys.1). Uzwojenie stojana wykonane jest jako trójpasmowe, dzielone, a między punkty wspólne cewek każdego z pasm uzwojenia są włączone kondensatory połączone w układ trójkąta.*

Przy obciążeniu niewielkim momentem, silnik wiruje z prędkością zbliżoną do podwójnej prędkości bazowej. W momentach komutacji tranzystorów falownika kondensatory przeładowywane są impulsami prądów. Impulsy przepływając przez połowę dwóch pasm twornika, wytwarzają impulsowy moment napędowy rozpędzający masy wirujące. Powiększanie obciążenia zmniejsza prędkość wirowania i powoduje, że impulsy prądowe przepływające przez połówki pasm są coraz większe i wytwarzają coraz większy moment. Kiedy wirnik zwolni do prędkości niższej niż prędkość bazowa, prąd zaczyna płynąć przez całe uzwojenie. Od tej chwili silnik zaczyna zachowywać się jak kla-syczny bezszczotkowy silnik prądu stałego.

Na rysunku 2 pokazano charakterystykę mechaniczną prezentowanego układu napędowego przy zasilaniu falą PWM o współczynniku wypełnienia zbliżonym do jedności. Na tym samym wykresie naniesiono charakterystyki mechaniczne tego samego silnika, pracującego w układzie klasycznym, przy pełnym uzwojeniu i przy połowie zwojów twornika. Widać, że wraz ze zmianą obciążenia, charakterystyka napędu zbliża się do jednej lub drugiej charakterystyki silnika pracującego w układzie klasycznym.

Ponadto w referacie omówiono wpływ zmian pojemności i rezystancji gałęzi poprzecznej na własności ruchowe całego układu napędowego (rys.5, 6, 7). Powiększanie pojemności zastosowanych kondensatorów powoduje zwiększenie prędkości obrotowej w zakresie średnich obciążeń, ale równocześnie wzrasta prąd pobierany przez silnik. Właściwie dobrana pojemność kondensatorów umożliwia wygodną regulację prędkości, bez przekroczenia prądu maksymalnego silnika. Wzrost rezystancji gałęzi poprzecznej zmniejsza wartość impulsów prądowych przeładowujących kondensatory, a tym samym zmniejsza prędkość wirowania silnika w zakresie średnich obciążeń.