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Dimensioning of Subsynchronous Cascade for Speed Regulation of Two-Motors 6kv Conveyer Drives

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***Abstract*—**One way for optimum loading of overdimensioning conveyers is speed (capacity) decrement, with attention for production capabilities and demands. At conveyers which drives with three phase slip-ring induction motor, technically reasonable solution for conveyer (driving motors) speed regulation is using constant torque subsynchronous cascade with static semiconductor converter and transformer for energy reversion to the power network. In the paper is described mathematical model for parameter calculation of two-motors 6 kV subsynchronous cascade. It is also demonstrated that applying of this cascade gave several good properties, foremost in electrical energy saving, also in improving of other energy indexes, and finally that results in cost reduction of complete electrical motor drive.

***Keywords*—**Conveyer with rubber belt, electrical motor drive, sub synchronous cascade

I. Introduction

Subsynchronous cascade drives from recently are in implementation for middle and large power induction motors speed regulation. That is possible mainly like result of power electronics development and impossibility for large power and relatively high speed slip ring induction motor speed regulation on the other way [1]-[3].

Big capacity conveyers generally are driven by several high power often slip ring HV motors. Speed regulation of driving motors, i.e. conveyers, are technically reasonable by usage of constant torque cascade with frequency converter and transformer for energy reversion to the power network. Furthermore, for subsynchronous cascade application in high power electric motor drives (EMD), it is important that cascades are comfort for including in modern automation systems. Rational energy usage is always important thing in electrical drives especially in high power drives. Anyway, in EMD with slip ring induction motor, it's not reasonable speed regulation with resistors in rotor circuit.

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II. Sub synchronous Cascade For Speed Regulation Of Conveyer

Conveyer speed regulation is necessary in the case of low efficiency coefficient in transportation systems. Characteristics of over dimensioning transportation systems is high exploitation costs mainly because of ;

- total electrical energy consumption per unit of transportation material,
- abrasion of rubber belt (which is most expensive part of transportation system).

Principal scheme of sub synchronous cascade with frequency converter and transformer for energy reversion to the power network is shown on Fig. 1.

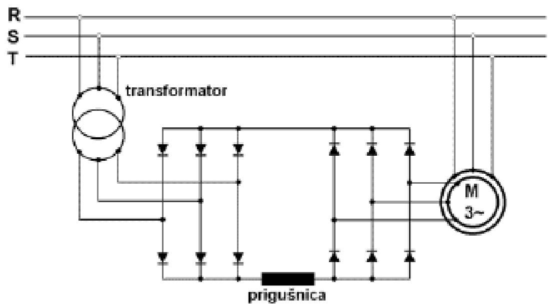

Fig. 1 Principal scheme of sub synchronous cascade

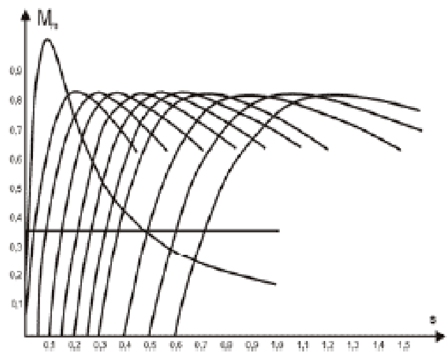

Fig. 2 Motor mechanical characteristics at sub synchronous cascade with constant torque

In this scheme, slip power P_s, which is on rotor side and which frequency is $f_2 = s \cdot f_1 = s \cdot 50\ [Hz]$, is going on rectifier, then coil correct them waveform, and on the end thyristor inverter and transformer backs it to the power network.

Change in angle of thyristor's control signal changes voltage on rotor side and because of that appearing motor spped change. This way proceeds parallel mechanical characteristics with law breakdown torque in comparison with natural mechanical characteristic [4]. Primary transformer voltage is defined by inverter voltage, and secondary voltage is defined by power network.

A. Sub synchronous cascade working principle

Fig. 3 shows sub synchronous cascade drive with static frequency converter and transformer for energy reversion to the power network for two engines conveyer drives.

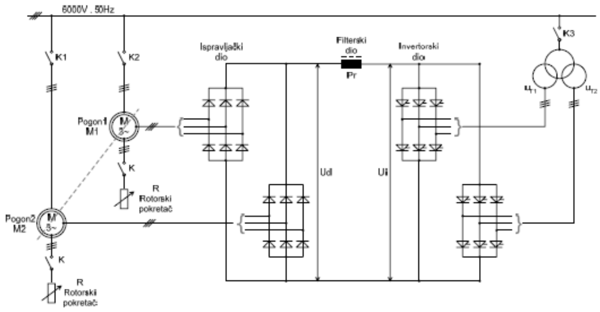

Fig. 3 Principal scheme of sub synchronous for two engines conveyer drives

Stator of slip ring induction motor is connected on three phase power network with constant voltage and frequency. At medium and high motor power that is high voltage network, usually 6 kV (rarely 10 kV). Rotor current I_2 rectifies with three phase bridge diode rectifier and coil. Coil use for decreasing rotor current pulsation in direct current circuit. Thyristor three phase bridge inverter converts DC voltage in AC voltage with power network frequency (50 Hz).

At motor's speed lower then synchronous speed rectifiied voltage U_d has value which is proportional to slip. Input voltage to the thyristor inverter U_i depends on control angle and it is almost equal to the rectified rotor voltage. Inverter voltage is only with opposite sign because thyristor inverter works in changer working regime. In steady state that two voltages are in balance, and direct current I_d and energy flows from diode rectifier to the thyristor inverter. Direct current by thyristor inverter converts to alternative current and by transformer backs to the power network. Therefore, slip power, which is transforms in losses in old regulation systems (regulation by rotor resistors), go back to the power network.

Change in angle of thyristor's control signal changes voltage on DC circuit and for keeping voltage balance that lead to change of AC rotor voltage U_2, i.e. motor's speed. Because of rotor's voltage falling with motor's speed increasing (that means slip decreasing), it comes to inverter voltage falling. At practical solutions control angle is limited on $150°$, where inverter voltage is maximal $U_{i\max.}$, and motor's speed is minimal.

B. Waveforms in cascade drives

Working regime of induction slip ring motor in this case is different from nominal working regime.

Three phase rectifier and coil in rotor circuit modify waveforms of important motor parameters. Rotor current have no sinusoidal waveform, but also trapezoidal waveform.

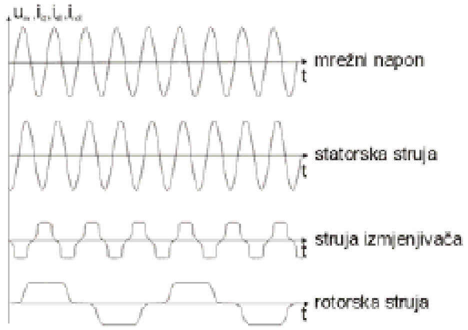

Fig. 4 Voltage and current waveforms in cascade drive (power network voltage, stator current, inverter current, rotor current, respectively)

Useful motor torque is result only of sinusoidal current component and sinusoidal magnetic flux. Whereas rotor current is not sinusoidal it is necessary to ensure larger rotor current for the same motor torque.

Stator current keeps almost equal waveform as well as without sub synchronous cascade. That is with relevance of adequate coil inductance for decreasing pulsation in direct current circuit. Commutation process in diode rectifier cause phase shift of fundamental rotor current harmonic which results in power factor deterioration. It is needfully to make mention of decreasing in maximum motor speed in comparison to working regime with rotor in short-circuit.

When angle of thyristor's control signal has value $90°$, i.e. in short-circuit inverter state, slope of motor mechanical characteristics is biger. It occurs because diodes, coil, thyristors and transformer possess some resistance.

III. Cascade Elements Calculation

Based on preceding explanations, that is clear, subsynchronous cascade rated power directly depends on speed regulation range, i.e. slip regulation range. Therefore, subsynchronous cascade have need of dimension on maximal rotor current (maximal motor torque), i.e. maximal motor speed, and on maximal rotor voltage which corresponds with minimal motor speed. This principle is with relevance for all basic structures: rectifier, coil, inverter and transformer. At

EMD design it is necessary to select speed range without large reserve because of unnecessarily power increasing of subsynchronous cascade elements.

Relevant quantities for dimensioning subsynchronous cascade elements are:

- power network voltage and frequency
- rated rotor current and blocked rotor voltage
- regulation range.

In addition to diode bridge, inverter, coil and transformer, complete system also contains:

- rotor resistors for motor startup
- switching and protection equipment in motor supply wires, for motor connection to power supply
- switches for subsynchronous cascade turning on.

For dimensioning and selection of cascade elements took:

- rotor voltage on lower regulation limit
- rotor current for largest motor torque
- lower frequency of rotor current - for maximal speed (minimal slip).

In rotor circuit is induced electromotive force which is proportional to slip s, i.e. $U_2 = s \cdot U_{2k}$, where U_{2k} represents blocked rotor voltage - in state of rest rotor [5]. This alternative rotor voltage rectifies via three phase rectifier bridge which produce DC voltage:

$$U_d = \frac{3 \cdot \sqrt{2}}{\pi} U_2 = \frac{3 \cdot \sqrt{2}}{\pi} U_{2k} \cdot s \quad [V] \tag{1}$$

This voltage gives balance to the inverter DC voltage U_i (inverter input voltage).
Maximum rectified rotor voltage value for maximum slip $s_{\max.}$ is:

$$U_i = \frac{3 \cdot \sqrt{2}}{\pi} U_{2k} \cdot s_{\max} \quad [V] \tag{2}$$

From the other side, inverter voltage has value:

$$U_i = U_{i0} \cdot \cos\alpha \quad [V] \tag{3}$$

Maximum allowed inverter control ungle is 150°, when appears maximum value of voltage on inverter DC side. If that two voltage equalize obtains:

$$U_{i\max} = -U_i \cdot \cos\alpha_{\max} = -U_{i0} \frac{\sqrt{3}}{2} \quad [V] \tag{4}$$

For power network side of inverter be worth:

$$U_{i\max} = -U_i \cdot \cos\alpha_{\max} = -U_{i0} \frac{\sqrt{3}}{2} \quad [V] \tag{5}$$

Inverter voltage from power network side U_{2tr} can be adapted by turns ratio so that gets contravoltage equals with rectified rotor voltage at lowest speed for chosen regulation area.
Diodes in rotor rectifier chosed by DC current value, which corresponds with maximal torque of working mechanism:

$$I_{d\max} = 1,22 \cdot k_t \cdot I_{2n} \quad [A] \tag{6}$$

, where k_t represents overload coefficient at motor startup

During rectifier elements dimensioning it needs to take into consideration that rotor current have no sinusoidal waveform and that frequency changes with speed changing.
Medium value of diode current in rectifier is determined by expression:

$$I_{sr} = \frac{1,22 \cdot k_t \cdot I_{2n}}{3 \cdot 0,9 \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot n_1} \quad [A] \tag{7}$$

Quantities in (7) are:

k_1 - coefficient which take into consideration diode current reducing due to lower frequency, i.e. lower speed,

k_2 - coefficient which take into consideration permited diode current reducing due to cooling conditions,

k_3 - coefficient which take into consideration permited diode current reducing due to their parallel connection,

k_4 - coefficient which take into consideration induction motor torque reducing due to commutation process,

n_1 - number of parallel connected diode pairs.

Maximal voltage on the rotor rectifier output side is:

$$U_d = \frac{1,41 \cdot U_{2k} \cdot s_{\max}}{k_p \cdot n_2} \quad [V] \tag{8}$$

, where:

k_p - coefficient which take into consideration phase voltage assymetry among serially connected diodes,

n_2 - number of serially connected diodes.

Voltage on the inverter output side is:

$$U_i = \frac{1,41 \cdot U_{2tr}}{k_p \cdot n_2} \quad [V] \tag{9}$$

Transformer has connection with power network because of slip energy return. Besides, transformer make use for power network voltage adaptation to rotor voltage. At three phase bridge inverter in use is mostly transformer with Yy_0 connection. Transformer turns ratio is defined by maximal rotor voltage, and transformer rated power for single motor drive is:

$$P_{tr} = 1,05 \cdot U_i \cdot I_d \quad [W] \tag{10}$$

For two motor drive (principal scheme on Fig. 3), calculation of one secondary turn in three-winding transformer is based on (3). Rated total transformer power is defined by calculated power for two secondary turns.

IV. Conclusion

Subsynchronous cascade drive with static frequency converter and transformer for energy losses reversion to the power network is technically reasonable solution for conveyer (driving motors) speed regulation in electric motor drives with slip ring induction motor. Implementation of this regulation method ensures optimal conveyer loading by speed reduction in accordance with actual requirement. In this way, specially at multimotor drives, obtains better energy indexes and electrical energy saving. Some specificity in usage depends of conditions and demands in concrete transportation system exploitation.

In the paper is displayed analytic method for parameter calculation and dimensioning subsynchronous cascade basic elements. At electric motor drive with subsynchronous cascade design, it is very necessary to take into consideration expected range in speed change.

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