Multi-motor drive with common inverter for pumping units

M M Khamudkhanov, Kh B Sapaev and Sh B Umarov
Tashkent State Technical University named after Islam Karimov, 100095, Uzbekistan, Tashkent, University St. 2A

E-mail: ilider1987@yandex.ru

Abstract. This paper presents the results of a research of a multi-motor drive with the electric coupling and a common grid-controlled inverter for pumping facilities of pumping irrigation systems. This system is the most preferable in compliance with the requirements for a controlled electric drive of water-lifting pumping facilities, in which a group of water-pumping sets works in parallel in a common hydraulic pressure circuit. In addition, this electric drive system can be used in multi-motor electric drives of the general purpose industrial grades that do not require absolutely strict coordination of the rotational speeds of their drive of the wound-rotor induction motor, depending on the requirements of the process conditions. In addition, a clear advantage of this system is that it is characterized by a high efficiency compared to other known systems of controlled electric drive, since it only converts the slip energy of the drive motors.

1. Introduction

It is commonly known that, one of the priority orientations is occupied by research related to energy and resource saving achieved by switching from the electric drive without speed control of energy-consuming machines of general purpose industrial grade to the speed controlled one, which is a contributory factor for obtaining the greatest effect, both in terms of energy saving and in a number of process flow parameters [1-2].

In engineering terms, in the advanced countries of the world such controlled electric drives and their elements as valve stages, commutator motors, frequency converters with the improved engineering-and-economical and energy indicators are most often developed. As the result of this, world practice has a number of examples of the use of medium and high powered controlled electric drives [3-5].

The efficiency of the hydraulic power pumping unites (PU) of the pump irrigation systems (PIS), and, consequently, the PU as a whole, is largely determined by the quality of controlling and management of water supply technological processes with the implementation of water-energy-saving technologies. It is related to the fact that advanced technological PU of the PIS are energy-consuming, multi-mode, structurally and parametrically complex hydroelectric electromechanical objects, characterized by intense and interrelated conditions of the processes occurring in them [6]. Therefore, the management of pumping units in order to achieve energy and resource-saving modes through the use of automatic electric drives, provided that the requirements of the water supply technological process are met, is an actual problem, the solution of which will save a significant amount of electricity and irrigation water.
2. Materials and research methods

The paper presents the results of researches on the development of the controlled multi-motor drive system with the electric coupling (MMDEC) on a rotor circuit with a common grid-controlled inverter (GCI), which is a network with an intermediate DC network in which the rotor currents of each induction motor are rectified using the corresponding three-phase bridge rectifiers and in the circuit of the rectified current, an auxiliary EMF (Electromotive Force) is introduced, obtained by means of a controlled valve inverter - inverter. Below in figure 1 was given our proposed schematic diagram [7].

![Figure 1. Schematic diagram of the MMDEC with a general GCI.](image)

**M1-M4** - phase-wound rotor induction motor; **V1-V4** - non-controllable valve inverter; **GCI** - grid-controlled inverter; **CUGCI** - control unit of the GCI; **SI** - smoothing-inductor; **IT** - impedance-matching transformer; **Rd1-Rd6** - starting resistors; **KM1-KM4** - electromagnetic contactors; **QF1-QF5** - automatic tripping circuit breakers.

Starting resistors Rd1 - Rd6 are introduced into the rotor circuit of the PU electric drive motor of the first sequence M1, which are activated by the contactor KM3 to start the induction motor M1. As M1 accelerates, the starting resistors are alternately shunted by the points of the contactors KM2 and KM1. When M1 reaches a rotation speed that allows it to operate according to the MMDEC scheme with a common (GCI), the contactor KM4 is connected and the points of the contactors KM3, KM2 and KM1 open. At the same time, the start-up process of the M1 induction motor is controlled from a separate control device (panel). Automatic tripping circuit breakers QF1 - QF4 are designed to connect induction electric motors to the supply mains, and the QF5 automatic tripping circuit breaker provides connection of the GCI through a matching transformer IT to the supply mains. The circuit design of the MMDEC with a common GCI allows for a coordinated change in the rotational speeds of the induction electric motors of pumping units (PU) between the stages of the unit control and disconnects and reconnects to the joint parallel operation of any of the drive motors without prior coordination of their rotational speeds during the pumping unit (PU) water supply process [8-9].

The basic electromechanical relations of a MMDEC with a common GCI for **N** homogeneous, electrically coupled induction motors with the identity of their parameters and elements of rotor circuits are determined by the equations below [10]:

\[
I_{ij} = \left(\frac{E_{bi} \cdot s_j - K_{ii} \cdot E_{ii} \cdot \cos \beta - \Delta U_j}{s_j \cdot (3 \cdot x_p / \pi + 2 \cdot r_{ci}) + 2 \cdot r_i + N \cdot (3 \cdot x_{ii} / \pi + 2 \cdot r_{ii} + r_{si})}\right), \quad i = 1, \ldots, N;
\]

\[\text{equation} \quad 1\]
3. Research results and discussion
As a result of the calculations according to equations (1-3) based on the developed mathematical model [11-12], the influence of the parameters of the hydromechanical and electromechanical equipment of PU equipped with centrifugal pumps of the D1600-90 brand and electric motors of the A12-41-4 type with a capacity of P = 500 kWt was studied, on the energy indicators of the operating modes of the MMDEC system with a common GCI. In figure 2–5 it was given the obtained dependencies of the corresponding indicators of MMDEC with a common GCI:

\[
s_i = \frac{K_2 \cdot E_{\text{lg}} \cdot \cos \beta + \Delta U_i + I_{b,i} \cdot [2 \cdot r_i + N \cdot (3 \cdot x_{\text{lg}} / \pi + 2 \cdot r_{\text{lg}} + r_{g,i})]}{[E_{b,i} - I_{b,i} \cdot (3 \cdot x_{p,i} / \pi + 2 \cdot r_{C,i})]};
\]

\[
M = \frac{\pi \cdot E_{\text{lg}}^2}{3 \cdot x_{p,i} \cdot \omega_{C,i}} \cdot \left[ \frac{s_i - s_{ui}}{s_i \cdot (1 + q_i) + \rho'_{i} + N \cdot \sigma_{T,i}} - \left( \frac{s_i - s_{ui}}{s_i \cdot (1 + q_i) + \rho'_{i} + N \cdot \sigma_{T,i}} \right)^2 \right],
\]

where \( q_i = 2 \cdot \pi \cdot r'_{C,i} / (3 \cdot x_{p,i}) \); \( \sigma_{T,i} = x_{\text{lg}} / x_{p,i} + \pi \cdot (2 \cdot r_{\text{lg}} + r_{g,i}) / (3 \cdot x_{p,i}) \); \( \rho'_{i} = 2 \cdot \pi \cdot r_i / (3 \cdot x_{p,i}) \).

![Figure 2. The dependence of indicators on changes in static.](image)

![Figure 3. The dependence of indicators on changes in pump speed pressure.](image)
Figure 4. The dependence of the indicators on the flow rate of the centrifugal pump.

Figure 5. Energy indicator of the PU at a different number of the workers at PS.

An analysis of the influence of the technological and operational parameters of hydromechanical and electromechanical equipment on the indicators of water-lifting pumping unit has established that:

- an increase in the static pressure caused by a decrease in the water level in the water intake structure of the pumping station leads to a decrease in the efficiency and supply rate of the pumping unit, as well as to an increase in its specific energy consumption (figure 2);
- for each discharge pipeline it is possible to determine a specific value of the rotational speed of a pumping unit, at which a maximum efficiency and a minimum of specific energy consumption are provided (figure 3);
- an uncontrolled increase in the supply of PS contributes to an increase in the mechanical power of the pump, overload of its drive motor and a spur increase in the specific energy consumption (figure 4);
the opportunity is given to determine the dependence of the energy indicators of the operation of the PU on the number of jointly operating pumping facilities, which makes it possible to determine the appropriate feed rates for their connection with parallel operation of the pumping facility electric drives (figure 5).

As a result of solving the differential equations [13] describing the “MMDEC – pumps – under pressure line” system, using the Runge–Kutta method, we obtained transient response curves of the rotational speed of induction electric motors and water supply by a pumping unit (Figure 6–8).

The use of a filter at the input of the speed control loop can achieve a slower increase in the rotation frequency and monotony of the water supply, which avoids the phenomenon of water hammer in the system MMDEC - pumps – under pressure line, while changing the number of parallel-running drive motors does not affect the transient response history due to the compensating effect of the speed
controller. With an increase in the number of jointly operating pumping facilities, the speed of the system in terms of flow rate increases, however, along with this, an increase in over controlling is observed, which is explained by a decrease in the time constant of the "pumps – under pressure line" system.

In the experience of the motor drive irrigation at the pumping stations, the most commonly used options are the structural layout of the group of pumping facilities, as part of a pumping facility for jointly parallel operation in a common pressure pipeline (hydraulic pressure network) with their equipping with AC electric drives of the same type. At the same time, the reduction of the specific costs of electric energy (EE) and the rational use of water resources can be achieved with the help of an adjustable multi-motor electric drive, due to the coordinated change in the speed (frequency) of rotation of the pumping facility [14].

A multi-motor electric drive with the electric coupling via a rotor circuit with a common grid-controlled inverter in which the slip energy of the rotor circuit is transmitted to the supply main can be considered the most promising controlled electric drive system with regard to the PU of the PIS (pump irrigation systems) [15].

The MMDEC system with the common grid-controlled inverter is characterized by high efficiency compared to other known systems of controlled electric drive, since it only converts the slip energy of the electric drive motor.

The main advantage of this circuit design is as follows:

- the valve inverter in the rotor circuits of induction electric motors should not provide circulation of reactive power to create their magnetic fluxes, since they are created due to the reactive power circulating in the stator circuits of induction electric motors.

The MMDEC valve inverter with the common grid-controlled inverter is calculated only for the proportional band of the electric drive motor control, while the converters for the induction electric motor power supply according to other control circuits must be made at full power of the electric drive system.

To be noticed is that the principle of operation of the MMDEC with the common grid-controlled inverter is almost similar to the double-motor asynchronously valve cascade (AVС) and can be explained as follows. When induction motors operate in a motor mode below the synchronous speed, the rectified voltages of their rotors are balanced by the auxiliary EMF (electromotive force) Edu, which is the average rectified voltage of the GCI (grid-controlled inverter) (back-electromotive force of the inverter), the voltage drop across the resistive voltage drop of the rotor circuits, and also the voltage drop due to commutation of the rectifiers. Since the moments developed by induction electric motors are proportional to the rectified current of their rotors, by changing the value of back-electromotive force of the inverter, it is possible to control the moments and rotational speeds of the PU drive motors.

The inverter's Edu value is adjusted by changing the current delay angle $\beta$ of the GCI (grid-controlled inverter). In the case when the rectified voltages of the rotors of induction electric motors are equal to each other and coincide in value with the inverter’s Edu, the currents in the rotors’ circuit of the electric motors do not occur; and, therefore, their torque is equal to zero. In case of decrease in Edu, the currents in the rotor circuit of induction electric motors increase, which leads to an increase in the torque developed by electric motors and their rotational speeds. In this case, the rectified voltages of induction electric motors are reduced until the torque developed by them become equal to the resistant torque. In case of increase in Edu, the rotor currents and the torque of the induction electric motors decrease, which causes a decrease in their rotational frequencies and, as a result, contributes to an increase in the value of the rectified rotor voltages of the electric motors. In this case, the rotor currents and the torque developed by induction electric motors increase until a steady-state mode of operation with such values of the rotational frequency is reached that corresponds to the equality of the torque developed by the electric drive motors, the applied resistant torque of the PU [16-17].

During the technological process of the PU PIS (Pump Irrigation Systems) water supply, the connection (start-up) for the joint operation of one of the electrical drive motors of the PU within a running of other induction electric motors, taking into account the constancy of impact (the current delay
angle of the GCI (grid-controlled inverter) is unchanged), is going along with the process of aligning their rotation frequencies. At the initial moment of time, the rectified rotor voltage of the newly connected operation, for example, M3, is greater than the rectified voltage of the rotors of the operating PU drive motors. This leads to the locking of rectifier valves in their rotor circuits, which is almost equivalent to turning off these electrical drive motors along the chain of their rotors and as a result, the speed of functioning induction electric motors begins to decrease. The rotation frequency of the connected to the operation of the drive motor of the PU increases. Upon reaching the equality of the rectified rotor voltages, and hence the indicated rotational speeds, previously functioning induction electric motors are again connected via the rotor circuit. Subsequently, taking into account the actual equality of the loads on each of the electrical drive motors of the PU, which takes place in the PU PIS (Pump Irrigation Systems), their rotation frequencies vary proportionally to balance the torque developed by induction electric motors with the resistant torque (RT) to the load of the pumping facilities.

The load rise process on one of the operating electrical drive motors (for example, when opening the pressure valve of the PU as part of the PF) is similar to the above, with the only difference being that, at different values of the resistant torque on the shafts of the PU drive motors, an induction electric motor with a lower value of $M_C$ on the shaft periodically turns off on the rotor chain.

Dropping of the load from one of the operating electrical drive motors (for example, with partial closing of the pressure valve of the PU as part of the PF) when accompanied by an increase in its speed and a decrease in the rotor rectified voltage. In addition, since the rectified rotor voltages of other induction electrical motors in operation are larger, the valves of the corresponding rectifier are locked and this drive motor is turned off by the rotor circuit, respectively, its rotation frequency begins to decrease. As soon as the rectified voltages of the electrical drive motors’ rotors of the PU are rectified, the induction motor is again connected via the rotor circuit to run together according to the MMDEC scheme with the common GCI (grid-controlled inverter) as part of the PU. In case of difference in the resistant torque is still remaining, then due to the fact that the air gap torque of the induction motor under consideration at the current value of the rotational speed (slip) is not balanced by its resistant torque, then its rotational speed starts to increase again. In turn, this leads to a decrease in the rectified rotor voltage and, therefore, to the repeated shutdown of the electrical drive motor along the rotor circuit.

Disconnecting one of the operating PU electrical drive motors from the supply line does not disrupt the technological process flow of water supply of the PU PIS (Pump Irrigation Systems) and maintains consistency of the rotation speeds of the induction electrical motors in the MMDEC system with the common GCI (grid-controlled inverter).

4. Conclusions

The most preferable one that meets the requirements for the controlled electric drive of water-lifting PU, in which the group of PF operates in parallel in a common hydraulic pressure supply network, is an electric drive system implemented according to the multi-motor drive scheme with electric coupling via a rotor circuit controlled by the common grid-controlled inverter.

Also, this electric drive system can be used in multi-motor electric drives of the general purpose industrial grade machines that do not require absolutely strict coordination of the rotational speeds of their drive AMs with a phase rotor, depending on the requirements of the process conditions.

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