Equipment for Energizing and Controlling the Operation of Synchronous Power Motors

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***Abstract* - It is known that the use of synchronous motors in variable speed drives to simultaneously generate mechanical power and reactive power is among the most effective methods of improving the power factor in electrical distribution networks. Also, the adoption of automatic excitation control has expanded the application field of synchronous motors to handle high-load shock drives. Modern digital control systems designed for controlling the excitation of synchronous motors have revitalized the significance of these machines. This paper presents a synchronous motor excitation control system that provides a fully digital solution for the design of equipment to supply excitation and control the operation of high power synchronous motors. This system can be easily parameterized for low and medium voltage synchronous motor drives of various rated powers, with asynchronous starting capability. An application of the system to the realization of an equipment for excitation power supply and operation control of high power synchronous motors is also presented. The equipment was realized in prototype version and after successful laboratory tests it was successfully produced in series and used to build electric drives for ore mills using asynchronous motors of 2.93 MVA.**

Cuvinte cheie: *excitație motoare sincrone, sisteme digitale de control și reglare, rețele electrice de distribuție*.

Keywords: *synchronous motor excitation, digital control and regulation systems, electric distribution networks.*

I. INTRODUCTION

This paper describes an excitation and control equipment for the operation of synchronous motors. It represents a continuation and extension of the work originally presented at International Conference on Applied and Theoretical Electricity (ICATE) 2024 [1].

The automatic control and regulation system presented in the paper is intended for the design and practical implementation of an equipment for supplying the excitation winding and controlling the operation of high-power synchronous motors.

In the past, the synchronous machine was mainly used as a generator, and its use as a motor was mainly hindered by the starting process. Today, advances in power and control electronics have eliminated the difficulties associated with the starting process. This has made the use of synchronous machines increasingly attractive up to the highest power ratings [2], [3]. Despite the starting difficulties, the synchronous motor is used in these cases instead of the cage-rotor induction motor because it has a number of advantages. It therefore helps to improve the power factor when operating in overexcited mode and has a higher operating reliability than asynchronous motors, especially at high power and low speed, due to the larger air gap. Compared to the asynchronous motor, the torque of the synchronous motor is more stable to variations in the supply voltage and the efficiency is better due to the higher power factor [4].

In order to optimize the performance of high power synchronous motor electric drives during start/stop and constant speed operation, it is necessary to efficiently control the machine through its excitation current.

Classical synchronous motor excitation systems are designed with DC generators controlled by regulators included in the excitation circuit of the exciter machine. For this purpose, the excitation circuit includes a variable resistor controlled by an electromechanical regulator. Disadvantages of this solution are:

- High response time;
- Low energy efficiency;
- Relatively high cost of implementation.

Another solution for the excitation supply is the use of rectifiers with controlled semiconductor devices, supplied by a transformer equipped with taps in the secondary winding, where the excitation current is controlled by switching them.

The disadvantages of this solution are:

- Coarse tuning of the excitation current;
- Relatively high implementation cost.

It is also worth mentioning the solution of using compound excitation systems with semiconductor devices. Disadvantages of these systems are:

- High cost due to use of special current transformers;
- Composite systems are difficult to size;
- Analog control scheme is relatively complicated;
- Relatively low efficiency.

In modern drives with high power synchronous motors, the excitation circuit is powered by controlled rectifiers fed by fixed ratio transformers.

This solution allows optimal control of the operating modes by efficiently controlling the excitation current. The control schemes of the machine operation, as well as the implementation of the excitation current control algorithm, can be done with analog technology or with digital electronic solutions.

This paper presents an advanced solution for a fully digital excitation command, control and regulation system for use in high power, constant speed, asynchronous squirrel cage synchronous motor drives.

The advantages of this solution are:

- The control system is fully automatic and digital, using a state-of-the-art DSP processor;
- The control software application is developed using a programming platform specifically designed for electric actuators, allowing easy parameterization for a wide range of actuator motor powers and speeds.
- Low cost;
- Safety in operation.

II. Theoretical Aspects

Below are briefly presented some theoretical aspects that describe the main operating modes of the synchronous motor. These will constitute the main requirements for the design of the automatic control and regulation equipment presented further in the paper [4]…[10].

The mains synchronous motor normally operates at a constant (synchronous) speed given by the frequency of the supply voltages and has a rigid characteristic.

The synchronism velocity is given by the relationship:

$$n_s = 60\,\frac{f}{p} \qquad (1)$$

where f is the mains frequency and p is the number of pole pairs.

The power absorbed by the motor from the mains is converted into torque at the shaft according to the equation:

$$M = m\frac{U E_0}{X_d\,\omega_1}\sin\theta = M_{\max}\sin\theta \qquad (2)$$

where:

m – number of motor phases

U – voltage applied to the terminals [V]

E_0 – electromotive force (EMF) [V]

X_d – motor longitudinal reactance [Ω]

ω_1 – rotor angular speed [rad/sec]

θ – internal angle of the motor [rad]

The problems that require particular attention in high power synchronous motor drives relate to the process of starting, stopping and maintaining synchronism under variations in torque and supply voltage (the stability problem).

For drives with high shock loads, it is necessary to over-excite the motor to prevent it from entering the unstable operating range with the risk of out-of-sync.

The V curves of the synchronous motor [3] show (Fig 1):

- To the left of the cosφ=1 curve, the synchronous motor is operating in INDUCTIVE MODE, absorbing reactive energy from the mains (under-excited synchronous motor).
- To the right of the cosφ=1 curve, the synchronous motor is operating in CAPACITIVE MODE, generating reactive energy in the mains (overexcited synchronous motor).
- If the field current falls below the *Iexmin*. curve, the motor will enter the unstable range and may go out of synchronisation.

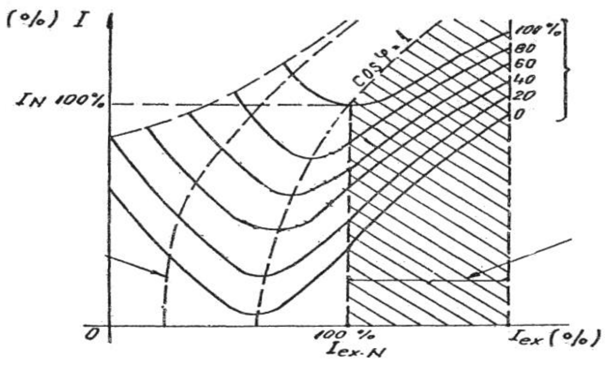

Fig. 1. V-curves of the synchronous machine [5]

- If the field current is increased above the value Iex_N in order to absorb some load shocks on the shaft, there is a risk of exceeding the heating limit of the field winding.

The conclusions are as follows:

- The upper part of the CAPACITIVE operating range is the heating limit of the field winding and therefore of the "Iex_{max}" protection characteristic;
- The lower part of the INDUCTIVE operating range is the stability limit of synchronous motor operation, i.e. the "Iex_{min}" protection characteristic.

The minimum supply voltage at which the synchronous motor can be maintained in operation at rated load (Mn) and rated field current [9]:

$$U_{min} = \frac{X_d\,\omega_1 M_n}{mE_n} \qquad (3)$$

where: *En* is rated EMF value

Forced excitation results in increased EMF (E) and therefore increased torque. This keeps the motor synchronised when the mains voltage drops below *Umin*.

For fast excitation, the excitation supply must provide three times the rated excitation voltage.

The main operating modes of the synchronous motor are briefly described below.

A. Starting the Synchronous Motor

The synchronous motor can be started [3] in several ways: by an auxiliary drive motor, by a variable frequency supply and by asynchronous starting. Asynchronous start is the most commonly used start method. During the first part of the starting process, the motor operates as an induction motor with a winding in the pole shoes, usually a squirrel cage, but sometimes a winding with coils and slip rings.

The size of this winding, called the starting winding, depends on the motor power and the parameters required for the starting process.

The asynchronous starting process is as follows: the field winding is disconnected from the excitation source terminals and connected to a resistor called the discharge resistor, which has a resistance 9-10 times higher than that of the field winding.

In this situation the synchronous motor is connected to the mains, either directly or via a 2 to 4 stage voltage transformer (or via a starting autotransformer).

The machine operates as an induction machine. When the slip is at a steady state value of 2-3%, the field winding is disconnected from the resistor and connected to the DC source, generating the field current flowing through it.

From this moment on, the mains synchronisation process begins, which is the result of a damped transient process. If a starting transformer is used, the voltage steps must be switched to increase the voltage to the rated value before the field current is set. This is also the case when using the autotransformer starter.

The lower the value of the slip Si at the time of setting the DC field current, called the input slip, the easier it is to achieve synchronism.

The best conditions for synchronisation are at idle. When starting on load, synchronisation is more difficult and is facilitated by proper control of the field current through a forced excitation process.

B. Stopping the Synchronous Motor

The synchronous motor is switched off [3] by disconnecting it from the mains after adjusting the field current so that the stator current is at a minimum. Reconnection of the field winding to the discharge resistor is mandatory for protection reasons and to prepare the synchronous motor drive for possible restart.

C. Synchronous Motor Operation in Synchronous Compensator Mode

Compensator mode [4] is a special synchronous motor operating mode. In this mode the machine exchanges reactive power with the grid according to the set field current. With respect to the mains, the synchronous machine, in this case the synchronous motor is equivalent to a capacitor bank when over excited (field current set higher than rated field current) and to a coil when under excited (field current lower than rated field current).

The maximum range of reactive power exchanged with the mains, obtained by correct control of the field current, is obtained when the motor is running at no load, in which case it draws from the mains only the active power necessary to cover the specific losses.

The synchronous compensator mode may also be available in on-load operation, especially when the load is variable and predominantly lower than the rated value.

Adequate control of the excitation current, obtained by using controlled rectifiers controlled by electronic regulators as a DC power source, allows excellent performance criteria to be obtained in the control of the reactive power flow exchanged with the power supply network, while maintaining stable operation of the actuators.

III. Equipment for Energizing and Controlling the Operation of Synchronous Power Motors

Below is presented the equipment for energizing and controlling the operation of synchronous power motors, built at ICMET Craiova, Microproduction Division, under the commercial name EEx-MS-500A-01 (Fig. 2).

The EEx-MS-500A-01 provides power supply and protection of the excitation winding of the synchronous motor, control of the synchronous motor operation (starting, load operation, intentional and fault shutdown) and implementation of criteria for optimizing the operation with respect to the synchronous motor power supply network.

The system was tested in all modes of operation on a dedicated prototype bench and then produced in small batches for delivery to beneficiaries throughout the country.

In the commercial version produced at ICMET Craiova, the device, coded Eex-MS 500V/500A-01, has been parameterized for synchronous motor drives with the following technical specifications:

- Motor Type: СДС 19-56-40У4;
- Rated power: 2500 KW;
- Apparent rated power: 2930 kVA;
- Rated power factor: cosφ=0,9;
- Nominal speed 150 rot/min.
- Stator:
  - -connection: Y;
  - -rated voltage 6 KV;
  - -rated frequency: 50 Hz;
  - -rated current 282 A.
- Rotor:
  - -rated excitation voltage: 145 Vcc;
  - -rated magnetizing current: 278 A;
  - -rotor inertial mass: 13.540 Kg.

The stator supply voltage of synchronous motor is measured using a voltage transformer (TMT) and the stator current is measured with a current transformer (TMC) (Fig. 2).

The excitation winding of the synchronous motor is supplied with a direct voltage obtained from a power transformer (TA) and a controlled rectifier (RC).

The motor excitation current is connected as follows, using the voltage of static contactor (realised with thiristors T7, T8) applied on discharge resistor (RD). At the same time, the rectifier pulses are blocked and the opening command of the I1 switch is activated.

As can be seen from (Fig. 2), the entire equipment is designed and built around the SRAEx system as the main automatic control and regulation system.

All control, protection and automation functions of the equipment and the motor are performed by the SRAEx-MCSK-2.0 - 01 synchronous motor automatic excitation control system.

The control of the static contactors is done from the SRAEx via the BCST block, using the control devices on the gate (BCT).

The cabinet in which the equipment is mounted is shown in (Fig. 3) (front view, with operator panel and inside view).

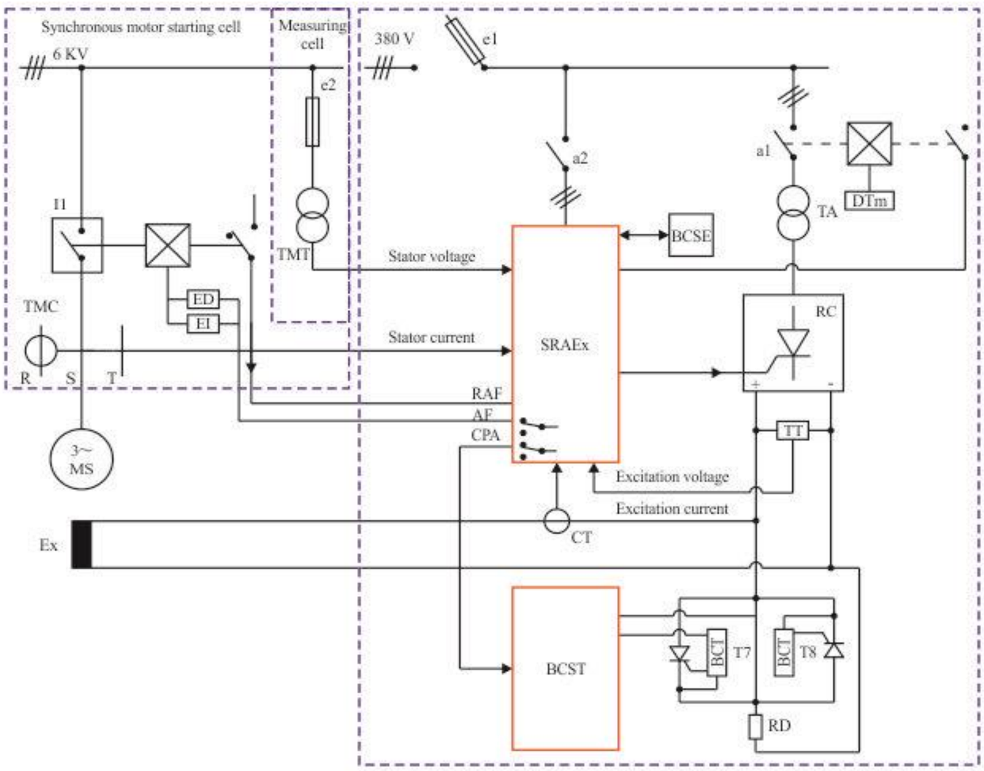

Fig. 2. Diagram of the Eex-MS 500V/ 500A-01 unit BCSE - External control and signalling unit; SRAEx - Automatic excitation control system; RC – Controlled rectifier; TC – Current transformer; TT – Voltage transformers; BCST - Thyristor control and monitoring unit; RD - Discharge resistor; TMT - Voltage transformer; TMC - Current transformer; TA - Mains transformer [1]

Fig. 3. The equipment cabinet Eex-MS 500V/500A-01

The central part of the presented equipment is constituted by the automatic control and regulation system.

It was designed and produced in the digital version at ICMET Craiova under the code SRAEx - MS - MCSK 2.0 - 01 (Fig. 4).

The automatic excitation control system (SRAEx) has the following operating modes:

A. Asynchronous Start

Asynchronous start is automatic according to the protocol described in section II.A and is controlled by the **SRAEx - MS - MCSK 2.0 - 01** control system**.**

B. Load Operation in:

*1) **MANUAL** mode with field voltage regulator*

In MANUAL mode, the output voltage of the rectifier (RC) supplying the synchronous motor excitation can be adjusted between zero and the maximum value set.

The minimum value of the bridge's control angle must correspond to the maximum voltage at its output. The minimum imposed value of the control angle should be considered as a parameter so that the same maximum excitation voltage can be obtained using transformers to supply the excitation bridge with different secondary voltages.

In MANUAL mode, the TEST option can be used to check the operating status of the excitation supply equipment, tune the control loops and troubleshoot. MANUAL mode can also be selected in FAULT mode as an operating option in the event of faults in the automatic control part of the system.

The rectifier voltage in MANUAL mode is set by a potentiometer/encoder and the mode is selected by a five-position switch (CRF) set to MANUAL together with a two-position switch: TEST or FAULT.

*2) **AUTOMATIC** mode*

*a) **CONSTANT CURRENT** with field current regulator*

In this mode, the excitation current is maintained at a prescribed value between the minimum field current and the maximum permissible field current, regardless of variations in the excitation rectifier (RC) supply voltage or variations in the field winding resistance.

The automatic control system uses a current regulator with a field current response provided by a Hall probe current sensor.

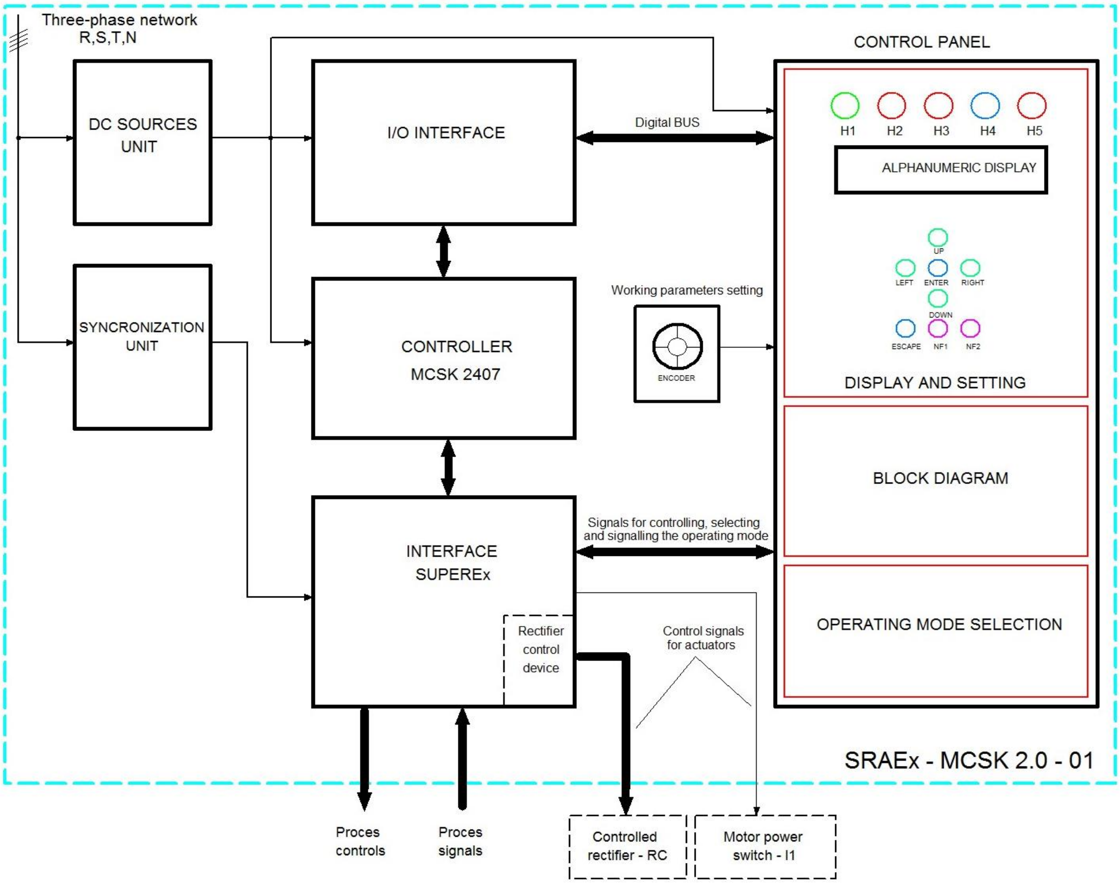

Fig. 4. Block diagram of the automatic control system SRAEx-MS-MCSK 2.0-01 [1]

*b) **CONSTANT STATOR VOLTAGE** with stator voltage regulator*

In this mode, the voltage at the motor terminals is maintained at a prescribed value between 0.9 and 1.1 of the rated stator voltage, with reactive power offset, regardless of the variation of the motor supply voltage (mains voltage).

In CONSTANT VOLTAGE mode, the terminal voltage is in the range 0.9÷1.1 UN and the setting refers strictly to this range (limitation of the prescribed values).

The CONSTANT VOLTAGE mode is selected with the CRF switch and the voltage is set with a potentiometer/ encoder.

The automatic control system operates as a stator voltage regulator with field current monitoring.

Response information is obtained using voltage transformers with the appropriate transformer ratio.

*c) **CONSTANT POWER FACTOR** with power factor regulator*

In this mode, the power factor at which the motor operates is maintained at a prescribed value between 0.5IND-1-0.5CAP, regardless of the active power corresponding to the motor load and the motor supply voltage.

The voltage and current reaction signals for calculating the current power factor are obtained from voltage or current measuring transformers with appropriate transformer ratios.

Important: The voltage and current reaction signals from the three-phase motor supply system required for the calculation of the power factor cosα and the reactive power are two current signals and two voltage signals on the same phases.

The control system acts as a power factor controller by limiting the stator voltage and field current (keeping them within the permissible range).

The CONSTANT POWER FACTOR mode is selected with the CRF switch and adjusted with a potentiometer/ encoder.

The control system acts as a reactive power controller by limiting the stator voltage and field current.

NOTE: The power factor, i.e. the reactive power, must be maintained at the prescribed value for a stator voltage range limited below 0.9 (0.7÷0.95) and above 1.1 (1.05÷1.3) of the rated voltage. If these limits are exceeded, operation at constant voltage without offset is required within the limits imposed by the field current.

Parallel, not cascade, limiting control is used.

The CONSTANT REACTIVE POWER mode is selected with the CRF switch and adjusted with a potentiometer/ encoder.

*C. Deliberate or Fault **STOP***

The controlled (intended) stop of the synchronous motor is selected by activating an appropriate command from the front panel of the excitation equipment (two-position

ON-OFF switch) and/or from the control panel of the SRAEx.

The fault stop occurs when the out-of-sync protection is activated, only during synchronous operation of the motor, if the motor goes out of synchronism due to an overload. This protection is not active during start-up.

It is based on monitoring the frequency of the AC component of the current induced in the field winding and controlling the motor to stop if the frequency rises above a certain value. If the frequency of the detected alternating component is lower than the threshold (2.5 Hz), the SRAEx controls the forced excitation to resynchronise the machine.

If the frequency of the AC component of the field current rises above the threshold during the operation of the forced excitation, the SRAEx controls the lowering of the ignition threshold of the thyristors T7, T8 in the static excitation discharge contactor (Fig. 2).

The SRAEx MS- MCSK 2.0 system allows the drive-specific protection to be parameterised using the technical data of the synchronous motor entered via the control panel, and provides the following protection functions [3], [6]:

- Minimum field current protection
- Maximum field current protection
- Out-of-sync protection
- Stator winding overheating protection
- Protection against two-phase rectifier operation
- Field winding short-circuit protection

The automatic control and regulation system SRAEx-MS-MCSK 2.0-01 consists of the following function blocks (Fig. 4):

- MCSK 2407-V02 digital control module (supplied by Technosoft Romania) with functionality adapted for synchronous motor control, based on the TMS 320 LF 2407 Digital Signal Processor (DSP) controller from Texas Instruments, designed for Digital Motion Control (DMC) applications;
- Dedicated interface module SUPEREx (manufactured at ICMET Craiova), which performs signal acquisition from the transducer/sensor system and transmission of commands to the actuators (mainly to the three-phase controlled rectifier bridge and to the synchronous motor power supply switch in the synchronous motor excitation supply equipment circuit);
- Figure 5 shows the SUPEREx interface together with the MCSK 2407 2407-V02 modules and the I/O interface.
- I/O interface between the control module and the control panel;
- The control panel is equipped with an alphanumeric display for setting parameters, programming operating modes and displaying signals and status (Fig. 6);

The synchronisation and power supply module contains the synchronisation transformers and the AC/DC converters that provide the supply voltages for the system.

Fig. 5. SUPEREx interface with MCSK 2407 development system and I/O interface [1]

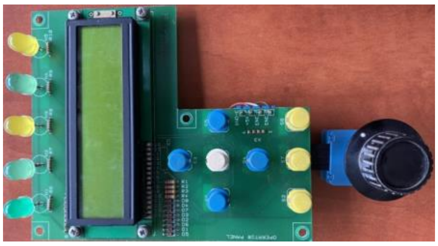

Fig. 6. Control panel [1]

IV. CONCLUSIONS

The equipment presented in the paper is produced by the National Institute for Research - Development and Testing in Electrical Engineering - ICMET Craiova and represents the final result of the collaboration with the University of Craiova.

The collaboration began with the design and development of an automated digital system to control and regulation the excitation of synchronous motors [1]. The SRAEx -MS-MCSK 2.0-01 is a fully digital solution for the design of equipment to supply excitation and control the operation of high power synchronous motors, and can be easily parameterised for low and medium voltage synchronous motor drives of various rated powers, with asynchronous starting capability.

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Contribution of authors:

First author – 35%

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Third coauthor – 10%

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