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Maximal reactive power compensation using loaded synchronous motors

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Abstract. The paper presents an intelligent system that aims to maximum possible compensate the level of the reactive power within a given power grid, usually present at factory sites or large electric vehicles such as ships. The novelty consists in the compensation method, which is performed using the already existing synchronous machines operating as motors below rated load. It is presented the control algorithm of the motor in order to achieve the maximum reactive power compensation and an example of an automated system implementation is provided.

Key words

synchronous motor, reactive power compensation, automated monitoring and control system

1. Introduction

The reactive power compensation is an important topic because it is related to electric energy savings. An appropriate level of compensation entails a minimum value of the total intensity current value for a given amount of active power flow and in effect the attaining of minimum active power losses. Examples of industrial electric installations that feature a low power factor are arc-electric furnaces [1], photo-voltaic renewable energy systems [2], small-size powering grids such as the micro-grids [3]) or poly-phased electric grids [4]. Thus, the reactive power compensation is a present concern.

The compensating process is achievable by various practices using synchronous machines: synchronous condenser [5], over-excited synchronous generator [6] or over-excited synchronous motor.

The paper aims to present an automated reactive power compensation system of a three-phase power grid within a factory site or an electric vehicle that is driven by a wound-field synchronous motor [7]. Another example of such motor applied for large ships is found in [8], with rated power ranges between 35 kW and 5 MW.

The compensation is achievable when the motor is loaded lower than its rated value. Such condition is present during the motor's practical operation, that is, the driving synchronous motor is not fully loaded and during this motor's loading state the compensation of reactive power is possible.

The amount of compensated reactive power is related to the level of the motor's loading. Therefore, when the motor is loaded less than its rated value (lower shaft output mechanical power), it is possible to initiate the compensation of the reactive power of the supplying grid. The compensated reactive power can be raised until the stator current is increased up to its rated value. While the synchronous motor is loaded, when the rated stator current is reached, the maximum compensation level of the reactive power is achieved.

During the compensation process it is not possible to overcome the rated stator current due to the heating of the synchronous motor which would be in excess, possibly larger than the admissible limits set by its thermal class.

The value of the stator current is controlled by the field current winding. In order for the compensation to be initiated, an over-excitation of the motor is required, that is, the field current is set to be greater than its optimal value I_e^* which corresponds to a unity power factor. When the motor operates under load and the field current is set to the optimal value then stator current of the motor, i.e. the current drawn by the motor from the power grid or power bus, is minimum. In effect, the stator Joule losses are also minimal and the motor efficiency is increased.

The optimum value I_e^* depends non-linear on the motor's output mechanical power P_{mech}, but the trend is that with higher generated mechanical output power the higher the optimum field current is required. In principle, when the compensation of the reactive power is performed using a synchronous motor, one should know the $I_e^* = f\left(P_{mech}\right)$ characteristic.

If this curve it is not previously known then it can be obtained at the beneficiary location. The motor is loaded step by step and so the curve is traced by experimental data points. Practically, for a given output mechanical power the field current is changed until a unity power factor is achieved and the stator current has the minimum value. Thus, this value of the field current is the optimum value for that given output mechanical power.

The proposed system is compatible with any wound field synchronous motor. In cases of permanent magnet synchronous motor the method is not applicable because the rotor magnetic field is constant.

For the proper operation of the system, the following input data it is required: motor's rated voltage U_r; motor's rated stator current I_r; $I_e^* = f(P_{mech})$ characteristic; and the maximum allowable field current $I_{e,max}$, that is, the field current for which the field winding is not overheating.

2. Optimal field current definition

As already presented in the first section, the optimal field current I_e^* depends non-linear on the motor's output mechanical power P_{mech}. The reactive power compensation of the power grid where the motor is connected to is achievable only when the field current is greater than the optimal one I_e^*.

In such cases, the synchronous motor generates a reactive power flow, and the operating regime is called over-excited [9].

In cases when the field current is less than the optimal value I_e^*, the synchronous motor becomes a receiver regarding the reactive power flow, and in this case the operating regime is called under-excited. This regime must be avoided because the power factor diminishes even more. In this vein, for each value of the output mechanical power P_{mech}, the optimal value I_e^* has to be found, while the field current must be set to a greater value than the optimal one. Thus, a determination method for $I_e^* = f(P_{mech})$ characteristic has to be applied.

The method principle is based on the first order derivative properties. When the derivative is positive then the function trend is to increase while a negative derivative signifies a decreasing trend of the function. Moreover, if the sign of the first derivative changes around a given point then that point is a local maximum or a local minimum.

Reverting to synchronous motor, the characteristics of the grid drawn stator current with respect to the field current are defined for a given constant output mechanical power. These curves are known as V-characteristics and they are given by the expression:

$$I = f(I_e)\big|_{P_{mech} = const.} \quad (1)$$

In Fig. 1 are depicted the V-characteristics for three different values of output mechanical power.

For a given synchronous motor shaft output mechanical power P_{mech}, the optimal field current I_e^* corresponds to the minimum stator current I_{min} on a V-characteristic. The issue is to find this optimal field current value.

Hence, let us consider the first order derivative $\frac{dI}{dI_e}$ of the stator current's RMS value, drawn by the synchronous motor from the power grid, with respect to the field current.

The derivative is zero for exactly optimal field current I_e^*, corresponding to a given output mechanical power.

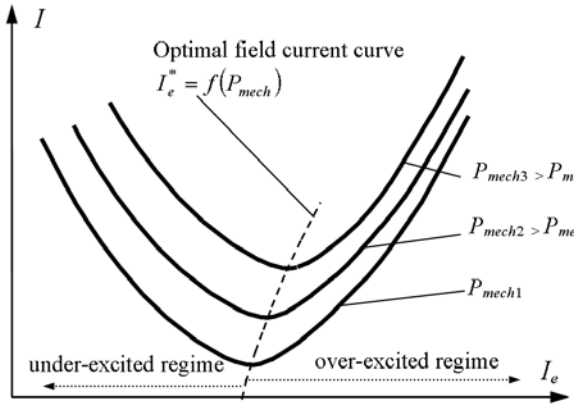

Fig. 1. Optimal field current characteristic.

3. Method for optimal field current evaluation

This method is applicable even when the non-linear characteristic $I_e^* = f(P_{mech})$ is not known at all. The method has two steps.

The first step consists in acquiring data using a data acquisition system. Thus, the discrete RMS values of stator current I and the values of the field current I_e are acquired.

The second step consists in processing the acquired data using a processing unit (microprocessor or microcontroller). The result represents the control signal for the field current, but the following restrictions must be considered:

$$I < I_r; \; I_e < I_{e,max} \quad (2)$$

A. *Data acquisition system*

This system contains all the required sensors for acquiring: the field current I_e, the stator current I and the voltage grid U. The system also includes the transducers for the conditioning of the signals at the microprocessor inputs. In Table I is presented the data storage principle for *n*-points.

Table I. - Data storage principle

Point	0	1	2	...	k-1	k	k+1	...	n-1	n
I	I_0	I_1	I_2	...	I_{k-1}	I_k	I_{k+1}	...	I_{n-1}	I_n
I_e	$I_{e,0}$	$I_{e,1}$	$I_{e,2}$	...	$I_{e,k-1}$	$I_{e,k}$	$I_{e,k+1}$	...	$I_{e,n-1}$	$I_{e,n}$

For numerical computation of the first order derivative $\left(\frac{dI}{dI_e}\right)_k$ in point k it can be applied a formula that uses the discrete values of the I and I_e currents in vicinity of point k, namely, $k-2$, $k-1$, $k+1$ and $k+2$.

There are many methods to numerically compute the first order derivative in a given point [10]. An efficient computation method is obtained based on Taylor series expansions with central finite differences [11] such as:

$$\left(\frac{dI}{dI_e}\right)_k = \frac{-I_{k+2}+8I_{k+1}-8I_{k-1}+I_{k-2}}{12h} \qquad (3)$$

where h represents the constant sampling step defined by:

$$h = I_{e,k} - I_{e,k-1} \qquad (4)$$

B. *The processing unit*

The processing unit numerically computes the first order derivative value $\left(\frac{dI}{dI_e}\right)_k$ and automatically validates if the sign of the derivative is positive. This condition means that the synchronous motor is over-excited. Thus, the field current is increased by the control unit, until the rated stator current is reached $(I = I_r)$. In this moment, the compensation of the reactive power is considered to be at the maximum allowable level.

C. *Grid voltage control*

When the grid requires an amount of reactive power that is less than the amount of reactive power that it is generated by the over-excited synchronous motor and it is injected into the grid, then the grid voltage can become quite large, larger than the maximum allowable safety value. In this case, the limitation of the consumer's grid voltage to a prescribed safe value is required.

In other words, the maximum reactive power compensation has to be performed by complying with following supplementary limitation:

$$U \le U_{max} \qquad (5)$$

where U_{max} represents the maximum allowable limit at the beneficiary's power grid location.

4. Automated system for reactive power compensation

An implementation of the described method for reactive power compensation can be achieved using the block diagram depicted in Fig. 2. This is the case of an industrial installation site where, for example the synchronous motor drives an air compressor (motor load).

The local inductive loads could be other industrial installations both main production and auxiliary and safety ones (cooling/heating equipment, lighting, gates drives, powering IT equipment for control and monitoring basis, charging electric accumulators etc.).

In general, such installation features large electric power. Hence, in order to reduce the grid's powering cables size that power many such industrial installations, the operating voltage is usually tens of kilovolts or more. The equipment operating within the beneficiary installation is in general designed for medium voltage (6kV) or low voltage (below 1kV, usually 400V). The voltage adaptation between the grid and the local electric installation is achieved using a transformer.

Nevertheless, a similar diagram is proper for an electric driving system, but the grid is replaced by the vehicle's main power bus or other power supply module. In case of large ships the local inductive loads represent main switchboard (navigation equipment, fully automatic machinery control - including motor and generator controls), auxiliary services (mainly lighting), emergency services (emergency lighting, navigation equipment)[12][13].

The proposed system has two main modules: the first module named - State Monitoring Module (SMM) that performs the monitoring, and limitation of electrical (expressions (2) and (5)), mechanical and thermal operating parameters and the second module named - Processing Software Module (PSM), which contains all the involved software programs applied during the system operation.

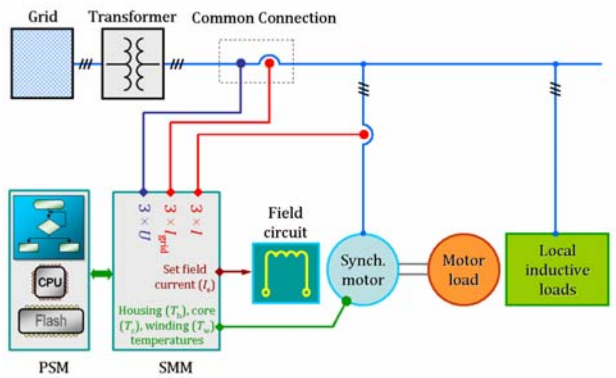

Fig. 2. Block diagram of the reactive power compensation method.

Between the two modules it is a continuous dependency and on-line communication, provided by the PSM.

The PSM has a CPU (Central Processing Unit) which can be a DSP (Digital Signal Processor), a microprocessor or a microcontroller. Its objective is to mainly compute the set the field current value based on the input data (as detailed at the end of the first section) for limitations and first order derivative (see expression (3)). The Flash represents the memory where the acquired data (see Table I) is stored for the computation of the numerical derivative.

The SMM requires the total power factor of the grid. Thus, the power factor is evaluated based on the stator current of the synchronous motor. The system drives the field current such that the synchronous motor is over-excited. The SMM, also monitors the grid voltage because the over-compensation of the reactive power can lead to an over-voltage.

5. Conclusions

Within the industry there are wound-field synchronous motors that operate within various electric drives application systems, such as: driving crushing coal mills at steam power plants, power electrical vehicles in transportation (ships, railway traction) etc. but not all the time at rated load. Thus, it is possible to generate reactive power using such driving motors, while they operate under load.

The electrical power grids that supply such synchronous motors also supply other reactive power consumers, mainly induction motors. These consumers diminish the global power factor of the grid with negative effects over their efficiency. As a result, the reactive power compensation is an important issue. In effect, the presence of an automated reactive power compensation system is fully justified, and moreover the compensation is performed using the already existing synchronous motors.

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