Abstract

As energy consumption is one of the main drivers for production and operational cost of a product, it is necessary to make operators of manufacturing units and machine tools aware of the current power consumption of their operating equipment. However, it is not sufficient to provide the current overall power consumption but to give different levels of detail. This paper presents an approach to combine power measurements, control signals and information with consumption simulation models to provide the operators with highly detailed power consumption data and how it is distributed over the components of their machine tools. An implementation of the monitoring approach on a HSC milling machine is presented in detail, followed by an overview of its use for energetic optimization.

Keywords: energy efficiency; consumption modeling; energy monitor; ECOMATION; energy optimization; machine tools

1. Introduction

Resulting from growing public and political interest as well as increasing energy and resource scarcity, energy and resource efficient production is of major interest within the manufacturing industry [1,2]. In cope with DIN EN ISO 50001 knowledge about all energy flows in a factory is necessary for successfully implementing and evaluating energy efficiency measures. However, it is a major challenge to collect the needed data within the needed level of detail from all energy sources and sinks within a production side. Thus, the internal enterprise knowledge is often limited to the energy demand on factory level. The energy demand of individual lines and machines is largely unknown. Making statements on future energy demands on all factory levels is even more challenging and usually based on historical measurement data [3] or not possible at all.

Facing this problem, this paper presents an approach of combining measurement data together with data generated with the use of static as well as dynamic simulation models to identify the electric energy demand of machine tools. A software tool was developed which is capable of merging real measured values as well as simulated values in real time. Besides illustrating current energy values also estimations about future energy demands are possible [4]. Using the gathered data in a second step a situation based machine control optimization takes place lowering the overall energy demand of the machine tool. In the further course of this paper energy demand will be used synonymously for electric energy demand.

The structure of this paper is as follows. Section 2 summarizes the theoretical background and preliminary activities within this field of research. Against this background, section 3 describes the developed general modeling approaches. The key facts of the simulation models, control information and additional measurement equipment for the developed approach are covered in section 4. Section 5 describes the modeling concepts applied in detail and in section 6, the prototypical implementation of the monitoring and simulation tool is presented. Section 7 gives a short
over view of possible energy reduction methods with the use of the presented approach with the consumption models and section 8 concludes the main ideas of this paper.

2. Theoretical Background

2.1. Estimation of the energy demand of machine tools

For estimating the energy demand of machine tools, basically two general approaches are commonly used. Based on historical measurement data, [5-8] assume mean power demand values for production machines in different machine states. Considering the average times spent in each machine state the overall energy demand can be accumulated. The second approach focuses on the use of continuous simulation for estimating the energy demand of production machines on machine or component level. Through simulating the physical behavior of the machine/component the corresponding energy demand can be derived [9-14].

2.2. Energy demand optimization of machine tools

Energetic optimizations of machine tools can be realized on hardware as well as on software level of the machine. In general four energy efficiency leverages can be identified:

- Efficient components and drives
- Right dimensioning of peripheral devices
- Demand oriented controls
- Process optimization

Research activities done by [9,15-19], focus on the machine hardware (first two bullet points): optimization of main drives (i.e. efficient control of (a)synchronous machines) and peripheral systems (i.e. demand controlled hydraulic & chiller systems). Software optimization approaches also promise great saving potentials. In this context energetic optimization by assessment and optimization of the NC-code has been examined by [17,20]. [21,22] developed an approach of implementing stand-by strategies to the machine control switching the machine to the lowest energy consumption state available in dependency of parameters such as expected time of stay within the new machine state or expected energy demand to change states.

3. General modeling approaches

For realizing a holistic modeling approach to map the energetic behavior of machine tools, different modeling layers are introduced. Within the first layer a general mapping of the energy demand of a machine tool can be done using an operating state-based approach. Using detailed simulation models within the second layer a mapping of a more detailed energetic machine behavior is possible. Introducing two modeling layers has the advantage that on the one hand the fundamental energetic performance of a machine tool can be mapped quickly on the other hand a higher level of detail (electric load curves in contrast to average energy demands) can be realized individually for each functional module.

3.1. Operating state-based modeling

Within the research project ECOMATION, Verl et al. [4] introduced an operating state-based modeling approach to calculate the power consumption of machine tools (e.g. milling machines) based on its available operating states. In this context operating states are e.g. ‘machine off’, ‘emergency stop’, ‘ready for operation’ or ‘energy saving mode’. For each state, the active and energy relevant components have to be defined and at least their average power consumption level within that state has to be analyzed. The definition of possible state changes and state trajectories concludes the modeling approach.

3.2. Detailed component modeling

While the operating state-based modeling approach calculates with average energy demand values simulation models have been composed during the project capable to compute detailed electric load curves for the most relevant functional modules. For doing so a general machine tool component model library was developed within the simulation environment Matlab/Simulink making it easy to build up different simulation models of functional modules (e.g. hydraulic system, cooling lubricant system, etc.) consisting of several component models ((a)synchronous motor, internal gear pump, etc.) [23]. With the focus on broad applicability the developed simulation models can exclusively be parameterized by publically available data from the manufacturer.

4. Machine control, measurement and modeling information

To enable the use of the modeling approaches from section 3, a large set of the energy information has to be made available for either the simulation or the monitoring software. Therefore, also within the ECOMATION project an automated approach to describe energy information has been developed [24] as an XML-based energy information description language. It provides information about the use of the consumption models mentioned above, available machine control information and existing power measurement devices, all three described in the following subsections.

4.1. Consumption model information

To use the different consumption models automatically, the necessary consumption model information has to be provided to the software tool. It needs the model type, its source file (e.g. DLL), the necessary model inputs and outputs and if applicable the model parameters. Typical model inputs are e.g. component status such as hydraulics or lubrication on or off,
current spindle speeds, axes feed rates and so on. Model parameters are e.g. look-up tables (characteristic maps) that define the specifics of e.g. a main spindle model.

4.2. Data from machine control

For the monitoring approach the models need input from the machine control. Up to date machine controls offer interfaces (e.g. OPC UA, DDE, ADS) to provide other software tools with control information. By modifications or definitions in the PLC program, selected PLC variables can be distributed over Ethernet e.g. with the mentioned protocol OPC UA. These distributed variables describe the control outputs to components such as the hydraulic pump, the machine lighting or cooling.

4.3. Data from measurement devices

Apart from the use of models in combination with data from machine controls, power measurement devices can further support the presented monitoring approach. Large global suppliers provide measurement devices, which provide measurement values, such as active power, over standard interfaces (e.g. Ethernet with the protocol Modbus TCP).

5. Monitoring and simulation concept

Within the described approach, simulation models are used on one side for real time monitoring the energy demand of existing machines and its functional modules within production environments. On the other hand they are applied for estimating energy demands of machine tools physically not available for hardware measurements. The resulting requirements for the simulation models are radically different and will be described in detail within the following sections.

5.1. Simulation approach

For estimating the energy demand of machine tools besides the physically/mathematically structure of the hardware components also the used control algorithms need to be considered within the simulation models. For main spindle units this means e.g. that besides the electrical and mechanical behavior of a (a)synchronous machine control instances for vector and speed control need to be implemented making the simulation model very complex (compare to Fig. 1). Thus some of the developed complex functional modules simulation models are not capable for real time calculations but they can be used for estimating purposes, where time is usually not a critical issue.

5.2. Monitoring approach

Monitoring applications have the advantage over energy demand estimations that actual PLC and machine control information are available. Thus no control instances within the simulation models are necessary. As an example the hysteresis behavior of an hydraulic system does not need to be integrated into the corresponding simulation model when the actual state (on/off) of the hydraulic pump can be extracted directly from the PLC. The absence of control instances within the simulation models opens the possibility to use static models in form of precalculated characteristics curves or maps, which contain the energy demand of a machine component in dependency of different input variables (e.g. drive speed and torque). This is essential for the described monitoring application since simple data queries basing on characteristic curves or maps are much less computationally intensive then running dynamic simulation models. Thus real time energy demand monitoring becomes possible. The downside of the described static approach is that dynamic effects like motor acceleration linked electric power peaks cannot be mapped. For calculating the needed characteristic curves and maps the dynamic simulation models described within the previous section can be used (compare to Fig. 2.) [10].

6. Prototypical implementation of monitoring software

For demonstration purposes, a prototypical monitoring software has been implemented within the ECOMATION project. The Energy Consumption Information System (ECIS) consists of two different user interfaces, one for the definition of the machine tool to monitor or simulate and one for the monitoring or simulation process itself. Both parts are described in the following two subsections.
6.1. ECIS – Energy information

The first user interface of ECIS (see Fig. 3) enables the user to define the machine tool or other manufacturing units to be analyzed by monitoring or simulation. The components of the machine tool have to be added in a component tree. The component tree consists of a root node that represents the machine tool itself. Underneath the root node, the following components are possible (see left column in Fig 3):

- Supply unit (power supply and filter)
- Control
- Peripheral equipment
- Tool change system
- Work piece system
- Chassis

Each sub-node has further sub-nodes that further detail the components subcomponents; for the supply unit these are e.g. the drive amplifiers and the electric motors itself. Within the component selection process the user is supported by a smart choice, ensuring that the user only adds components that are technically possible underneath the current node of the tree.

For each component added the user is supplied with a properties window in which the necessary model info (refer to section 4.1), the available control variables (refer to section 4.2) and if applicable the power measurement information (refer to section 4.3) can be inserted.

Prior to the use of the defined machine tool in the monitoring part of the prototype, the links between control variables and model inputs have to be set.

6.2. ECIS – Monitor

The monitor screen of ECIS consists mainly of two graph windows, the upper window showing power consumption values from devices or calculated model outputs and the lower window showing other auxiliary values, such as PLC variables. The user selects the datasets to be displayed in the graphs. The selection process is supported by a tree-like structure of components (refer to section 6.1) and for each component the user selects which variables, model outputs or power measurement values will then be displayed in the respect monitoring graph.

While the monitoring is active, the user has the ability to recognize direct dependencies between actions (control inputs) and the respective power consumption. Fig. 4 shows a screenshot while the monitoring of a milling machine is active. The upper graph shows the power consumption of the machine tool and its components, the lower graph the changes in PLC control variables of type Boolean (100 equals TRUE). It is obvious that each change in power consumption has its cause in a switched control output. The overall power calculated from the state based consumption model ‘MainPowerMdl’ (see section 3.1) follows the measured signal ‘MainPower’ very precisely. It can obviously replace the additional measurement devices for an average power consumption assessment with respect to its operating states. Within the processing state however, the average power
consumption value is not sufficient for a detailed analysis, as seen during the time periods 135s to 175s in which the main spindle is active. Here the component models (refer to section 3.2) prove their level of detail. The ‘SpindlePower’ signal is the measured power from the main spindle motor and its frequency converter and the ‘SpindlePowerMdl’ is the calculated power consumption from the equivalent model. It is shown, that the model clearly represents the power consumption of the main spindle depending on the spindle speed and torque.

7. Approach for power consumption reduction

As stated in section 2.2 there exist a wide variety of approaches to reduce the energy consumption of machine tools and manufacturing systems. The optimal energy efficiency will only be reached when applying multiple harmonized approaches.

The first step towards energy consumption reduction is taken by making the user aware of the dependencies of his actions (control inputs) on the power consumption. The monitor provides the user with a clear view of the power consumption in direct combination to changes of the state of PLC variables. For each component equipped with an energy consumption model the operator is shown the current power consumption and can react when the consumption is above of what it was with a previous setup.

Within the next sub sections, energy optimization approaches with the use of the described models are presented.

7.1. Component optimizer

The optimizing approach for components can be separated into the energetic control optimization of main drives as well as the control optimization of peripheral devices.

For the optimization of the main drives, when the load of the main spindle as well as the feed drives is known over the entire production process, adjusted control algorithms can be derived. A result could be to lower the magnetization current in combination with a torque-forming current increase during partial load operations resulting in a lower overall energy demand. By parameter variation within the developed simulation models the optimal parameter configuration can be found.

Demand oriented control strategies for the peripheral devices can be optimized by a more accurate knowledge (gained through simulation) about demand periods. As an example hydraulic systems need to be controlled to a certain pressure value to guarantee functionality. Thus pressure leakages must be compensated permanently. Knowing the time of the next hydraulic fluid demand (tool change, etc.) the required pressure level needs to be controlled just right before that event. A similar approach can be used for cooling lubricant systems.

7.2. Operating state optimizer

During non-productive time periods, the machine control is able to switch into energy saving modes or even shut down the machine entirely. Currently, the switching to these energy
saving modes is mostly either based on fixed time periods or the user has to start the operating state change manually. [25] propose a self-learning algorithm for energy-efficient state trajectories, no detailed information is given. With the use of the above mentioned state-based consumption model in combination with graph optimization theory, it is possible to calculate an energy optimal operating state trajectory. The approach is presented in detail in [26].

8. Conclusion

To raise the awareness of machine tool operators and manufacturers concerning the energy consumption of their equipment and to clearly demonstrate the consequences of their actions towards energy efficiency, the paper presented a model- and signal-based power consumption monitoring concept. It is based on available control information such as component state variables from the PLC and additional measurement devices. To reduce the cost for additional devices, it is shown, that consumption models with different levels of detail can replace these devices. Some approaches to reduce the power consumption with the help of the described models are given to conclude the paper.

Acknowledgements

The authors are grateful to the German Research Foundation (DFG) for funding the presented work in project FOR1088 “ECOMATION”.

References