A Mobile Agent for measurements in distributed power electronic systems

Ferdinanda Ponci¹, Aalhad A. Deshmukh¹
¹Department of Electrical Engineering, University of South Carolina
Swearingen Center
Columbia, SC 29208, USA
[ponci, deshmuka]@engr.sc.edu

Abstract – this work introduces the use of a mobile agent for the purpose of power quality assessment in systems with distributed control. The mobile agent introduced here leverages on the agent-based distributed control of the electrical loads of a power electronic distribution system. While the stationary agents control local loads autonomously and are capable of negotiations for reconfiguration purpose, they have to rely on external resources for certain types of more sophisticated evaluations of operating condition, such as power quality pollution. The authors have already considered the option of a stationary monitoring agent capable of providing these information and the option of embedding additional algorithms in the load agents. In this work a new approach based on a mobile agent is investigated. The advantage of such solution consists primarily in its flexibility, in fact the mobile agent can be easily re-deployed to serve various purposes exploiting the distributed computational capability.

Keywords – power system monitoring, power control, power quality

I. INTRODUCTION AND OBJECTIVES

The complexity of power systems and power electronic systems is growing in terms of number and type of components, spatial location and extent and sophistication of control. In centralized monitoring and control architectures, this results in a very large amount of data that needs to be collected and elaborated in one location. This may prevent fast local reaction to unforeseen events. Furthermore, such centralized approach may make the system less robust to local disruptions. Finally, some systems are naturally evolving towards a more distributed architecture, as power systems in the form of microgrids. For these reasons distributed monitoring and control for such systems is currently a main topic of research. The application of Multi-Agent Systems (MAS) in particular seems to be a very promising approach to distributed control and monitoring [1], [2].

The vast majority of MAS considered up to now in power systems and power electronic systems applications, [2], do not comprise mobile agents, because the size and type of test-benches would not particularly benefit from them. This conclusion may be different in certain types of systems in need to expand their operative features, while limiting the customization of the stationary agents, thus preserving reusability and allowing for a leaner architecture. In particular, within a system with groups of agents with the same common standard functionality, the use of a Mobile Agent (MA) may allow the deployment and use of custom routines when needed, without integrating these routines in the stationary agents. A very targeted application to power quality issues can be found in [14].

The framework of this work is the control of power electronic systems, that is, power systems where power flow is fully controlled, in particular through converters feeding DC zones, [6], from the main three-phase AC distribution system. These systems are currently under consideration for the future all-electric ship of the US Navy. Furthermore, their successful implementation would greatly benefit the operation of terrestrial systems, such as microgrids and in the longer term, terrestrial power distribution systems in general.
distribution line, if energy storage is available. A system of this kind has been presented in [7]. The simulation scheme of a DC zonal system, developed for the Virtual Test Bed (VTB) environment [3], [5], with six interface converters (encircled) feeding three DC zones from the three-phase AC distribution system (each zone is actively fed by one converter at a time) is shown in Figure 1. The VTB simulation scheme of interface converter, inverter and motor load is shown in Figure 2. This set of components represents a load for the distribution line and this is to be intended as one three-phase load herein.

The control problem addressed with the agents consists in smoothly controlling the power flow depending on load power demand, power availability and static and dynamic conditions. In this work, the authors address the problem of utilizing local data and elaboration for the assessment of power quality impact of each load, which in turn affects their chances to be fed. Notice that, with reference to the zonal system, the control level with which this work is concerned, is the power absorbed by each zone. Equivalent loads represent entire zones in the system under analysis in this work. The load management inside the DC zone has been addressed in [4]. In this work, instead, the main focus is at the upper AC level. With the flexibility allowed by the PEBBs, each zone interface can regulate the power flow and correct power quality issues. Thus, the agent approach proposed here is a way to promote local awareness of power quality issues, thus enabling independent intervention.

The objective of this work is to experiment advantages and hurdles of using a Mobile Agent within the MAS, for the assessment of the power quality impact of loads. This is the basis for the determination of dynamic load priority levels, used for the soft reconfiguration of the system [12], [13]. When power demand exceeds power availability, the one Load Agent (LAs), that realizes its load has minimum priority level, and/or worse power quality impact, makes the decision to shut it down or to use the features of its PEBB converter, where available, to correct, in part or completely, the power quality issues. In the following paragraphs, the nature of the Mobile Agent and its operation with the stationary Load Agents in a MAS framework is explained.

II. THE MOBILE AGENT APPROACH

Starting point of this work is the MAS described in [9] and [10]. In this architecture, each agent managing a load computes its priority level in response to a request message. This priority value is sent out to the remaining LAs for the determination of the lowest priority. Thus, with the increase in the number of loads and their associated LAs, the number of messages exchanged increases exponentially potentially causing delays in decision making.

Another issue in implementing such system is the need to provide the LA with the functionality of computing the priority of its load based on the current state. Suppose that such control criterion arises after the LAs have been implemented, then the LAs must be changed. In general they must be changed every time a similar new functionality is required. This would make the generalization of the architecture of the LA heavily dependent on the specific functionality, and this deviates from the overall aim to develop a standard LA, while this type of standardization is considered an enabler to the use of agent technology in power applications [1], [2]. The objective in this work is for the LAs to be responsible only for load management, giving directions and references to the device level control. The LA should be oblivious of any other computation that makes use of local data. The use of a MA within the multi-agent platform helps addressing the aforementioned problems. The MA moves on the network visiting all nodes that carry LAs and communicates with them to extract, and locally elaborate, the data. This helps the reduce the number of messages that are exchanged to request and receive the high volume data and priority values. In this sense, the trade off between the burden of circulating the MA with reduced data and the burden of communicating data directly is a design parameter. Also, functionalities like priority level calculations or operating condition assessment, such as power quality indexes, can now be a part of the MA. Any new such functionality can be potentially incorporated in a MA. The need to change LAs is now eliminated.

The authors are working on two testing platforms. The first platform is an agent-in-the-loop environment, where the physical system is simulated while the agents are executed on their actual final target. The second platform comprises the same agent set-up but this time controlling a physical system. The agent-in-the-loop platform has been developed for the purpose of testing a MAS in its final implementation, with all the actual hardware and communication constraints, while controlling a simulated power electronic system. The simulated system interfaces the MAS through a Simulation Agent. In [11], the Simulation Agent (SA) was introduced, together with its ability to answer the request of other agents (in particular the Monitoring Agent). The SA accepts input data, from measurement and control systems (physical measurements, control parameters) and can enforce schematic parameters and/or simulation parameters; also, the SA provides data to the measurement and control systems in form of simulated voltages and currents. In this case study, the features of the SA have been integrated with the LA. Each LA controls its own simulation representing the actual physical system. However, each LA acquires data for a different load from its simulation. All LAs load the same schematic for simulation with the same time step. They also control the stepping of the simulation in exactly the same manner, for example, each LA steps the simulation 50 time steps before it starts acquiring data. Thus at the time of data acquisition, all simulations associated with each LA are synchronized and give consistent data values. As a consequence, the agents behave as if they acquired data from a physical controlled system. Thus all the effects of communication delays and bottlenecks are visible. This allows for the testing of the upper level agent-based control
architecture with no immediate need to operate on a physical system from the early stages on control design.

This work demonstrates the use of MAs as support in dynamic reassessment of the load priority. In particular, the dynamic load priority is assigned based on the power quality impact of each load. This characteristic is evaluated by analyzing the instantaneous power in the Park domain, as proposed in [7] and [8]. The authors use the Java Agent Development Framework (JADE) for development of the multi-agent system, including the MA. The LAs register themselves in the AMS with an index number. Each LA resides in a separate machine.

In Figure 3, the scheme of LAs controlling simulated loads is depicted. The simulated controlled system is based on the model of the physical system that is the final target and is shown in Figure 4. Notice that in this scheme is simplified since it was built for the purpose of generating data for the calculation of power quality conditions.

![Figure 3: scheme of the agent-in-the-loop configuration, the simulated data are obtained from the Virtual Test Bed (VTB)](image)

When the controlled system is simulated, each LA acquires the voltages and currents at the terminals of its own load from the simulation that it controls and sends the reference signal to the device level control. When controlling a physical load, the LA acquires current and voltage at the terminals of its own load from the device level controller, that is realized with a DSpace platform.

The primary objective of the LAs is to accommodate the feeding of loads with highest priority levels, making sure that low priority level loads are not interfering. This results in the voluntary decision, taken by the LA, to reduce or cut its own load if its own load has the lowest priority while the total power demand is exceeding availability. This behavior acts in the direction of supporting the operation of the most critical loads. The load priorities may be static or dynamic. Static priority levels are assigned once and for all, while dynamic priority levels change with the operating conditions or with time.

In a three phase AC distribution network, each load affects the operation of the other loads depending on its own power demand and depending on the power quality perturbation it introduces. In previous work, [8], [9], the authors used run-time information on the power quality perturbation introduced by each load as a punitive factor in deciding which load should be sacrificed in case of need. In particular, the authors assumed that the load negotiation based on pre-assigned priority levels had resulted in multiple loads in a tie condition. A second priority level then had to be computed for the LAs to reach an agreement on the identity of the load with the lowest priority. This second priority level was based on power quality indexes, indicating the nature of the load in terms of linearity, unbalance and non-linearity. The meaning of the power quality indexes and their calculation are described in detail in [8], [9]. The calculation of the power quality indexes requires the acquisition of voltage and current at the load terminals. In the agent system described in [10] and [11], this data acquisition and elaboration was performed by the Monitoring Agent upon request of the LAs. In particular, the Monitoring Agent took care of executing a dedicated Virtual Instrument in LabVIEW. The resulting power quality indexes were elaborated in terms of priority levels and were sent to the LAs, enabling them to decide which was the load with the lowest priority level.

The architecture mentioned above, presents some weaknesses that can be addressed with a different approach based on MAs. In first place, all the data acquisition and elaboration burden fell on the Monitoring Agent. This may constitute a single point of failure, also, much of the data acquired by the Monitoring Agent are actually known by the local control of each load. Notice that, deciding whether or not this weakness is critical, depends on the granularity of the agent control, the size of each agency and other design specific choices. In second place, if certain functionalities (such as power quality indexes calculation) are to be distributed, then, in a static structure, they should reside with the LAs. In this case, each new functionality represents a customization of the LA features. This choice is not in the direction of reusability and of standardization of fundamental types of agents for power system applications. The approach proposed here, relies on the use of MAs for these additional functionalities, in particular for the computation of power quality indexes at load terminals.

The MA moves from one node to another and exchanges information with the resident LA to calculate the power quality index for that load.
A schematic representation of the case in which the controlled system is physical, is presented in Figure 5. The Simulation Agent is not present. The LAs have local access to the physical loads through the control platform from which they can get current and voltage readings and to which they can send control signals. The LAs support a local circular buffer to store the readings and are willing to transfer them to the MA at its request. The remaining operational features are the same as in the case of the simulated controlled system. Figure 5 shows the architecture and Figure 6 shows the migration of the MA. The internal state of the MA is depicted right after the computation of the first set of power quality indexes of Load 1. This portrait of the migration of the MA represents its operation either on the simulated loads or on the physical loads.

III. THE INTEGRATED OPERATION OF THE LOAD AGENTS AND THE MOBILE AGENT

A. MobileAgent configuration

The Agency consists of the LAs, with their local database, and the MA. In this system each LA resides on a different computer and is capable of starting and controlling the simulation of a power distribution system. The load agents differ in the fact that they retrieve data from a different load on the simulated power distribution system.

The database associated with each load agent is a local MySQL database setup on each computer on which the agent resides. The agents interact with the database through a JDBC driver for the MySQL database server. The LAs store the retrieved current and voltage values in their own database.

The mobile agent is structured to move from one LA to the next, interacting with them and using its own algorithm to process locally the stored data to calculate the power indices for unbalanced power and distorted power for each load.

B. Integrated Operation

The mobile agent initiates the operation by requesting all the load agents to start acquiring the three phase line current and voltage values for their respective loads. In the scenario of the simulation, this acquisition is synchronized because the the simulation is executed with the same step at all locations and it is started with the same initial conditions. And this is practically achieved thanks to the fact that the simulating environment for the power system, the Virtual Test Bed (VTB), [3], [5], is controlled by the LAs. Each LA gets VTB to load the simulation scheme in the “steppable” mode, which allows the load agents itself to control the stepping of the simulation with a specific time step and to perform the required number of steps. Thus each LA starts acquiring data for their respective loads at the same time from the simulation. When this architecture is applied to a physical system, each load agent acquires data from the local hardware load. Notice that, since each load agent in charge of managing its load, we assume it has access at least to terminal quantities and also possibly to other internal quantities. In this case the synchronization of data collection must completely rely on time stamps assigned to each data acquisition set. The potential issues in this case, are related to the lack synchronism of the absolute time at each load agent and the possible jittering of the local clock. Notice though that, instead, the issue of start acquisition time for each data set can be overcome by acquiring sets of data larger than what is needed and picking the set that starts with the desired time label.

In this application, each load agent collects 512 samples of current and voltage values for all the three phases of the power distribution system and stores them in the MySQL database. The time step of the simulation is controlled in a way that the 512 samples cover one complete period of the waveform. The name of the load associated with these samples is also stored in the database. For each command that the load agents receive from the mobile agents for acquiring data, the load agents create a new database table for string values. Each new table is named using the unique Conversation-ID from the Request message sent by the MA. Thus, when the MA starts hopping from one load to another retrieving data from each load agent database, it knows which
table stored the latest current and voltage values. Figure 7 shows a screenshot of an agent mobbing to a new location.

In this application, the MA is equipped with an algorithm to calculate the unbalanced power and distorted power for each load in the system. The MA can be reprogrammed before a new deployment to satisfy a different purpose without changing the entire multi-agent system. The LA remain generic and can keep performing the same functions. The MA can also interact with the local database for each load. Thus, it can retrieve the latest current and voltage values depending on the latest Conversation-ID. Figure 8 shows the screenshot of the LA calculating new power indices for load 2.

At this point, the decision to shed or reduce one load can be taken locally. Figure 9 shown the updated and labeled worst values in the mobile and local agent.

Some comments on the synchronization issues in the physical setting are herein provided. In the scenario where a physical system is controlled, different design choices can be made. Wishing to maintain full local awareness and readiness, the LAs should continuously acquire data, and be ready to provide these data to a visiting MA, or to other agents if needed. Each agent should thus label the acquired data with a time stamp and be ready to retrieve them. Under the assumption that the initial acquisition is started in a synchronized manner, and that the number of data points in each acquired set remains constant, then we assume that assigning one time label to each data set is satisfactory.

With the MA operational steps followed in this work, the LAs must store enough buffers of data, $N_b$, to allow the MA to complete the tour of the three LAs computing the indexes based on sets of data acquired in the same times (within certain limits). Thus, assuming it takes $T_LA$ for the MA to dialogue with each LA, exchange data, compute the indexes, update the local state and its own and reach the next LA, assuming a buffer of data is acquired every $T_s$, assuming there are $N$ loads in the system, each LA should store at least $N_b$ sets so that $T_{LA}N=N_bT_s$.

IV. CONCLUSIONS

An architecture for the integration of a MA in a multi-agent system for power electronic systems control has been presented. In particular, the MA is used to identify polluting loads based on the power quality impact of each load. The MA approach allows for the introduction of additional functionalities in a multi-agent system with no need to modify existing agents and limiting the data exchange by exploiting local computation instead. The authors intend to develop a metric to support design decisions on the integration of MA in this type of multi-agent systems.

The frequency at which the mobile agent tour the network looking for the worst unbalanced loads or loads that cause power distortion, depends on the dynamics of the system. For systems with slower dynamics, the agent system can afford more time to isolate the power polluting load.

It can be safely concluded that while the calculation of the power indices is extremely fast, data acquisition and the time taken by the mobile agents depending on the traffic on the TCP/IP network are the factors which may cause bottlenecks for the agency operation. These limiting factors vary depending on the type of the hardware platform for the agents, the type of data acquisition system and its efficiency and can be overcome depending on the availability of better resources.
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