Towards a New Fully-Flexible Control Approach for Distributed Power Electronics Building Block Systems

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Abstract- In this paper, we propose a novel control architecture for a complex power electronic system. A ship power system is studied in particular; however, the control architecture can be generically applied to any industrial power system. The work is founded on the substantial progress made during the 1990s with respect to standardization of power cell structure by use of the Power Electronics Building Block (PEBB) concept. Now, it is time to build new control concepts to fully exploit the standardized power hardware. The nascent IEEE Guidelines on Control Architecture for Power Electronics in Power System serve as a basis for proposing a new approach to the design and implementation of a power control system. The new concepts are described and analyzed in the context of a network-based control architecture that is under development in our laboratory.

I. INTRODUCTION

For many years, power electronics was widely considered as much an art as a science. Every new application required a new design, which in turn required extensive analysis of parasitic impedances, thermal management, and switch timing, all in an effort to better exploit the available semiconductor technology. Thanks to the US Navy All Electric Ship initiative, substantial progress was made towards standardizing power stages in the form of Power Electronic Building Blocks (PEBBs) [1][2][3][4][5]. The PEBB concept is now widely accepted and adopted, and many companies now describe their power converters as “PEBB-based” or “PEBB-like”[6][7]. Full implementation of the PEBB concept though, requires a yet higher level of standardization that reaches beyond the power stage; the plug and play philosophy that is the cornerstone of the PEBB concept also requires standardization at the control level. Efforts in this direction have been started under the initiative of IEEE Working Group PAR1676 which is currently drafting guidelines for standardization in this area. In the rest of this paper, the philosophy of that document will be used as a basis for defining what could be done at the top (control) level to fully exploit the flexibility afforded by standardization at the low (hardware) level. Several previous works [8][9][10] showed how standardization at the low level can be easily obtained. The new IEEE Guidelines will allow us to precisely understand the interfaces that are available at a higher level. More attention should be given to focus on the system level to define a new paradigm for control design. The approach described in the rest of this paper is founded on the use of mobile agents to achieve a high level of flexibility in both the power processing and information processing capabilities of these future power systems. The authors believe that the pervasive use of power electronics in power systems will enable radically new approaches to energy management. Such approaches may find immediate applications in ship power systems because they are isolated in nature. It is also quite reasonable to believe that such an approach will eventually become the paradigm for terrestrial power systems, where the future lies in a tight interaction of communication, information and power.

II. A DIFFERENT VISION FOR SHIP POWER SYSTEMS

Figure 1: A simplified view of a future naval power system.

Figure 1 shows a highly simplified schematic of a possible structure for the power system of a future battleship. The main element we want to focus on is the pervasive presence of power electronic converters that determine the interfaces between different areas or zones of the ship. Eventually, we expect that every single load will be connected to the power distribution system through a power electronic interface that...
contains substantial processing power. Every PEBB is controlled by an embedded hardware platform, a PC with control channels or other control platforms. Therefore, the power system is an interconnection of intelligent elements that are able to collect information, elaborate information, take independent actions, and communicate and cooperate with other elements to reach global maximum benefit. Such an idea is summarized in Figure 2 in which we highlight how each converter can be considered to be an intelligent element able to perform measurements on the system, elaborate those measurements, communicate with other power converters, and control the flow of energy at its terminals. Depending on the operating condition of the system, one or any combination of these functionalities can be active. The flexibility of the PEBB structure creates the conditions for which is possible to control the energy flow in a way that can vary from situation to situation. This flexibility extends the concept of a PEBB in a more radical way. While one can currently purchase single-purpose PEBB-based power modules that come pre-loaded with application-specific software, in the future, the software of these devices needs to be able to be dynamically loaded so that the function of a power module can be dynamically reassigned.

At any given instant the drive may be either active or non-active. Whenever the drive is operating, it functions as a regular AC drive so that the InputPEBB works as an active rectifier and the OutputPEBB works as a variable-frequency inverter. If this drive powers something like a bilge pump, for example, it might be non-active most of the time so that its power processor and information processor will be under-utilized. Thus, when the drive is not operating, some other options to use its power electronics and its digital processor become available:

1) The InputPEBB could operate as an active filter to benefit the rest of the power system.
2) The system could operate as a distributed energy resource if its DC link capacitor is sized appropriately.
3) The system could operate as a temporary power generator if a pulse load, such as a laser weapon, is started and needs large energy in short time.
4) If no specific power processing is required, then the signal processing capabilities of the controller could be used to solve tasks that benefit the rest of the power system (such as state estimation and power quality monitoring).

One piece of power processing hardware can play many different roles if it is designed so that it can run different application software at different times. Thus it is imperative to carefully define the control interfaces and architectures to support this versatility.

III. THE IEEE STANDARD AND THE CONTROL LAYERS

The IEEE Guide for Control Architecture for High Power Electronics takes a significant step towards standardizing the control architecture by defining specific control layers. Common control layers, as shown in Figure 4, include a system control layer that determines the overall mission of the system, an application control layer responsible for maintaining overall functions of the power electronics, a converter control layer that implements many common functions of converters, a switching control layer that handles the switching logic/sequence, and the PEBB hardware control layer that manages everything specific to the power hardware. Each layer has characteristic processing and communication-speed requirements, irrespective of the final applications [11].

The three lower layers, the PEBB hardware, the switching, and the converter control layers, are mostly hardware dependent. Two more layers are defined higher up: the application and system control layers and these are the focus of the work discussed here. The application layer defines exactly what the converter does for the system, while the system layer integrates the converter action within the system architecture. Assuming that the interface between the application layer and the converter layer is properly defined, the same converter control can operate with a different application layer so that this layer does not need to be specified a priori. In effect, from the point of view of the application layer, the lower levels are supposed to behave as...
controlled voltage or current sources. From this level of abstraction, it is possible to assume the automatic plug-in of different control algorithms as detailed in the following section.

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**Figure 4: Control architecture for PEBB-based power electronics [11]**

**IV. MOBILE AGENTS FOR FLEXIBLE CONTROL ARCHITECTURE**

In order to reassign tasks to PEBB’s dynamically, a flexible structure for the control system is critical. For this reason a network-base structure is proposed.

Some commercial PEBB systems, which embed the three lower level control layers, support network structure; one example is the PEBB module (PM1000) of America Super Conductor. The communication channel for the PM1000s is CAN bus. A commercial CAN/Ethernet bridge can be used to expand the CAN bus to an Ethernet network.

Based on these devices, a network-based structure can be built (Figure 5). In the structure displayed, stations stand for hardware platforms running the system and application controllers. The stations can be standard PCs or embedded systems with Ethernet interface. The PEBBs can be any standard PEBBs with CAN Fieldbus interface.

In this structure, the tasks running on stations can be assigned dynamically and are not combined with a specific PEBB. As result of that PEBB1 can be controlled by controllers on station 1 at time point 1 and then by station 2’s controller later. In addition, the controllers on one station can control several PEBBs at the same time if the PEBBs connect the same loads and run in the same status. With this approach a complete plug-and-play can be achieved.

**Figure 5: Network based control structure**

To further increase the overall flexibility of the system the application and system layers are implemented by means of agent-based technology. This solution, as better detailed in the following, allows the designer to easily reconfigure the functionalities of every station even at run-time.

**A. Mobile Agent**

A mobile agent (MA) is the composition of software and data that can move from one platform to another autonomously and continues its execution on the destination computer. There are several advantages to using the MAs in the power system:

- Reduce network traffic: The MAs process data locally instead of exchanging data frequently in server-client mode or distributed mode. Using mobile agent technology can save network bandwidth for more important data or commands, and therefore the performance and response time of the whole system can be improved. This characteristic is important when the power system is in an emergency or damaged condition.
- Work in unreliable network environments: In the past, for client-server mode, a relatively static and reliable system structure was needed. However, the mobile agent technology might support disconnected operation.
- Realize flexible maintenance: For updating system’s software, the MAs are updated, thus eliminating the need to update every station. With this characteristic, the plug and play philosophy of PEBB with control may be fully demonstrated.
B. Control architecture based on mobile agents

Following the previously described approach, each converter, including its intelligent processing unit, can be in one of the three possible states (Figure 5):

- **Available**: The power converter is not currently utilized, and no computing task has been assigned.
- **Computing**: The converter is not currently utilized, but the processing capability is used by the system to accomplish some specific task, such as signal processing and system monitoring.
- **Controlling**: The converter is accomplishing a task involving power management. Current references are generated for the lower-level layers.

In each of the active states, i.e. controlling and computing, the system could allocate different tasks to the converter in different situations. These tasks will assume the form of mobile agents.

In the system studied, the task is defined by the code to be executed. This solution allows for complete flexibility in the definition of the control algorithms and easy maintenance and updating of the software itself. A higher priority is given to the state of controlling than to computing; if the converter is in the controlling-mode, it will not be interrupted to execute computing tasks, though computing tasks can be interrupted by controlling-mode requirements. For safety reasons, each code must be validated before it is activated. One possible solution to validation is to provide each intelligent element with a reasonable model of its environment and a procedure to update the model itself. Figure 7 summarizes the software architecture here introduced. The lower layers are for standard control functions. The upper layers are where an intelligent local agent (LA) manages communication with the rest of the system and is in charge of accepting or rejecting mobile agents that wish to use the local structure.

The LA logic, which cooperates with the MA, plays an important role in the whole system. For the example power system, the LAs should be assigned the following information and functions. These functions can be easily modified for different systems.

![Figure 6: Finite State Automata for the Application Level Control](image)

![Figure 7: The complete software architecture of a reconfigurable power converter that uses agent technology](image)

**Information:**
- Local load type and power information: For example, the LA must know which electrical device is connected, an electrical drive or passive load, and what the power range is for the local load.
- Bus connection of PEBB’s two terminals: i.e. AC/AC, DC/AC, DC/DC, or AC/DC.
- Configuration/status: For example, in the first time-step, PEBB works as an inverter. The configuration may change when LA logic decides that PEBB should work in a different status, for example a converter.
- ID number and static priority of every LA in the power system: These numbers should remain constant.

**Functions:**
- Communicate with other agents.
- Negotiate with other agents.
- Monitor the health status of the power system.
- React to abnormal situations: For example, the LA is able to judge local abnormal situations arising from disturbances or serious damage.
- Make decisions independently, such as:
  - Call a MA.
  - Protect data and information when the work of the MA is interrupted by some other higher priority event.
  - Change current status.
  - Calculate dynamic priorities: For example, based on power quality, the LAs can compute their current dynamic priorities. Combined with static priority, these dynamic priorities can be used as a second criteria when some loads need to be shed in damaged condition.
  - Isolate PEBB itself from the power system if damage occurs or if local load may hurt or pollute the health of the power system.

The three lower-level controls should be standardized, and the two upper levels should be customized. This scheme offers flexibility to PEBB’s applications without having to take into consideration the control of the lower layers.
V. LABORATORY SET UP AND IMPLEMENTATION

The software/hardware architecture introduced in this paper has been developed in our laboratory. A baseline power-system structure has been defined as shown in Figure 8. Each of the elements identified as a PEBB is PM1000. PM1000 has embedded control boards and communication channels. The PM1000 interface to CAN fieldbus network by its fiber channel and the CAN fieldbus interface to Ethernet by Eth/Can bridge.

![Figure 8: The structure of the hardware for investigation of flexible agent-based control methods](image)

A sub-power system (Figure 9) is building to demonstrate several functions of the MA and LAs.

![Figure 9: A subsystem to study the functions of the MA and LAs.](image)

In this sub-power, the priority of the DC motor will be lower than that of the passive load.

In order to de-risk the technology this system is simulated in Virtual Test Bed (VTB) [12][13] as shown in Figure 10.

Notice that while the power system is simulated the agents are actually executed in their final target machine. This step can be considered an intermediate step before final deployment to the power system where the agent software is carefully tested while running in the final target.

![Figure 10: Simulation schematic of the subsystem](image)

The simulation scenario is described as follows:

1. PEBB I works as a DC-DC converter to control the speed of the DC motor, and PEBB II works as a DC-single-phase inverter (Figure 10).
2. Switch 1 closes simulating a short circuit condition in parallel to the main source.
3. PEBB I's LA (LA 1) detects the faulty condition and calls the MA (Figure 11).
4. The MA arrives and determines whether the error is true. If the error is verified, the MA tells LA 1 to open switch 2 to isolate the DC power source. In order to direct the DC motor to work as a DC power source to supply the passive load, the MA tells LA 1 to assign a negative value for the current reference of DC motor controller. Because the MA works with LA 1, the information of the MA prints out at same screen with LA 1 (Figure 11).
5. LA 1 executes the commands and tells the MA where to go next (Figure 11).
6. The MA moves to LA 2 and decreases the reference value of the passive load. Instead of shutting down completely, the passive load steps down to a lower power level, which is useful for emergency situations (Figure 12).
7. The MA moves to next station.
In the process described above, the capacitor on the DC bus must be large enough to supply the passive load before LA 1 and LA 2 perform any changes.

In this simulation, two PCs running the same schematic are used to represent the two PEBBs separately. In step 4, the MA moves to PEBB I’s PC and in step 7, the MA moves to PEBB II’s PC. Figure 11 and Figure 12 show the LAs and MA’s activities. The simulation plots show that an error occurs at time 0.01 second because the switch 2 creates the faulty condition: the current of the DC motor changes to -20A and then DC motor works as a power source (Figure 13). In the process of delivering energy the speed of the motor decreases (Figure 14). The communication channel and protocol between the two PCs are Ethernet and TCP/IP. The MA and LAs codes are written by JAVA and Jade.

Here, only the subsystem (Figure 15) is set up to demonstrate a couple of the LA and MA’s functions.

The experiment steps are:

1. A DC source powers the PEBBs. The PEBBs controller boards can communicate with their LA’s PCs. At the initialization, the PEBB are in stop status.
2. Two PEBBs are initialized. This processing includes:
   - assigning a CAN address for each PEBB.
   - setting up parameters for control loops.
3. The PEBBs begin to run when “Start” command is given.
4. The LA of every PEBB reads variables from PEBB’s controller boards and LA changes the speed reference of DC motor.
5. The PM1000 has on-board sensors to detect the voltages of its DC bus and Legs. If the DC bus voltage is lower than pre-set value, LA1 detects this error and calls the MA.
6. The MA arrives and if error is verified by the MA, the MA will tell LA1 to open switch 2.

The structure of the MA is shown in Figure 16. At very beginning, a dummy agent tells MA where the MA should move to. In this experiment, the MA should move to LA1 first. After MA finishes its job in LA1, LA1 tells the MA to move to LA2. LA2 will address MA what is its
next station. Dummy agent is only for the first jump and the MA will not go back to dummy agent again.

VI. CONCLUSION

This paper presented an innovative control architecture for a complex power electronic systems. The concepts were described and analyzed in the context of a network-based control architecture. This developed work references a ship power system, but is generically applicable to any industrial power system.

VII. ACKNOWLEDGMENT

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