Integrated Simulation of Communication, Protection, and Power in MVDC Systems

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***Abstract*—We present an integrated approach to design and simulation of the Protection Management System for a Medium Voltage DC distribution system. A new model-based approach to the design process integrates representations of the communication, control and power systems. A co-simulation approach is used, incorporating three best-in-class tools -- the Virtual Test Bed for representation of the dynamic system, Simulink for representation of the controls, and Opnet for representation of the communication network. Using this new framework, we explored the performance of a new two-level alarm system including consideration of the communication constraints.**

I. INTRODUCTION

Nowadays the distribution of electrical energy in naval applications is primarily based on AC-systems with any DC-bus used only to supply relatively smaller loads at low voltage. In the last few years, mostly under the impetus of the US Office of Naval Research, several groups have begun to consider the use of a medium-voltage DC distribution bus. This represents a dramatic change in the management of power distribution and creates new unexplored challenges, particularly related to protection and control.

Protection of multi-branch medium-voltage dc-systems (MVDC) is one of the most important challenges because this kind of power distribution system is different even from two-terminal (single-branch, end-to-end) high-voltage DC systems (HVDC) that have long and reliably been used in intra-continental bulk power transmission. Protection systems for these proven HVDC systems rely on coordination between power electronic converters and AC-beakers. In contrast, protection in multi-terminal MVDC plants is more challenging because interruption and isolation of any fault must not isolate any healthy area, especially those loads that are designated as vital. Many of these vital loads, such as motors on fire pumps, are directly linked to the DC bus through power converters. Loss of the bus would then be a critical failure.

An enabling technology for MVDC is the availability of modern dc circuit-breakers [1][5]. These breakers together with proper intelligent relays, can permit independent protection of each zone of a system so that a fast detection and isolation of the fault is possible. But this entails a rapid communication between sensing, control, and power devices. The performance and efficiency of the protection system can also be improved by exploiting the use of power converters and Power Electronic Building Blocks (PEBB) to directly interrupt or limit fault currents [2][4].

As shown in [2], the shipboard plant can be divided into several zones, linked together at the DC-bus through power converters, which also have the task of protecting the zone that they supply. For this kind of system, smart agents, embedded with the power converters, can assure the selectivity of the protection system, based on different action thresholds for the various cascaded devices [6].

Starting from these assumptions, this study addresses the design of the protection system for a MVDC application by integrating a model of the electric power network with a model of the communication system. The performance of the communication system is a vital determinant of system performance because it conveys the information that must be exchanged among the various PEBB devices.

The design of these two elements of the power system (power and communication) cannot be performed independently; an integrated analysis is fundamentally important to a successful design.

The model-based design reported here follows the IEC 61850 [7] communications standard recently developed for automation of substations in terrestrial power systems. As described in [7] and [8], the use of an Ethernet physical layer brings significant improvements in the real time performance, which opens the door to time-critical applications such as protection.

Integration of the communication infrastructure into the power system allows effective management of abnormal

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Figure 2: The ship power system

situations, and creates a new way of conceiving the protection as an active element that contributes to the security and reliability of the ship.

Therefore, considering the PEBBs and the related protection software as Intelligent Electronic Devices, (IED) whenever a change of the operational status is detected, decisions can be made not only on the basis of local information, but also on the basis of data communicated by peers.

II. MODELING STRATEGY

The integrated design process is supported by a co-simulation strategy that uses three best-in-class tools:

- the Virtual Test Bed, to represent the power system
- Simulink, to represent the reconfigurable control architecture
- OpNet, to represent the communication network.

Interactions among to the tools are summarized in the following picture.

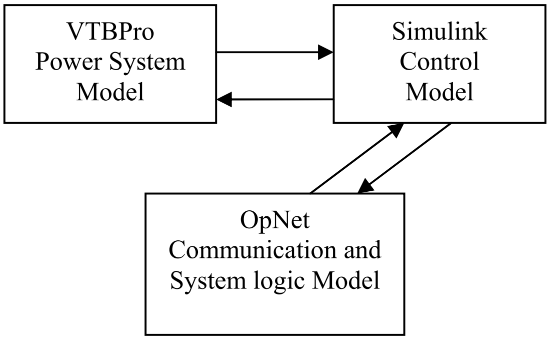

Figure 1: Co-Simulation architecture

This architecture allows the designers to work independently in the early stages of the design and at the same time to easily integrate their work when it comes time for system testing.

Notice that each tool talks directly to only another tool. This approach dramatically simplifies design of the software interface.

At the current stage, the co-simulation is performed according to the following structure:

1) the power system is designed in VTBPro. The schematic is then exporting using the C-code generation feature of the newest version of the tool

2) the C-code generated by VTB is imported into Simulink by means of an ad-hoc S-Function written in C

3) The Simulink schematic is designed and equipped with an interface port to support communications with OpNet

4) An ad-hoc OpNet model is used to periodically step Simulink. In very simple words, the Simulink model execution is integrated in the event-based OpNet simulator, thereby creating a periodic event.

III. SHIP POWER SYSTEM MODEL

The grid presented in Figure 1 shows five areas linked together by two bipolar busses, one for port side and one for starboard side. The busses operate at 5 kV DC, in particular the plus pole has +2.5 kV and the minus pole -2.5 kV. Areas 1 and 2 constitute the power supply, while the remaining areas are load zones. Area 5 contains a high power load while Areas 3 and 4 are low voltage zones, each fed by two secondary dc busses.

Let us now zoom in each of the area to describe the implementation details. In the power supply area, a three phase generator feeds an AC/DC converter based on two conversion stages: the first stage is comprises two diode bridges that supply two DC/DC switch mode resonant converters that are represented by two switching-average models of buck converters. This design increases the efficiency by limiting power losses and allows galvanic isolation between the AC and DC sides. The buck converters permit controllability of the output voltage and current. The converters are connected in series on the dc side and the junctions between them are grounded to realize the bipolar links.

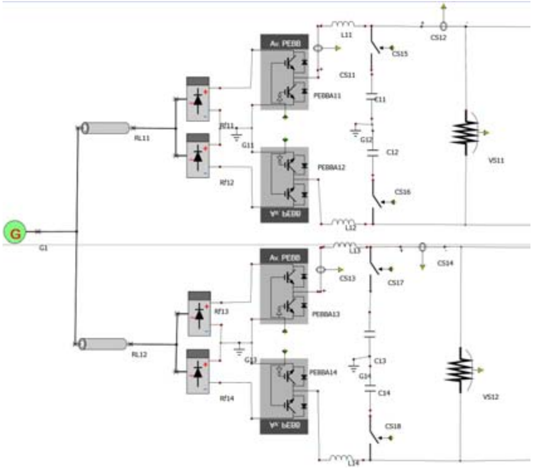

Figure 3: Power Supply area

The switching-averaged models of the buck converters obviously do not produce any switching ripple, but the LC second order output filters do present dynamics that are important in assessing the effectiveness of the protection scheme. These filters have been designed to give 80 dB suppression at the 1 kHz switching frequency which leads to a cut-off frequency at 10 Hz. Every capacitor is also provided with a DC circuit breaker that prevents current from flowing into a fault.

For each group of converters the following measurements are acquired: the inductor current, the capacitor voltage and the output current. These are sent to the controller, which is represented within Simulink.

In Figure 3 are represented two groups of conversions, one for each bus. This scheme refers to the bow section but it is the same also for the one in the astern.

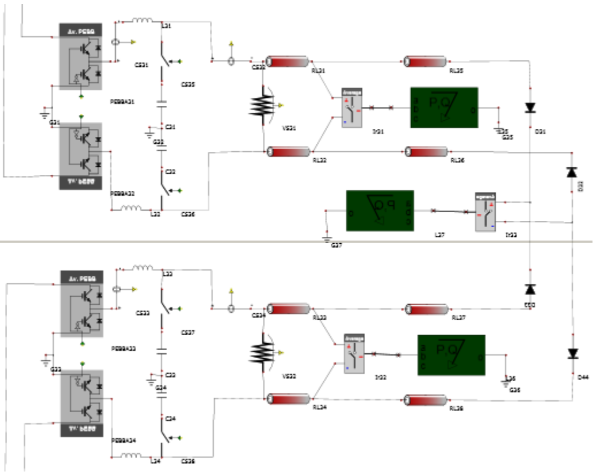

Figure 4: low voltage area

Power Electronic Building Blocks (PEBBs) have been employed to represent the step-down converter. As it was shown for the rectifiers, two PEBBs connected in series create a bipolar 800 V DC link. In this case the LC filter is designed for the 10 kHz switching frequency of the PEBB. The data acquired for the control system are the same as in the previous stage.

Each bus feeds two kinds of loads: vital loads (100 kW) and non-vital ones (50 kW). A vital load can be supplied from either the starboard bus or the port bus but not by both buses at the same time. Auctioneering diodes affect this function. The two buses are kept at different voltages (800 V-750 V) so that if a contingency occurs on the primary bus that causes the voltage to drop, then the auctioning diode allows the load to be picked up by the secondary bus. By increasing the output voltage of the backup converter, the load can be reinstated to full operating voltage. The loads are represented by an ideal inverter that feeds a constant power three phase load (this could represent a low power drive such as a pump).

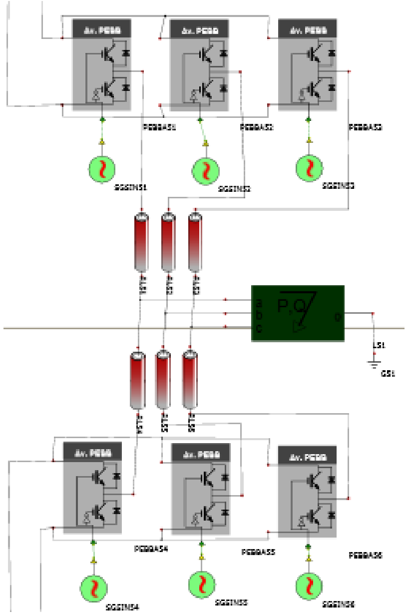

Figure 5: high voltage area

In the high voltage area, three PEBBs have been used to define a three phase inverter. These are again switching average models controlled by three sine wave references shifted by 120° one from the other. The load is modeled by another constant power component. The rated power of this load is 20 MW and represents one of the propulsion motors of the ship. This motor is fed from both the buses in order to split the current and to minimize voltage losses.

IV. RECONFIGURABLE CONTROL MODEL

As described before, the two main buses are fed through a power conversion stage consisting of an ac-dc conversion and a dc-dc buck conversion.

The first stage (i.e. ac-dc conversion) is made by an uncontrolled diode bridge. The second stage consists of a dc-dc buck converter made based on power electronic building block (PEBB) modules. This buck converter permits regulation of the system voltage and control of the output current while at the same time providing protection features thanks to a reconfigurable control architecture.

An averaged model of the buck converter is the PEBB element used in the VTBpro schematic which receives the rectified voltage and the desired duty cycle as inputs, and provides an ideal dc-dc conversion at the output port.

This power converter has a switching frequency of only 1kHz, considering the very high rated power. Notice that, because an averaged model is used, this step down converter could at the same time represent either a traditional buck topology or a more-sophisticated resonant converter, based on suitable choice of the parameters. In this second case, this stage could provide also galvanic insulation as described in the introduction.

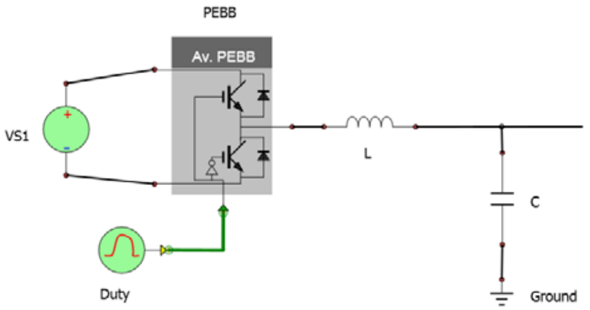

Figure 6: Converter implementation in VTBPro

So the task of the system control is to provide an appropriate duty cycle to the PEBB element in order to satisfy the desired requirements of voltage regulation and output current control. A proper coordination of the two loops can also provide protection features in the system control. In effect, four working conditions have been identified:

- Normal condition: no faults or overload are detected by the control system; hence the voltage control only operates to establish the pre-defined voltage at the output of the PEBB and the current is within the normal limits.
- Low-risk level: the devices detect an anomaly that is not classified as a failure. The control system acts to maintain the operating voltage at its rated value with a fast and stable response and the current itself is maintained within secure levels.
- High-risk level: the device that detects a failure acts instantaneously without waiting on any other communications. This immediately reconfigures the PEBB to operate in current-limiting mode.
- Overall protections: the gate signals are inhibited and the converter completely disconnects.

Figure 7 represents the control system for the buck converter.

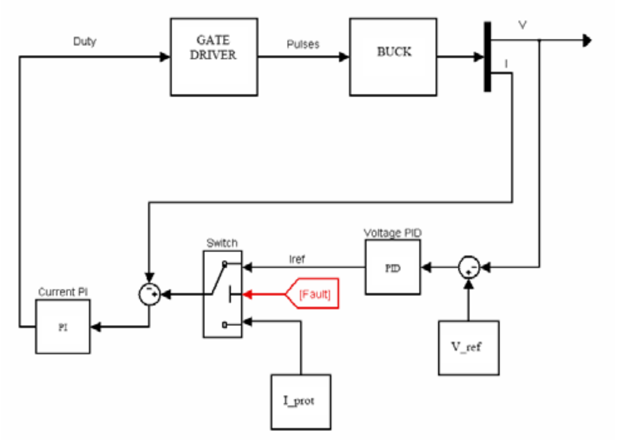

Figure 7: Control Schematic

There are two loops: the first is the voltage-external loop and the second is the inner-current loop.

Voltage loop: the output buck voltage is compared to a reference value thus generating a signal error. The Voltage PID provides a feedback control signal which is a reference value for the output current. The Voltage PID increases the phase margin at the crossover frequency of the voltage loop providing stability and increases the low-frequency loop gain such that the output voltage is better regulated at dc and at frequencies far below the crossover frequency.

Current loop: the comparison between the measured current and the reference current gives an error signal which is processed by the Current PI controller thus obtaining the averaged duty cycle; the gate driver provides the pulses for the converter.

The switch shown in the bottom of the schematic allows the switching to current-limiting operation.

When a high risk level event is detected, a signal from the communication and protection system is sent to the switch in order to limit the fault current and to prevent damage to the converter.

The possibility of using the buck control system for protection leads to a higher survivability of the electric plant. The voltage control loop assure maintenance of the rated voltage in every normal and non-fault situation, while the current control loop limits the output current when a dc bus fault occurs.

V. COMMUNICATION INFRASTRUCTURE MODELING

Considering that the communication introduces delay in the reaction time of the system, it is important to design of the protection architecture consider the several different levels of risk. At least two levels must be considered:

- High-risk level (corresponding to the third and fourth operating modes of the converter): the device that detects the failure acts instantaneously without waiting any other communications.

- Low-risk level (corresponding to the second operating mode of the converter): the devices detect an anomaly that is not classified as a failure. Since they are unable to make an optimal decision, they exchange data with neighboring devices about the type of anomaly detected in order to reach a shared solution. During this stage, the device automatically switches into a state of alert, waiting for a final decision.

The category of risk is identified by analyzing the following characteristics of a given waveform:

1) peak instantaneous value

2) wavelet-based analysis of the transient waveform

The combination of these two key elements allows reaching a higher level of selectivity. The idea is to identify different thresholds for the peak instantaneous values able to trigger different operating modes of the protection devices:

1) highest threshold: immediate protection, reconfiguration of the power electronic devices to operate in current-limiting operation

2) one or more minor thresholds that triggers the time-frequency analysis and the data exchange with the neighbors.

While the first level deals with the classical idea of protection, the second level introduces the possibility of managing more complex situations or also to detect incipient faults.

A. Communication architecture simulation

The communication delay is estimated using the discrete event simulator Opnet Modeler 14.5 (see Figure 8).

Simulation models are divided in hierarchy that consisting of three main levels: Starting from the bottom there is the Process Model, that consists of Finite State Machine (FMS), C code and ProtoC function that define how the process is able to react to an event that happens in the system, and where is possible to characterize the connection with the other process. The second level is the Node Model that is an organized set of modules describing the various functions of each node. Each node is implemented by process model. The top part of the hierarchical construction is the Network Model that defines the network layout and characterizes the node attributes for a particular scenario.

Opnet permits extension of its library and so it is possible to call Matlab functions directly from the process model.

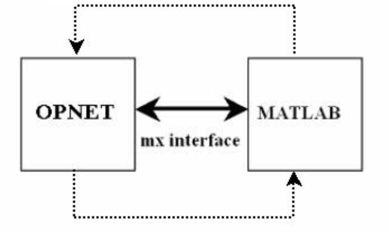

Figure 8: OPNET Matlab Co-Simulation

Communications are based on IEC61850 GOOSE messaging (Generic Object Oriented Substation Events). This choice has several features that are important for the system. First of all, the message is directly published on the Ethernet layer and there is the possibility of choosing the priority level to move the message at the beginning of the queue message from an Ethernet switch. Another important feature is that GOOSE messages can be multicast so all the power converters can be alerted at the same time, but can also possible create a Virtual LAN, by adding 4 bytes to the Ethernet data frame per the IEEE 802.IQ standard, to restrict the dataflow.

Because the message is sent from the transmitter without certainty that the power converter receiver is free in that moment, there is no guarantee that a message will arrive at the IED. For this reason the standard IEC61850 defines a repetition mechanism that defines a incremental frequency for sending until the receiver IED answers it to stop or after 1 second.

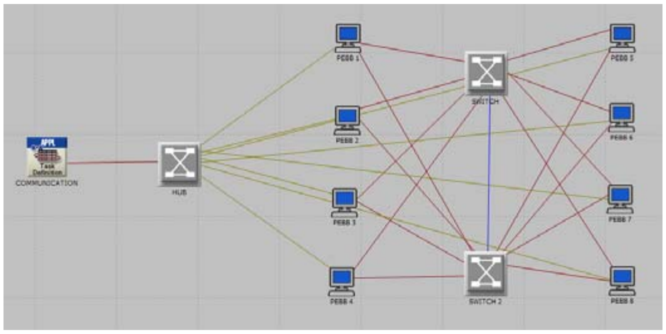

Figure 9: Communication network model

Figure 9 shows the Opnet simulation network. On the left there is the Communication block. It is the block that gives Start/Stop commands to the Matlab/Simulink simulation and manages the exchange of the data vector of the state condition of all the power converters.

Moreover the data vector includes also the Simulink simulation time. The link between Communication box and the Hub is made by one ad Hoc link, without communication delay. The aim of the simulation is to evaluate the end to end communication delay in which a signal starts from a power converter in a faulted state and reaches all the other power converters through a switch.

When a fault happens, the Communication block sends the packet to the HUB block that reads every state from the packet and it sends to each PEBB block a vector summarizing the status of each converter. The status of each converter is represented by an integer number..

In order to have a redundant structure, a star topology architecture is built with two switches (one per side of the ship) that connects all the power converters (four on the starboard side and four on the port side), through an Ethernet Link, creating an Ethernet LAN.

Finally, the delay calculated in OpNet is passed to Simulink, that will insert a proper delay before acquiring the information.

Let us now take a more detailed look at this process.

As show in Figure 10, the process starts in the Init state, underlined by a big black arrow. The aim of this state is to directly open the Matlab engine with the Matlab function engOpen() and also to initialize all the variables in both simulation programs. For example there is a function that creates the array that permits data to be exchanged with the Matlab engine. Before ending his work, this state asks to start the electric simulation for a first step time. For the current analysis a time step of 1ms is used. Notice that this determines the rate of exchange of simulation data between OpNet and Simulink, but Simulink could actually perform more than one step for each call.

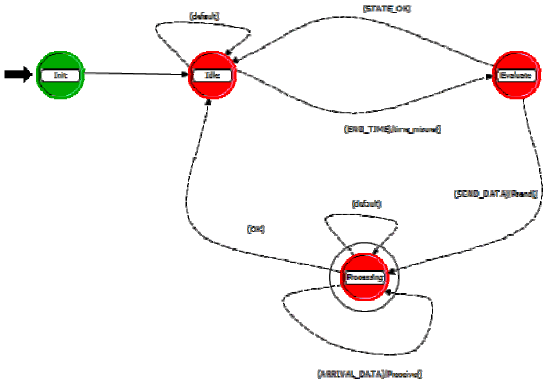

Figure 10: Process model

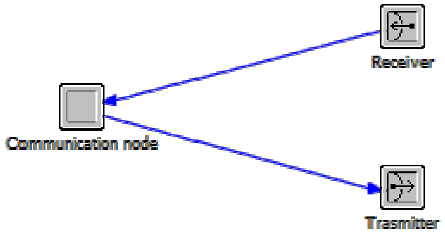

Figure 11: Communication node block

This node is not forced and so, when every command is done, the process passes directly to the next state (idle state), without waiting for any particular event.

Here, the default condition is to wait until the end of the step time, when the event END_TIME happens, the function time_misure() records the simulation.

So the process alternates between Idle state and Evaluate state. While in Evaluate state, a new step of the system simulation is performed. If one IED detects a fault condition, the Evaluate state generates an interrupt and the event SEND_DATA happens.

This brings the process to the Processing state and the function Psend() is performed. This function writes the state condition of the electric power converter into the packet structure and it sends the data packet to the Hub with a stream interrupt through the node transmitter as shown in Figure 11. At this point the Communication block waits in the Processing state until the delay time is expired.

When the Receiver node receives the packet, another stream interrupt is called and the event ARRIVAL_DATA happens. So, the function Preceive() reads the delay time from the new packet and adds that to the Matlab time simulation. This calculation defines when the fault has to be sent to the power converter. After that, it schedules the self interrupt that sends this data and the communication block returns in the Idle state.

VI. PRELIMINARY SIMULATION RESULTS

All the components of the simulation have been fully developed. Currently the authors are working at the testing phase. Nevertheless, some preliminary results are already available and demonstrate the capabilities of the system.

In Figure 12 and 13 an example of transient is reported.

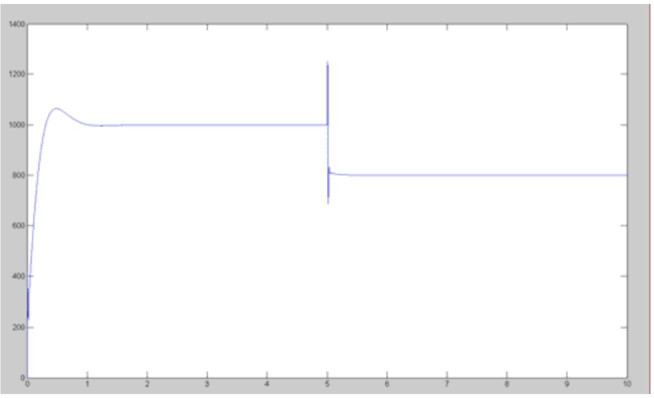

Figure 12: Current transient during faulty condition

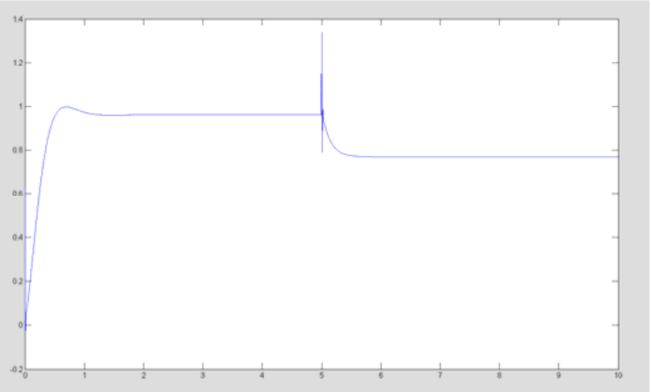

Figure 13: Duty Cycle transient during faulty condition

Analyzing these figures it is possible to identify a sequence of status:

- in the first second of simulation the voltage control brings the system to the nominal operating point.
- between the first and fifth second the system operates normally
- around the fifth second a fault determine a violent change in the current absorbed
- the system reacts and switches from voltage control to current limited control

While Figure 12 reports the current behavior, Figure 13 reports the output of the controllers of the converter i.e. the duty cycle.

VII. CONCLUSIONS

The paper presented an experience in the design of the protection architecture for an MVDC system. Here, in particular, we focused on the modeling challenges. In order to have reliable models, it is important to integrate the simulation of the power system with the control and the communication infrastructure. This result has been achieved here by integrating VTBPro with Simulink and OpNet.

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