Real-Time Simulation of Large-Scale AC System with Offshore DC Grid

P. Le-Huy, P. Giroux, J.-C. Soumagne

***Abstract*— For the purpose of HVDC or FACTS device studies, the AC power system is often reduced to an equivalent seen by the device at the point of common coupling (PCC). This practice is encouraged by the fact that electromagnetic transient simulation of large AC power systems is computationally expensive and time-consuming and might not respect the real-time constraints (for real-time commissioning studies). However, it is no mean feat to build system equivalents for a device that has multiple PCCs on the same AC system (e.g. a multi-terminal HVDC system). This paper synthesizes the work done at Hydro-Québec's Research Institute on large-system simulation, modular multilevel converter (MMC) and wind power plant (WPP) modeling and gives an example of real-time simulation of a large-scale AC system with a complex multi-terminal offshore HVDC grid, based on MMC technology, used to power isolated loads and harvest offshore WPPs. This test system is subjected to disturbances and its behavior is observed and commented. Through those examples, the importance of full-system simulation is shown.**

***Keywords*: DC grid, electromagnetic transient, large AC system, modular multilevel converter, power electronics, real-time simulation, voltage-source converter, wind power plant.**

I. Introduction

TRADITIONALLY, electromagnetic transient (EMT) simulation tools are regarded as accurate but computationally expensive and thus reserved for studies with a limited scope. On the other hand, transient stability (TS) software uses simpler modeling enabling very large-scale studies (several tens of thousands of buses). As the phenomena studied are not the same, it is perfectly acceptable to overlook fast transients and harmonics.

Another distinction must be made as EMT simulations can be done offline or in real-time. For offline simulations, the computation burden grows much faster than the size of the studied power system. Several techniques were developed to cope with this but offline EMT simulations remain time-consuming. As the name implies, in the case of real-time simulations, power system representation, partitioned on multiple processing units, can be solved within a single simulation time step, usually in the order of 50 us or less. As such, the scope of this type of simulation is usually restricted to the device under test, required grid elements (transformers, circuit breakers, surge arresters, etc.) and a Thevenin's equivalent representing the rest of the AC grid.

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The line between EMT and TS simulations keeps changing as both software and hardware evolve: nowadays, it is not uncommon to simulate in real-time, or faster than real-time, several thousands of nodes in EMT simulators with several nonlinear elements and power electronic devices as well as complex control systems. With such powerful tools, transient-stability studies of large-scale EMT systems are feasible, which includes fast transient phenomena. Furthermore, this enables exploration of controller coordination and interaction issues [1] and the development of wide-area control strategies on a transient-stability time scale.

This paper examines the ramifications of using a complete large-scale AC grid for the study of an offshore DC grid with multiple points of common coupling (PCCs) between both systems instead of the usual Thevenin's equivalents. As the DC grid is connected at several points on the same AC grid, a conventional network equivalent at each point would not be adequate since it would not take into account the interaction between the converters' actions and the AC grid dynamic.

The hypothetical offshore DC grid presented in this paper is used to collect the generated power from an offshore wind power plant (WPP), provide power to offshore passive loads and close the loop on a radial region of the power system. This DC system is based on the latest technology of modular multilevel voltage-source converters (MMC-VSC). These converters are well suited for multi-terminal (MT) operation in contrast to line-commutated converter technology.

The paper will first describe the EMT simulation tool employed along with the MMC-VSC and WPP modeling and their related control systems. The large-scale AC power transmission system used for the case study is briefly presented. An offshore meshed DC grid will then be added to it in order to demonstrate, through selected power system disturbances, the importance of large-scale AC power system representation in the study of MT DC systems with multiple PCCs to a single AC system. Following the results and their analysis, concluding remarks will be given.

II. EMT Simulation Tools

Before diving into the details of the case study, the EMT simulator is described in this section and the modeling of the MMC-VSC and the WPP in the following section.

A. Real-Time EMT Simulator

Hydro-Québec's real-time EMT simulator, Hypersim, is a large-scale multiprocessor simulator used for power system studies and for the development, validation, tuning and commissioning of control systems [2]. The computational effort is automatically spread across available processing units using the natural propagation delay of the transmission lines. As a result, the large power system impedance matrix is divided into several smaller submatrices which can be solved in parallel by several processor cores without introducing any error, thus drastically improving the simulation speed [3]. For computational load reasons, the network equation solver of Hypersim uses piece-wise linear models to represent nonlinear devices such as power electronics and saturable elements. Furthermore, reactive elements are reduced to a single admittance in parallel with a current source representing the reactive elements' historic values, exactly like the original EMTP [4].

The Hypersim simulator is not limited to real-time applications: if a hardware-in-the-loop configuration is not required, Hypersim can be used for offline simulations on any personal computer and, if multiple processing cores are available, the automatic taskmapper will make use of them. In that case, the simulations are executed as fast as the processing unit can manage, which can lead to faster-than-real-time simulations depending on the simulated power system and the processing power of the computer. This feature is highly desirable since it allows the groundwork for real-time studies to be conducted without monopolizing real-time hardware resources.

B. Simulation Environment

To enhance productivity, several applications were added to the Hypersim simulation environment (see Fig. 1) over the years: Hyperview is a suite of utilities to configure and monitor Hypersim; Scopeview is a signal acquisition and processing tool that accepts Hypersim as well as EMTP-RV, Matlab and COMTRADE data sources and, lastly, Testview provides tools to automate and customize test routines. Hyperview and Scopeview were instrumental in obtaining the results presented in section IV.

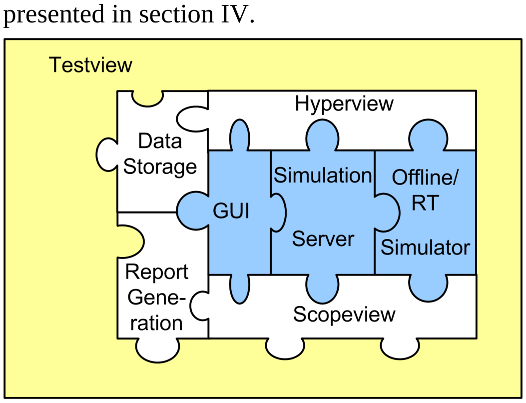

Fig. 1 Hypersim simulation environment. The light blue boxes represent the Hypersim real-time EMT simulator software per se.

III. EMT Modeling

A. Iterative Engine

Iterative solvers are usually frowned upon in the context of real-time EMT simulations but the advances in processing units allow us to go beyond that dogma. Iterative solvers are useful for nonlinear elements since they allow the algebraic loop introduced by the non-linearity to be adequately managed. Power electronic devices, surge arresters and saturable inductances, found in transformers and electric machines, all benefit from such solvers. The alternative is to introduce a delay in the handling of the nonlinearity, which in turn may cause inaccuracies, uncharacteristic behaviors and numerical oscillations. To avoid all this, the modeling of MMC systems in [5] and [6] included an iterative solution to determine the status of all switches. This approach was then applied to all switching elements [7] and nonlinear elements [8][9] in Hypersim. More details on the iterative solver (see Fig. 2) can be found in [7] and [8].

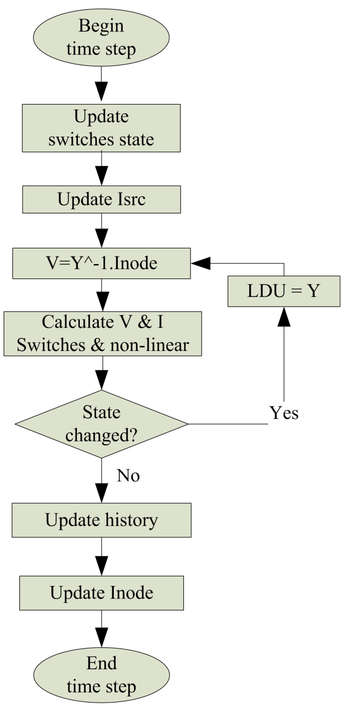

Fig. 2 Iterative engine flowchart.

B. Modular Multilevel Voltage Source Converter Modeling

The fundamental unit of MMC, usually referred to as a power module (PM), submodule or cell, is essentially a half-bridge two-level converter, as seen in Fig. 3. A large number of basic units are then stacked to create each of the six converter arms (see Fig. 4). A serial reactor is placed in each arm and, in some cases, a second harmonic filter is also added for each phase.

The operating principle of this kind of converter is fundamentally simple: the high-level control system determines the voltage waveforms to be synthesized and these are then translated into a certain number of active and inactive PMs per arm by the low-level control algorithms. An active module inserts its capacitor into the circuit while an inactive one shorts its terminals. Each arm can be considered as a variable voltage source.

Direct simulation of this kind of converter with conventional EMT simulation models is quite tedious, since the number of power electronic devices and nodes can reach several thousands [10][13]. Through circuit-law analysis, arm equivalents are easily constructed and solved [5][6][10][11]. Each arm boils down to a single equivalent admittance and current source based on the current state of all the power electronic devices involved. Once the terminal voltages are known, the internal conditions are determined analytically [5][6]. This representation suppresses all the internal nodes from the admittance matrix, considerably reducing the computational burden, but remains mathematically equivalent to solving the complete equation systems since no simplification is made. More details, as well as a description of the control system, can be found in [5] and [6].

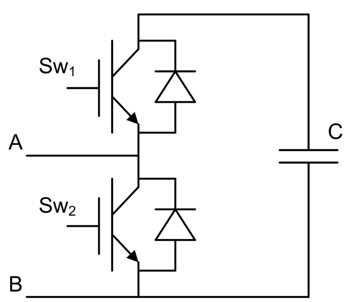

Fig. 3 Simplified power module content.

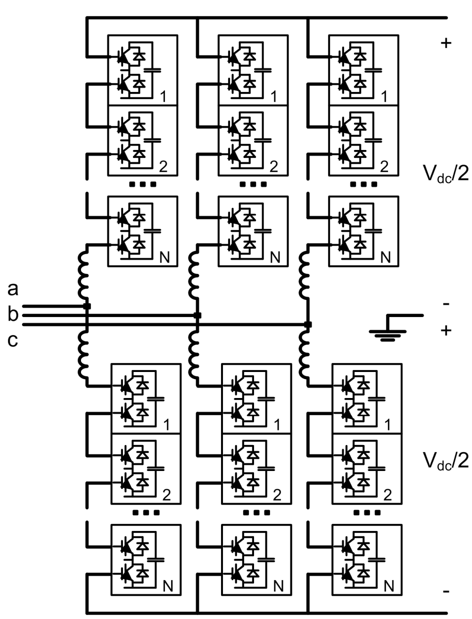

Fig. 4 Modular multilevel converter basic topology (double star-point).

C. Wind Power Plant Modeling

The wind generator (WG) with full power converter, or type-IV wind turbine generator (WTG), shown in Fig. 5, represents one of the most modern technologies. The power captured by the wind turbine is transmitted to the drive train modeled as a two-mass system, while the mechanical power is converted to electrical power using a synchronous generator. The pitch of the wind turbine blades can be adjusted to maximize the power transfer and/or regulate the rotation speed. The particularity of this topology is the fact that the entire power of the synchronous generator goes through an AC/DC/AC power converter, allowing fast control of the active and reactive power delivered by the WTG over a wide range of generator speeds.

For the purpose of this paper, the network behavior is of interest and not the switching phenomena inside the WGs. Consequently, instead of a very detailed model such as [8], an average-value model (described in [12] and [6]) is used to represent the major parts of the harmonics, except the high frequencies related to switching harmonics.

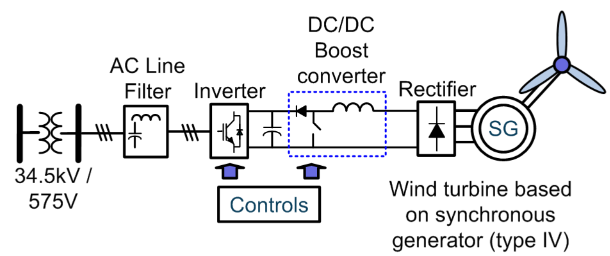

Fig. 5 Conceptual block diagram of the type-IV WG.

It has been demonstrated that real-time simulation of a large WPP is quite difficult without resorting to aggregate models [1]. This is explained by the fact that the WPP collector system is composed of very short overhead lines or underground cables, which render EMT decoupling methods inoperative for partitioning the computation load on multiple processing units. In order to avoid this, the National Renewable Energy Laboratory (NREL) equivalency method [14][15] (see Fig. 6), promoted by the Wind Generation Modeling Group (WGMG) of the Western Electricity Coordinating Group, is applied. An exhaustive validation study of WPP aggregate models [16] has confirmed that the accuracy is adequate for load flow, stability and EMT simulations for prospective or preliminary studies.

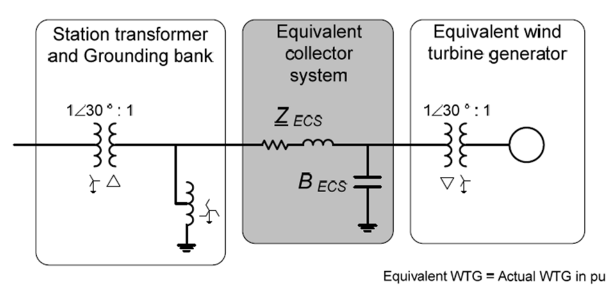

Fig. 6 NREL's single-machine equivalent WPP promoted by the WGMG.

IV. Case Study

To demonstrate the simulation of a large-scale AC power system with a DC grid with multiple PCCs, a four-terminal DC system is connected to an AC power system comprising more than 350 three-phase buses, 40 synchronous machines and hundreds of lines, transformers and nonlinear elements (see Fig. 7).

A. Large-Scale AC Power System Modeling

The AC system, illustrated conceptually in Fig. 7 (more details in Fig. 8), is characterized by very long EHV transmission lines that connect two major power generation areas, Gen1 and Gen2, with the main load centers.

To enhance system performances, series and shunt compensation (synchronous condensers and static var compensators) are used at strategic points on the EHV corridors.

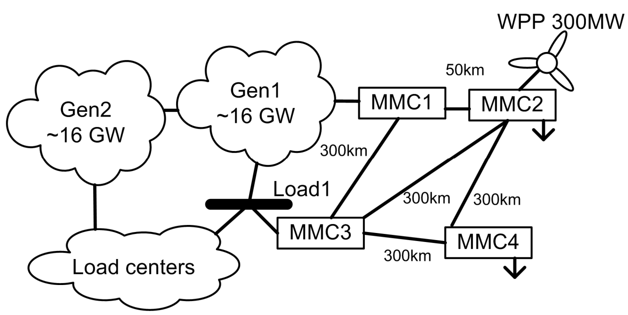

Fig. 7 Conceptual representation of the large-scale AC system used for the case study with the offshore meshed DC grid.

The Hypersim modeling of this transmission system (from 735 down to 120 kV as well as power generation busbars at 13.8 kV) is given in Fig. 8. Smaller details are lost due to the sheer size of the schematic and available space but key elements are quantified in Table I in order to appreciate the complexity of the power system represented. All these elements are simulated in real-time at the EMT-level without polynomial equivalent or other schemes that approximate the EMT behavior of the power system.

B. Offshore DC Grid Modeling

The DC grid consists of four terminals, as shown in Fig. 7, operating at ±320 kV. All converters have 36 PMs per arm and low-level control is done with a phase-shifted pulse-width modulation scheme with an added capacitor voltage balancing algorithm (as described in [6]). MMC1 is connected at 735 kV in the first power generation area (Gen1) and is rated 800 MW; it can provide 400 Mvar, either in capacitive or inductive mode. It operates in AC voltage regulation mode and acts as a DC “slack-bus”, regulating DC voltage at 1.0 p.u.(640 kV). MMC2 (400 MW ± 200 Mvar) is located offshore, where it acts as a voltage source for the local passive load (60 MW and 6 Mvar) and a 300 MW WPP. The excess power from the WPP is transmitted to the DC grid when the generated power exceeds the local load. MMC3, as MMC1, is an 800 MW ± 400 Mvar VSC connected to the main AC system (at 230 kV). It feeds a remote load and is connected to the rest of the system at bus “Load1”, which is half-way between Gen1 and the major load centers. MMC3 regulates the voltage at 1 p.u. at its end of the feeder and pushes 720 MW towards bus Load1. In doing so, MMC3 is actually reducing the stress and the losses on the first part of the AC transmission path between Gen1 and the load centers. Finally, MMC4 is also located offshore and has the same rating as MMC2. It provides voltage and frequency references for a passive load. As seen in Fig. 7, the DC grid is meshed and provides path redundancy if one link should be severed.

Control systems and the WPP model, all developed in Matlab/Simulink and SimPowerSystems, are included in the Hypersim simulations through the Hyperlink interface. This interface allows the “Simulink Coder”-generated C code to be used (see [17]).

C. AC System Single-Line-to-Ground Fault

A single-phase fault is applied to bus “Load1”, which is half-way between Gen1 generation center and the load center. This part of the system is sensitive, since the MMC3 feeder is connected to it. As seen in Fig. 9, MMC3 is highly affected by the fault and finds itself enabled to push the ordered active power into the AC system. This results in a DC voltage increase which affects the other MMCs as well as the WPP. On the main AC system, power generation facilities are subjected to imbalances that result in a very weak over-frequency. Inter-area oscillations can be seen in the speed of the machines, which are damped in less than 4 s, followed by global speed oscillations. The AC system eventually returns to pre-fault conditions. The DC system recovers much quicker than the AC system since it is not affected by the slow dynamic of inter-area and global modes. This full system recovery is very interesting: since it runs in real-time, during the time required to properly format/visualize the data and save it, the system has stabilized and is ready for the next test. It reduces the time required to run through validation testing and/or controller fine tuning. It could also be possible to do stability analysis and appreciate the converters’ behavior and influence on the whole system dynamic.

This example is interesting since it shows the AC power system dynamics and how it affects the DC system, mainly MMC1 and MMC3. Reproducing the patterns seen by both converters with a time-varying system equivalent is not an easy feat as it requires very intimate knowledge of the AC system dynamic, which is highly dependent on the fault parameters such as the type of fault, its location in the power system, as well as its duration and impedance. In-depth knowledge of the power system is also required to model it in EMT simulation software but subsequently it is far easier and more convenient to try different scenarios and disturbances.

D. Offshore AC System Three-Line-to-Ground Fault

A three-phase fault is applied to the offshore AC system without local generation (MMC4). As seen in Fig. 10, this event has a major impact on the DC system but a very mild one on the main AC system. DC voltage on the cable system presents major deviations but remains within safe limits as MMC1 modulates its power input to the DC system. This DC voltage swing is due to the rapid increase in MMC4 power consumption as it feeds the fault. MMC2 and MMC3 measured power outputs to their respective AC system are slightly affected as the DC level falls below its nominal value but return to optimal operations after the disturbance. As for the WPP, it suffers very mild transients and continues to operate normally.

In the main AC system, several devices are used to dampen oscillatory modes, inter-area and global ones. They are effective, as may be observed from this event, but if they were not properly tuned or simply not present, this “small” disturbance on the offshore system could potentially trigger an oscillatory mode in the main AC system. This kind of adverse behavior could not be detected and studied if system equivalents were used.

E. Real-Time Performances

Table I gives the content of the complete simulated power system (AC and DC). All simulation results presented in this paper were obtained from real-time simulations (t_s = 50 us). 16 SGI UV cores (Intel Xeon E7-8837 @ 2.67 GHz) are required for the whole system (half for the AC system and the other half for the DC system and the WPP).

TABLE I
TOTAL CONTENT OF THE AC-DC POWER SYSTEM IN HYPERSIM

Power system element	AC system only	Total system
Electrical nodes	1099	3018
Electrical machines	37	37
Synchronous condensers	4	4
Static var compensators	7	7
Power lines	170	182
Three-phase transformers	131	136
RLC elements	3117	4342
Non-linear elements	249	249
Switches	106	1842
WPP (complete subsystem)	0	1
Comm. (Control, monitoring, etc.)	332	1630

V. CONCLUSION

As more and more “intelligence” is added to power transmission systems, the more it becomes difficult to predict exactly the dynamic behavior and the system response to certain events. The current paper presented a way to deal with this reality: doing EMT simulations of whole systems instead of partial-system studies with system equivalents. The feasibility, as well as the importance, of such full-system studies was demonstrated by simulating a large-scale AC system connected at two points with a MT DC grid system. If full-system EMT simulations are not possible, it is important to be aware of the limitations of system equivalents: due to the complexity of modern power systems, realistic system equivalents are not easy to compute and do not provide the same flexibility as representing the corresponding AC system in EMT.

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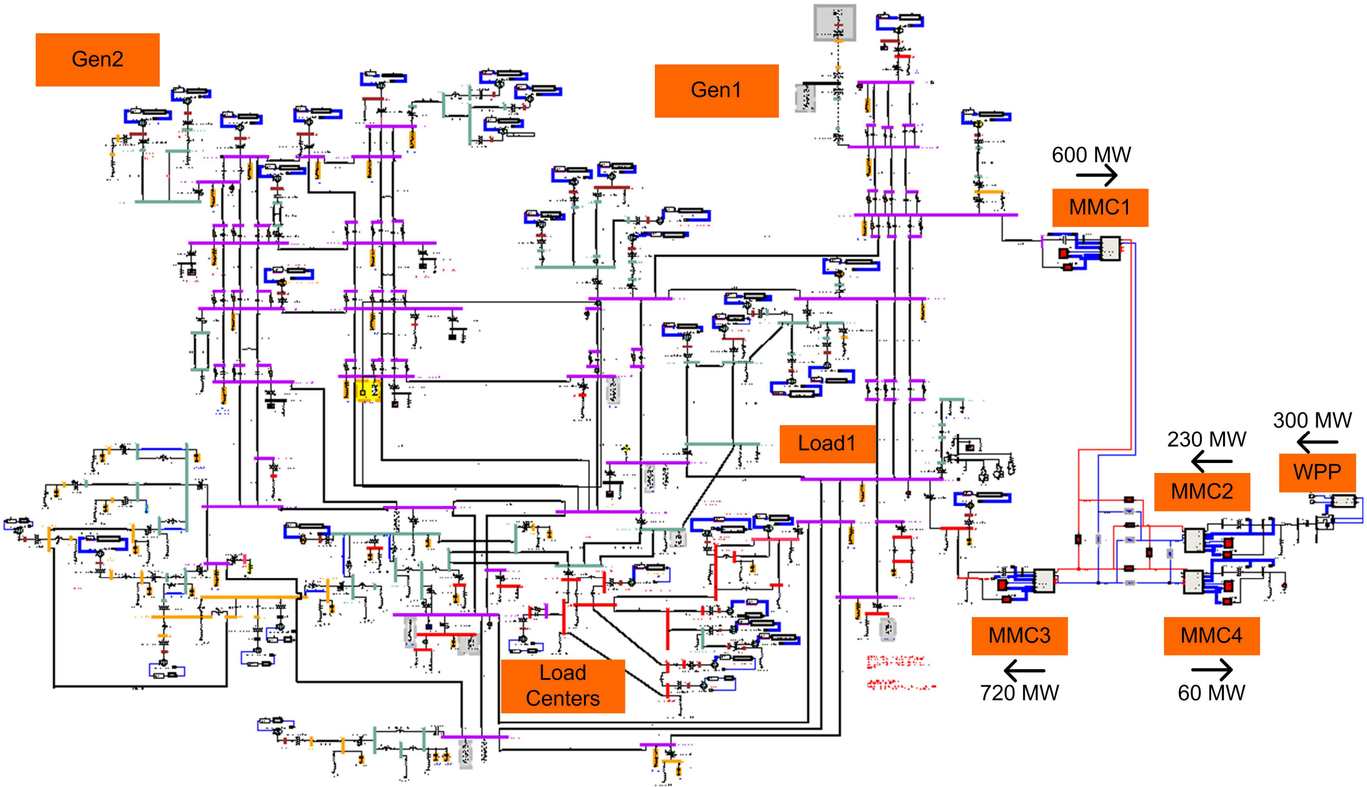

Fig. 8 Hypersim representation of the large-scale power transmission system. Note the DC grid on the-right side.

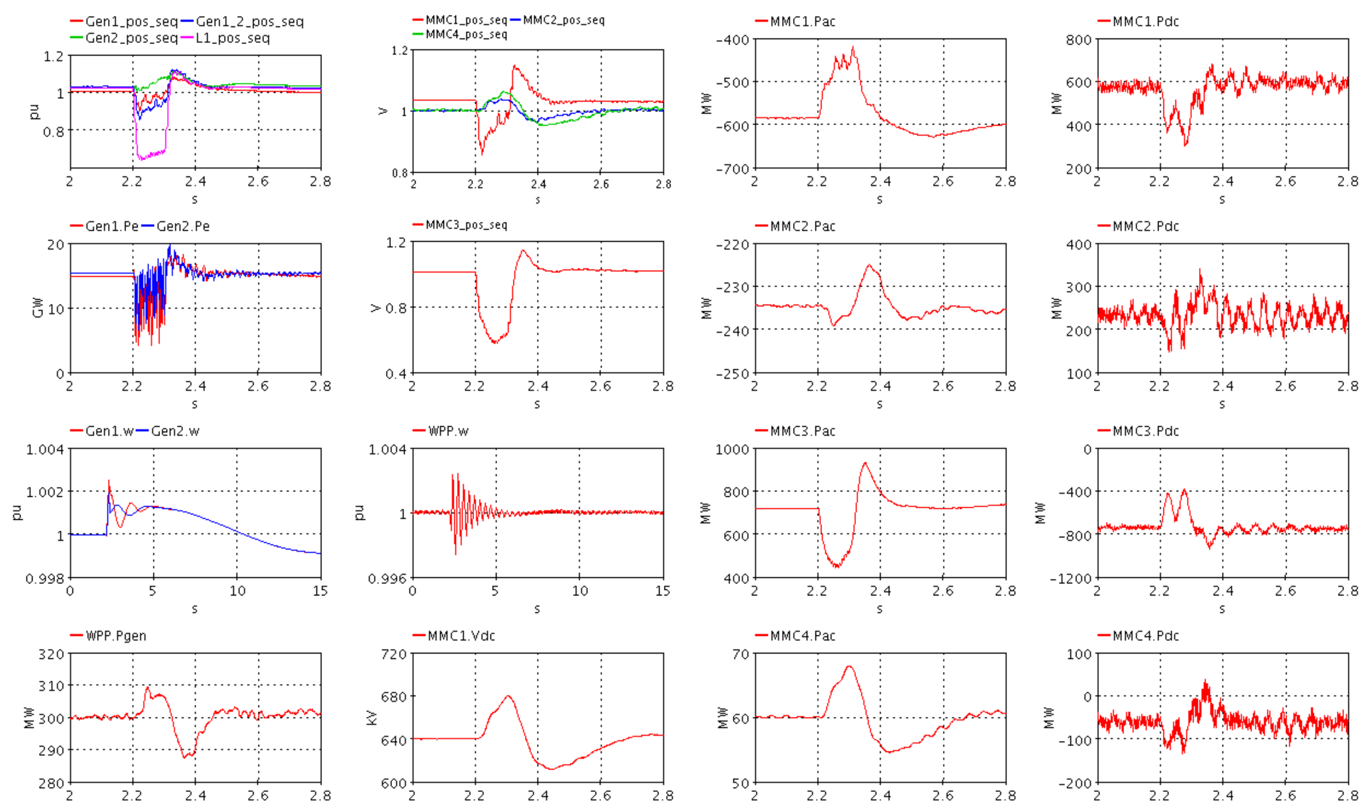

Fig. 9 System response to a 6-cycle single-line-to-ground fault at bus "Load1". Pac and Pdc are respectively the active power delivered to the AC and DC side of the converter.

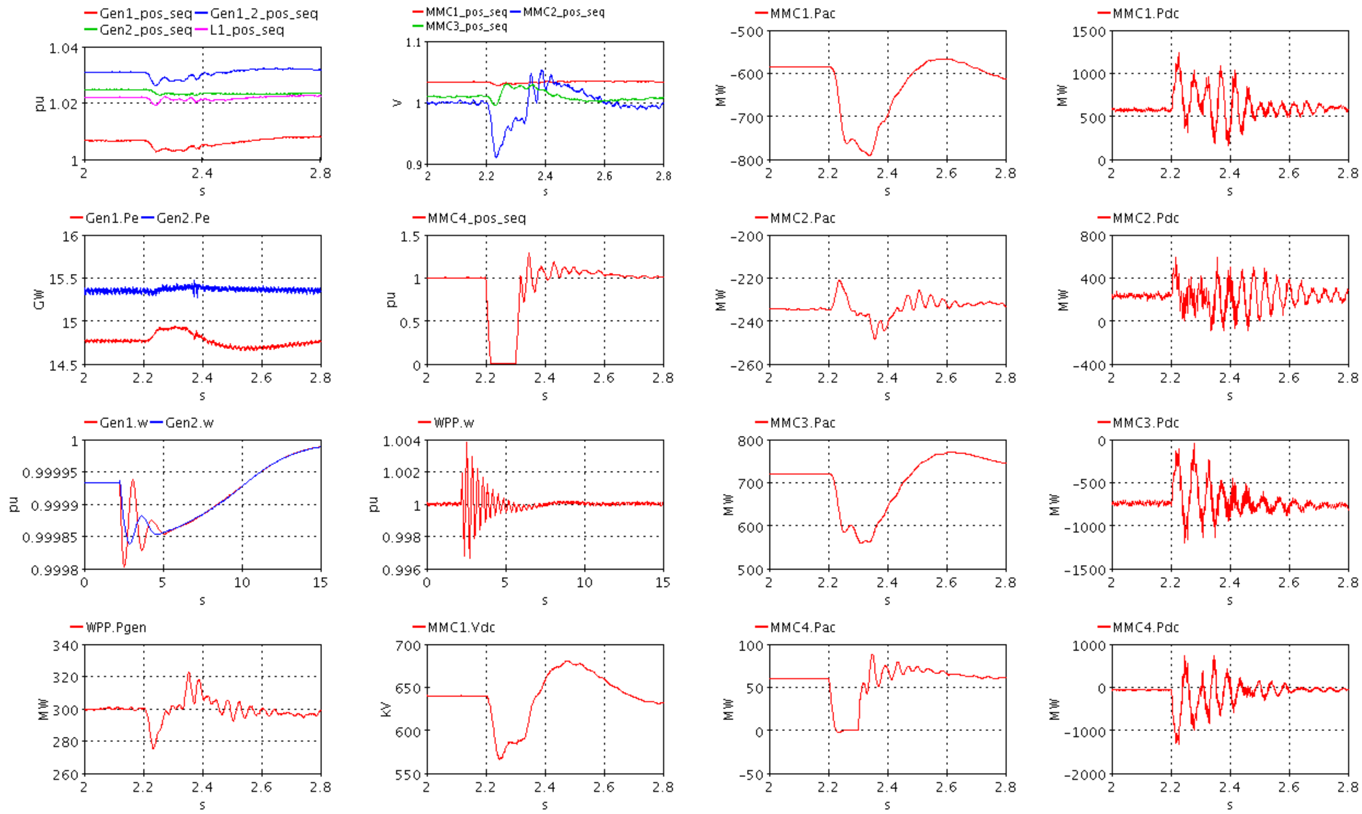

Fig. 10 System response to a 6-cycle three-phase fault in MMC4's offshore AC system. Pac and Pdc are respectively the active power delivered to the AC and DC side of the converter.