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# Testing 750 Node Distribution Grids and Devices

## Using optimized parallel delay-free real-time solvers and modern grid protocols

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*Abstract*- **This paper explains how distribution grid renewable integration and protection studies are conducted using a digital real-time simulator (DRTS). Distribution grids are difficult to simulate in real-time because they are very large and have only short lines, making the parallel calculation of the equations particularly difficult. The SSN solver is an Electromagnetic Transient (EMT) solver used to compute the time-domain solution of these large distribution networks in real-time. The SSN solver is able to handle networks with more than 750 nodes without the use of Bergeron-type line models and without artificial delays. Real-life distribution grids, including a real one from ENEL Distribuzione, are used to explain these concepts and evaluate the performance of the SSN solver.**

**Some distribution grid challenges, such as those involving PMUs, can also be studied using Transient Stability (TS) solvers. TS solvers use sample times in the millisecond range to tackle much bigger problems than EMT solvers. e*PHASOR*sim, a real-time solver designed to tackle larger problems in the transient stability domain with a node count up to 50000, is also demonstrated in distribution grid applications.**

**The paper also explains the various grid protocols supported by the real-time simulators running these various solvers, such as DNP3, IEC-61850 Goose and Sampled Values, IEC60870-5-104, C37.118, OPC and Modbus.**

## I. INTRODUCTION

Today, most utilities use real-time simulation to plan and test the protection and control systems for their power grids. The need for this technology is clear when one considers the large capital investments and commissioning effort needed to ensure that these very complex power systems function at extremely high levels of reliability. When protection and control systems are deployed in the field, they have to work correctly and reliably. Digital real-time simulators (DRTS) play a key role in ensuring that this happens.

Renewable energy sources have been around for a while now. What is rather new, however, is the relatively high percentage of their contribution to the total power generated in some countries. In Italy, for example, at some times of the year, a huge part of the total power generated comes from renewable sources and this can have a significant impact on the controllability and stability of the grid (in the Enel Distribuzione grid, the renewable installed power is close to 20 GW). Renewable power is also often integrated directly into the distribution grids. This direct integration has an important impact on voltage control, power flow control and protection coordination.

For many years now, real-time simulators have been successfully used to simulate very large transmission grids. For example, power systems with more than 670 tri-phase buses (i.e. many thousands of nodes) and dozens of power system devices such as HVDC, SVC and synchronous machines have been simulated in real-time on 72 parallel processors, using Electromagnetic Transient (EMT) simulation [1][2]. This is possible because of the presence of long transmission lines in these networks. These lines, typically modelled as Bergeron lines, with frequency dependence when required, effectively decouple and parallelize the equations that describe the complete grid, without any approximations.

From the view-point of real-time simulation, distribution grids can easily be as large as transmission grids, because of the increased level of detail. The problem with most distribution grids is that they typically only have short lines (usually 1-10km) that do not allow the Bergeron‘s line-type of task separation. Task separation must therefore be made by other means, such as adding simple delays or stublines (short one-time-step delay transmission lines) in the model. However, these delay-based approximations can induce significant accuracy problems, especially in transient protection studies.

This paper presents novel power system equation real-time solvers called State-Space-Nodal (SSN) [2] and e*PHASOR*sim. The SSN solver, within the e*MEGA*sim real-time simulator, is capable of simulating, in real-time, large distribution grids with more than 750 single-phase nodes. SSN is demonstrated to successfully simulate distribution grids from Enel Distribuzione, the major DSO of Italy, as well as typical distribution grid configurations in France. These SSN simulations are notably made without the addition of artificial delay elements such as stublines.

Some distribution grid challenges, such as those involving PMUs, can sometimes be studied using ‘only’ Transient Stability (TS) solvers. TS solvers use sample times in the millisecond range to tackle much bigger problems than EMT solvers. e*PHASOR*sim, a real-time solver designed to tackle larger problems in the transient stability domain with a node count up to 50000, is also demonstrated in distribution grid applications.

## II. DISTRIBUTION GRID TESTING OBJECTIVES

Today, the control, testing and development planning of distribution grids are more complex than ever. New relay and SCADA technologies, ever increasing integration of renewable energy and the widespread adoption of new standards like IEC-61850 make this a challenge [10].

### *A. Protection of smart distribution grids*

The protection challenges have evolved quite a lot in recent years. TCP-IP protocols have emerged for the control of relays and substations, such as IEC-61850, DNP-3 and PMU data standard IEEE C37.118, which in turn made possible the development of many advances and complex protection schemes. This global communication capability enables the development of advanced protection strategies that must be tested thoroughly before deployment in the field. Also, as the various devices may come from different manufacturers, it is important to verify if they work correctly with each other.

Power system protection has the main objective of avoiding damage to the system in case of faults. This has to be done intelligently, with no need to shut down the entire system for most faults. Modern protection techniques aim at locating faults and isolating them, leaving the rest of the system powered on. This is typically done with automated algorithms that will try to locate the fault by switching certain relays to isolate the fault.

### *B. Renewable Integration*

Renewable sources (with the exception of hydro-generation) are very fluctuant by nature, which makes the global control of voltage profiles and power flows quite challenging. Wind turbine and solar cell power outputs depend mostly on the weather. Electric vehicles, which can serve as a temporary energy reservoir, have a charge and grid connection status that is also quite variable.

One major challenge of modern, smart distribution grids is dealing with the distributed connection of numerous small power sources directly into the distribution grid. In this case the N-1 contingency analysis must be extended to deal with the variability of natural phenomenon such as wind and sun.

Part of the integration process is also to verify that the various active devices respect the grid specifications in terms of Low Voltage Ride-Through (LVRT) capability, possibility of islanding and neutral floating operability, for example[12]. This is also done with a mix of off-line and real-time simulations.

### *C. Optimal power flow and voltage control*

Optimal power flow and voltage control problems are also more complex because of the higher variance of power availability of active distribution grids. Usually, these types of studies can be done using EMT of phasor-type simulation, in real-time when required.

## III. GRID PROTOCOLS

Smart grid information and communications technologies have become more essential than ever to allow communication between smart devices. Modern real-time simulators must ensure that communication protocols are easily implantable on our hardware and software.

Numerous protocols exist today for grid control and measurements such as DNP3, IEC-61850, IEC-60870, C37.118, OPC and Modbus. A description of the most common protocol in power systems can be found in [3].

### *A. IEEE C37.118 for PMU measurements.*

The C37.118 (Synchrophasor Protocol) is the IEEE standard for using synchrophasors in power systems. The protocol can be used to validate PMU, for example. In [13], the OPAL-RT eMEGAsim simulator is used to implement a distribution network model with internally simulated PMUs and with unbalanced lines and dynamic loads, like the IEEE 13 bus test feeder used in this test. As depicted in Fig. 1, the simulator is also connected to real PMUs that are fed by the simulator node current and voltages. Both RT-computed and real PMU phasor data are streamed to a phasor data concentrator (PDC) via the IEEE C37.118 protocol. The PDC is based on the OpenPDC platform. Notably, the system allows the DRTS to time stamp its measurements with an external GPS source using GPS synchronization signals from a Spectracom card. It also makes it possible to precisely synchronize the simulation time with real world time [11].

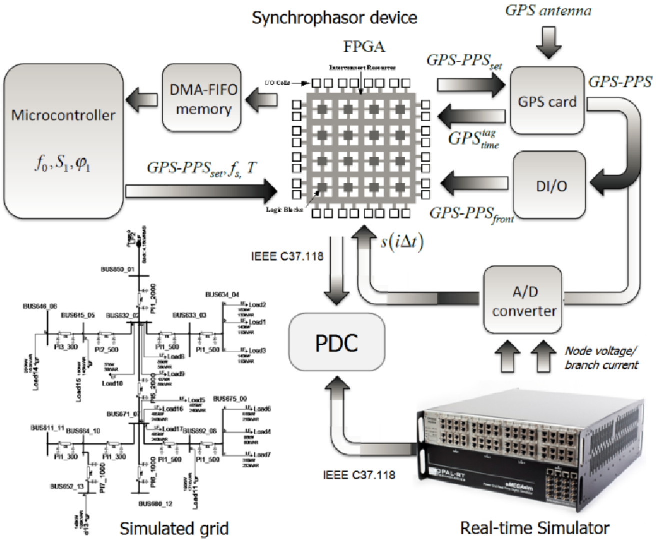


Fig. 1. PMU testing with a real-time simulator

### *B. IEC-61850-8-1 and IEC-61850-9-2*

IEC 61850 is a standard for the design of electrical substation automation. These protocols are Ethernet based using high speed switching devices to obtain the necessary response times for protective relaying. For power grid protective relay testing using a DRTS, the standards currently supported are IEC-61850-8-1 GOOSE (Generic Object Oriented Substation Events) and IEC-61850-9-2 SV (Sampled Values).

This type of study involving the IEC-61850 protocol is being investigated at KTH Smart-TS Laboratory, in Stockholm, Sweden [14]. The IEC-61850 protocol implements the data transfer between primary equipment and IEDs through Ethernet network. The protocol has two main components: GOOSE, for the transmission of digital data like trip signals, and Sampled Values, used to transmit analog values such as currents and voltages. Use of IEC-61850 based relays eliminates the need for costly copper wires and facilitates interoperability between equipment from different vendors in a substation. The reliability of the IEC-61850 protocol is still being analyzed and pilot projects have been implemented world-wide to evaluate its performance as compared to traditional copper wiring architecture.

As described in Fig. 2, the differential protection feature of ABB RED-670 is evaluated for a two winding transformer model executing in real time using eMEGAsim, OPAL-RT's real-time simulator. An extensive testing procedure of Schweitzer's SEL-487E relay with IEC-61850 and the RT-LAB simulator relays was also done in [15].

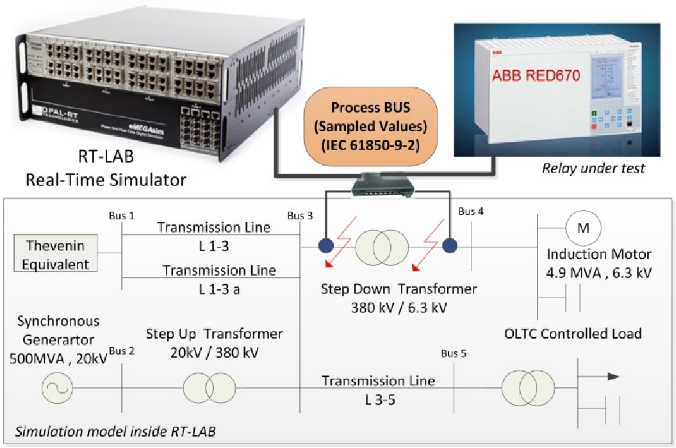


Fig. 2. Relay testing set-up using the IEC-61850 protocol.

### C. DNP3(Distributed Network Protocol)

DNP3 is a set of communications protocols used between components in process automation systems. Its main use is in utilities such as electric and water companies. Usage in other industries is not common. It was developed for communications between various types of data acquisition and control equipment. It plays a crucial role in SCADA systems, where it is used by SCADA Master Stations (aka Control Centers), Remote Terminal Units (RTUs), and Intelligent Electronic Devices (IEDs). It is primarily used for communications between a master station and RTUs or IEDs, as depicted in Fig. 3.

Support of the DNP3 protocol enables DRTS users to build applications with virtual IEDs and RTUs for example.

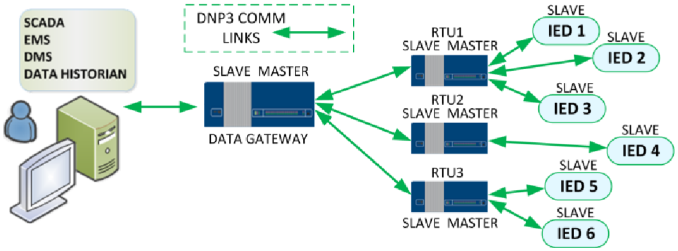


Fig. 3. Typical DNP3 configuration

### D. IEC60870-5-104

IEC-60870-5-104 is an International Communications Protocol Standard for the remote control of electric power transmission systems, which is being widely adopted in many countries throughout the world. The standard specifies the use of permanent directly connected links between remote control stations. Dedicated base band cables, power line carriers or radios may be used for analog channel communication or direct digital links may be used.

It is used, for example, in power supply network automation (i.e. Siemens SICAM AK 1703 ACP), distribution and transmission control centers and various industrial control systems (i.e. SIMATIC TDC), grid automation controllers (i.e. ABB COM600) and wireless gateways (i.e. ABB RER601). Fig. 4 shows a typical configuration using IEC-60870-5-104, in which a DRTS could be interfaced.

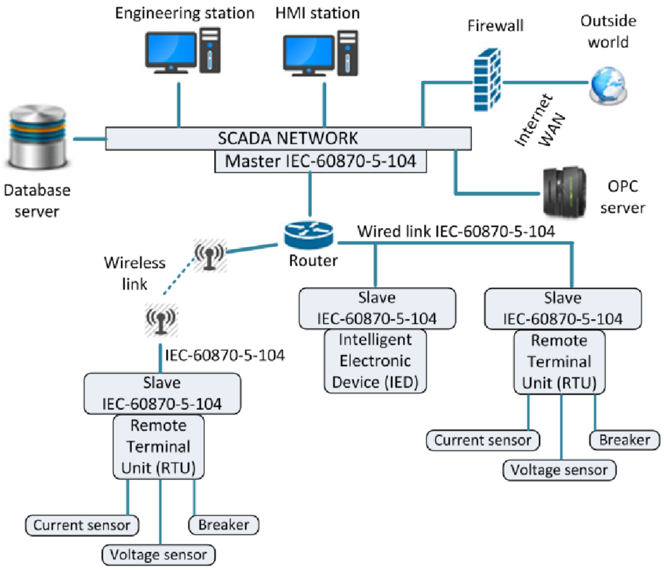


Fig. 4. Typical IEC-60870-5-104 configuration

### E. Modbus, Modbus-TCP, OPC

Modbus was intended as the internal point-to-point communication protocol between Modicon PLCs and programming panels used to program the controllers. One important factor that contributed to the increased popularity of Modbus is the addition of Modbus-TCP that allows communication over TCP/IP Ethernet based networks. This mode is supported by RT-LAB universal Modbus TCP interface.

The various OPAL-RT DRTS platforms (eMEGAsim with SSN, e*PHASOR*sim and Hypersim) also support the Open Platform Communication (OPC) protocol.

## IV. SSN: A REAL-TIME DELAY-FREE PARALLEL SOLVER

At the core of the eMEGAsim simulator is the State-Space Nodal (SSN) solver [4]. SSN is based on the well-known nodal admittance algorithm (often called the Dommel algorithm used in EMTP) but with several additional key features, including:

- Customized partitioning of the network branches and nodes;
- Use of high-order discretization to obtain the discrete-time state space models of these partitions [5][6].

The SSN algorithm is currently part of the ARTEMiS add-on to SimPowerSystems for SimulinkTM and works transparently from within the RT-LAB and Simulink environments within the eMEGAsim real-time simulator used by Enel Distribuzione.

### A. *From branches to partitions: extending the EMTP algorithm with SSN*

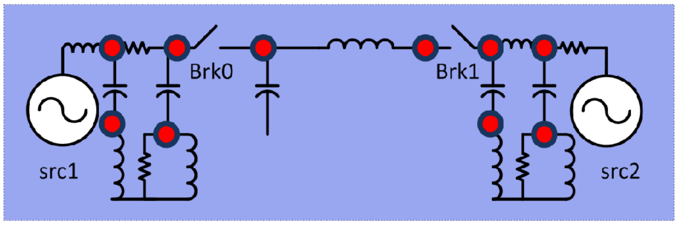
In EMTP-type algorithms, branches are pre-defined and are typically small, like RLC branches. Nodes are therefore automatically obtained as the connection points of the various branches. By contrast, in the State-Space-Nodal (SSN) solver, the user selects the node location and the solver computes the resulting branch equations. These branches are really partitions or multi-terminal groups, a generalization of the branch concept. This approach has 2 major advantages for real-time simulation:

1) The nodal admittance matrix size is smaller and thus faster to compute. This is because LU factorization of a matrix of size $r$ is an $O(r^3)$ problem in numerical algebra and can therefore become dominant when solving large grid problems.

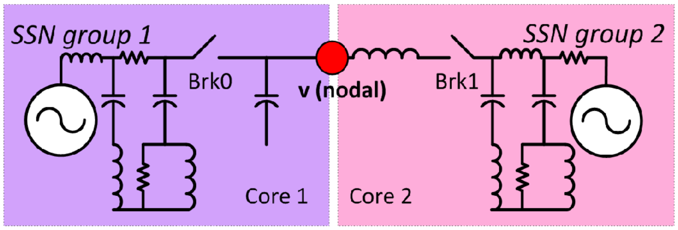
2) The partitions or groups are bigger which makes them suitable for parallel calculation using computer threads. This branch/partition/group parallelization is effectively implemented the current version of SSN.

The SSN group concept is illustrated next. Basically, an SSN group is a generalization of the classic EMTP branch concept. Using a small grid as an example, one can observe that the classic EMTP-type building of the circuit in Fig. 5 a) results in 10 nodes for the nodal admittance method, for which an admittance matrix of size 10 is found by EMTP. By contrast, single user-selected ‘SSN node’ in Fig. 5 b) results in a rank-1 admittance matrix, separating the circuit into 2 large partitions of elements on which SSN routines automatically compute the state-space equations. These 2 partition equations are effectively computed in parallel in SSN on different cores. This partitioning is fully flexible: for example in Fig. 5 c) 2 SSN nodes are used, resulting in a rank 2 admittance matrix and 3 large partitions that can be computed in parallel. The nodal admittance solution is made without parallelization. The partition number can be modified by the user in SSN, which provides some flexibility to reach the best possible real-time performance.

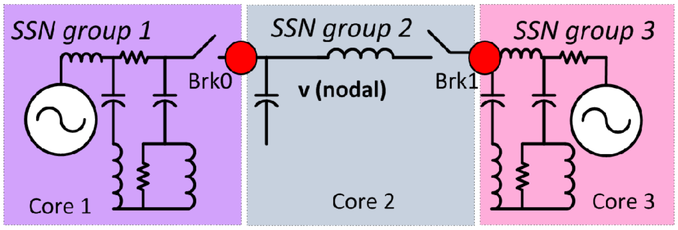
For the sake of clarity, one must understand that standard EMTP equations can also be computed in parallel (i.e. for loop of so-called ‘history source update’). But in this case, the equations are small and numerous, and actual CPU computational efficiency is low because of inter-core communication delays between cores of the CPUs.



a) Standard EMTP approach: 10 nodes



b) SSN approach: 1 nodes (2 groups/partitions)



c) SSN approach: 3 nodes (3 groups/partitions)

Fig. 5. SSN vs. standard EMTP node definition and impact on the size of the nodal admittance matrix.

The state-space formalism of the SSN – partition equations are modelled with state-space equations, only the nodal admittance solution part is not – also allows the use of high-order discretization methods, different from the traditional trapezoidal method used in most DRTS today. The family of L-stable Padé approximations to the matrix exponential [5] is particularly useful in real-time simulation as they are more immune to numerical oscillations than A-stable methods like the trapezoidal method. The Backward Euler (1st order) and the (2, 3)-Padé matrix exponential approximation method (5th order) are two examples of L-stable discretization methods available in SSN. This increased stability can become important in certain fault study cases.

### B. *Usage of Higher-Order L-Stable Discretization Methods to Increase Numerical Stability and Accuracy*

It is well-known that the exact solution to the state-space equation (Eq.1) is equal to:

$$x_{n+1} = e^{Ah}x_n + \int_{t}^{t+h} e^{A(t-\tau)}Bu(\tau)d\tau \qquad (1)$$

where $h$ is the discretization time step. It should be recognized that 2 distinct approximations are necessary to obtain a numerically computable expression:

1- The approximation to the matrix exponential $e^{Ah}$
2- The way the input $u$ is approximated during integration

The traditional EMTP approach uses the trapezoidal approximation (Padé 1,1) of the matrix exponential, equal to:

$$e^{Ah} \cong \frac{I + hA/2}{I - hA/2} \qquad (2)$$

combined with a linear interpolation of the input during the integration step. The trapezoidal rule is however unstable during fast disturbances. This problem is solved in offline simulation with a method called CDA [16]. With CDA, during switching steps, the Backward Euler method is used for both matrix exponential and input terms, in addition to a time-step change in the original implementation.

Using other approximations in Eq. 1 can lead to interesting results especially with regards to stability issues. For example, the ARTEMiS 'Art5' solver, based on the (2, 3)-Padé order 5 approximation of the matrix exponential, of formula equal to

$$e^{Ah} \cong \frac{I + 2hA/5 + (hA)^2/20}{I - 3hA/5 + 3(hA)^2/20 - (hA)^3/60} \qquad (3)$$

has a property called L-stability [5][6], an extension of A-Stability, which makes it immune to the kind of numerical instability of the trapezoidal rule.

In real-time applications, CDA is avoided in its original implementation because of the time-step modification. Constant time-step CDA can be performed to remedy this in real-time applications, but is rarely used in practice.

One can also observe that the order-5 L-stable formula of Eq. 3 has a higher precision than the trapezoidal rule of integration of Eq.2. The concept of 'order of discretization method' directly refers to this fact. Indeed, the division of the numerator by the denominator of Eq.3 will result in a series expansion that match the 5 first terms of the Taylor expansion of the matrix exponential.

### C. *SSN vs. delay-based parallelization methods*

The classic technique to achieve real-time simulation of super-large grids, like the one at Hydro-Quebec, is based on the use of the propagation delays that are embedded within the lines models. Good examples are 'long' Bergeron-type transmission lines and frequency-dependant variants. Such 'long' lines – by long we mean that the propagation delay is greater than the DRTS time-step - are numerous in power transmission grids. Using these delays, system equations can be parallelized and computed on many CPUs/cores in parallel, without approximations.

In distribution grids however, line lengths are much shorter, typically 1-5 km, and this Bergeron-line decoupling technique cannot be used. The best decoupling technique that remains in this case is the so-called 'stublines'. A stubline is basically a Bergeron line whose parameters are set to obtain exactly one time-step of delay. One can then try to substitute one short pi-line of the model by a stubline. The problem is that it modifies the impedance of the network at the point of stubline insertion, typically adding more capacitance than in reality. Fault currents can be erroneous in this case.

With SSN by contrast, one can avoid this kind of approximation because of its huge node count handling capability.

## V. E*PHASOR*SIM REAL-TIME TRANSIENT STABILITY SOLVER

The e*PHASOR*sim tool [9] offers real-time dynamic simulations for transmission and distribution power systems. This is the same type of solver than the well-known PSS/e, for example, that simulates a set of differential equations (machine and control devices) linked by an algebraic constraint, the power grid at the fundamental frequency.

Applications such as contingency studies, testing control devices, operator training, and SCADA system tests are examples for employing this tool. Its real-time performance has been tested with a time-step of 1 to 10 milliseconds on a real-time simulator for large-scale power systems in the order of 50000 buses, 15000 generators, and over 20000 control devices. e*PHASOR*sim phasor solution supports 3-phase modeling and is therefore adapted to distribution grid simulation, in which phase unbalance in common.

Notably, e*PHASOR*sim solves the complex arithmetic nodal admittance equation in parallel on up to 16 cores using METIS routines to achieve recent performances.

e*PHASOR*sim uses Excel-type netlist format and can also read and run PSS/e files and models.

## VI. ACTUAL DISTRIBUTION GRID REAL-TIME SIMULATION CASES

### A. *Enel Distribuzione distribution grid (SSN)*

At the Smart Grids Test Center of Enel Distribuzione, in Milan (Italy), radial distribution systems, like the one in Fig. 1, with more than 750 nodes (with 980 L-C states mainly coming from short pi-lines) have been recently simulated in real-time at a time step of 52 µs, without algorithmic delay, using four cores Intel-Xeon Processor-E5-2687W running RT-LAB. To achieve this performance, SSN reduced the network into a system with only six nodes and six multi-terminal branches (i.e., SSN partitions/groups) and used threaded process to compute the SSN groups in parallel, without any delay.

The system in Fig. 6 is a real Enel Distribuzione grid, automatically imported from the Asset Management System database, and is being used as a pilot project on Smart Grids called "Grid for Europe" (Grid4EU) funded by the European Community.

Enel Distribuzione objectives are mainly to verify the IEC-61850 protocol and relay on a set of faults and to develop smart grid solutions in terms of control and regulation of distributed generators. Testing remote control systems, like SCADA and Remote Terminal Units (RTU) are part of these objectives. In general, the purpose of the Enel Distribuzione Test Center is to have a complete hardware-in-the-loop simulation structure to test and develop systems actually in operation and new smart grids solutions [7]. The OPAL-RT real-time simulator is a key device for Enel Distribuzione because it allows simulation of large networks, like distribution grids, in real-time.

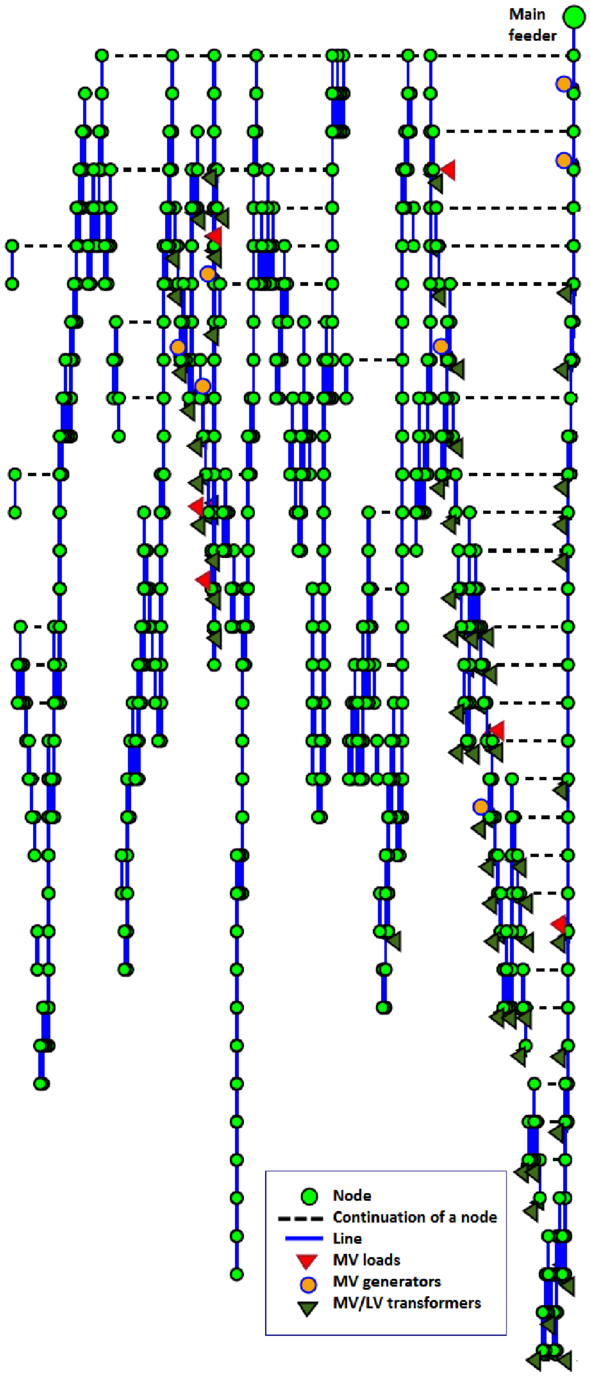


Fig. 6. Enel Distribuzione distribution grid (model case E1a)

## B. *France Distribution System (SSN)*

In [4], the authors simulated the F1a grid depicted in Fig. 7, a typical configuration in France, to study the impact of various load profiles and control strategies. They achieved real-time simulation with simple delays and reactive power compensation injection. However, such a technique is not adequate for fault and protection studies.

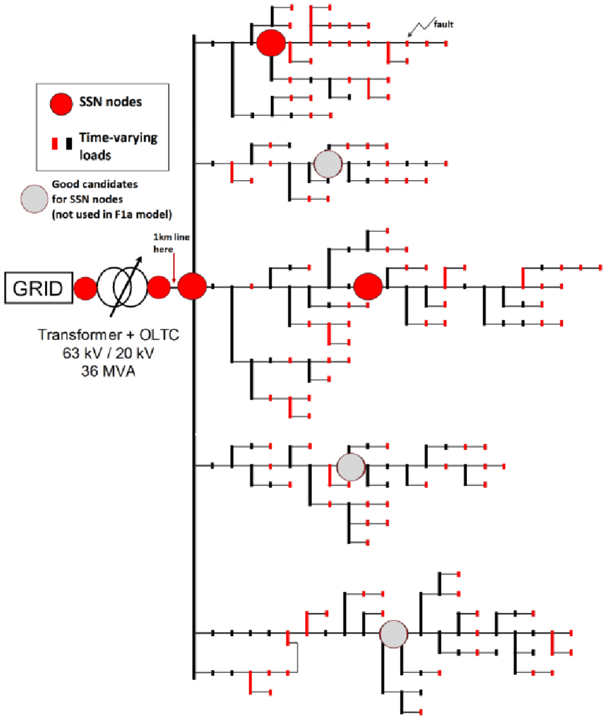


Fig. 7. France distribution grid (model case F1a)

The F1a distribution system with an on-load tap changer (OLTC) transformer at the feeder point, 120 3-phase time-variable loads (TVL), 3-phase fault and more than 650 equivalent EMTP nodes can also be simulated in real-time with the SSN solver. Using SSN and a 15 SSN nodes separation of the network (the 5 red dots in Fig. 3), the F1a model with OLTC and one 3-phase fault can be simulated in real-time at a time-step of 70 µs on an Intel-Xeon Processor-E5-2687W (Xeon V3), again using only 4 of the 20 available cores, without any delays or stublines.

The grey points in Fig. 7 also show other points where SSN nodes may have been used to further decouple the grid into more partitions for SSN. Active research is currently being done to find ways to determine the best strategy for node/partition determination in SSN. Usually, one will look for a low node/partition ratio.

## C. *F2 Distribution Grid using ePHASORsim*

In [8], the impact of the plug-in electric vehicle (PIEV) fleet on the distribution grid of the Deux-Sévres department in France was studied using a real-time simulator. The authors wanted to know if the PIEV could be used as an energy reservoir to stabilize and control this grid (model F2a) under various contingencies, like when the power loop is opened (*Switch* in Fig. 8). Because no transient study had to be made during this study, the author used a real-time 'Phasor' domain solver called e*PHASOR*sim, a solver used for Transient Simulation, adapted and optimized for real-time simulation.

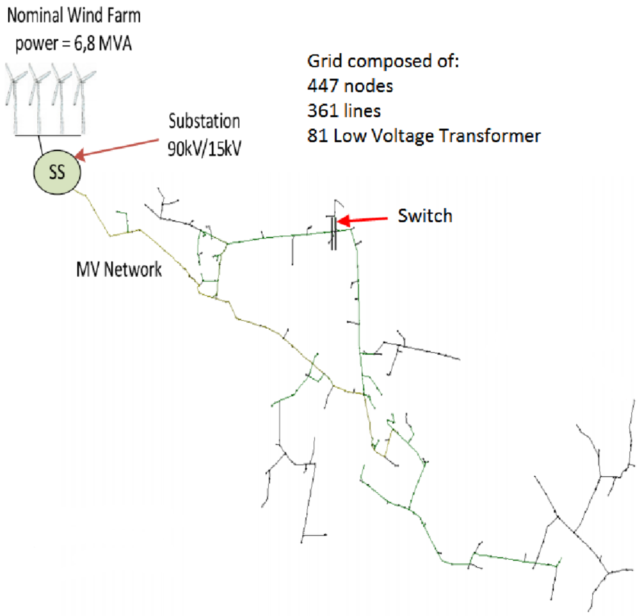


Fig. 8. Model case F2a using e*PHASOR*sim

Reference [8] uses e*PHASOR*sim to validate a distributed energy test platform with a real time simulator and advanced metering infrastructure and to verify various electric vehicle supervision strategies in the network. The simulator was also used to evaluate communication constraint and test smart meters and EVs charging station.

As mentioned earlier, e*PHASOR*sim is designed for a much higher node count (50000 as of 2015) but this example is used to show that this type of phasor solver is sufficient in case of voltage and power flow control studies.

## CONCLUSION

The use of a real-time simulator helps Enel Distribuzione to verify their protection schemes and protocols as well as to study the smart grid concepts required to run their grid effectively and reliably.

The real-time simulation of the Enel Distribuzione distribution grid is possible with the advent of SSN, a delay-free solver designed for grids with 500-1000 nodes, depending on the complexity and topology. Adding delays in this type of grid, by the means of stublines, alters their impedance and greatly diminishes the accuracy of simulation. The fact is that SSN has no internal delay, because it's derived from the EMTP algorithm. The parallelization capability comes from the fact that the use of very few and large branches (or partitions) in SSN makes their parallel calculation efficient on modern Intel-type processors. TABLE 1 summarizes the real-time performance on the latest Xeon-processor based PC available as of May. 2015.

The real-time performance of the F1a grid is actually worse than the Enel Distribuzione one (E1a), despite the fact that it contains fewer nodes. The reason for this is that the F1a grid contains 120 3-phase TVL, modelled as 'constant PQ loads' (meaning that the prescribed PQ values are computed from the actual voltage at the load), substantially increasing the calculation burden of the model. TVL used in F1a are simple dq-type injection but they nevertheless increase the size of the state-space matrices of SSN. A user could use available simulator cores to implement complex loads without affecting much the performance of SSN if desired.

TABLE 1: Real-time performance of distribution grid models on ARTEMIS-SSN 7.0 with Intel-Xeon Processor-E5-2687W (Xeon V3)

| **Case name** | **# of EMTP nodes** | **# of grid L/C states** | **SSN nodal matrix size** | **# of core used** | **Real-time step** |
|---|---|---|---|---|---|
| Enel Distribuzione E1a (SSN) | 750 | 984 | 6 | 4 | 52 µs |
| F1a (SSN) | 650 | 369 | 15 | 4 | 70 µs |
| F2 (e*PHASOR*sim) | 447 | n/a | -- | 1 | 1- 10 ms* |

* user selected time step

The large count of inductance and capacitance states in the E1a grid (ENEL) is due to the used of pi-line model while in the F1a model mutual inductance (without capacitance) where used. It would be worthwhile to verify the performance of the E1a grid with mutual inductance links instead of pi-lines but this has not been done in this paper. In the case of the F2 grid simulated by e*PHASOR*sim, the grid is represented by a complex impedance matrix and therefore has no L/C states.

The paper also described the various protocols available in the various DRTS platforms of Opal-RT (e*MEGA*sim with SSN, e*PHASOR*sim and Hypersim). These protocols include DNP3, OPC, IEC-61850, IEC-60870, C37.118 and Modbus.

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