ANALYSIS OF A HYBRID AC-DC MEDIUM VOLTAGE BENCHMARK NETWORK WITH RENEWABLE PRODUCTION USING QUASI-STATIC TIME SERIES

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Benchmark networks, known also as test networks developed by renowned international organizations need to be upgraded in order to keep pace with current and future trends regarding grid development.

This paper presents a hybrid AC-DC MV benchmark network in order to study its behavior and advantages in various situations. A novel method for dynamic analysis of the grid is presented and demonstrated using the proposed hybrid network by implying Quasi-Static Time Series (QSTS), with time series short enough not to require complex modelling of what is happening between two time steps.

Keywords: grid modelling, QSTS, renewable sources integration, hybrid AC-DC network

1. Introduction

Specialists in the field of electrical networks analyze specific scientific aspects both in concrete and particular cases, as well as within networks that have been studied by other experts, so-called benchmark grids.

Prestigious international organizations have defined such electrical networks within working groups for various voltage levels and specific situations that present unique challenges.

The majority of benchmark electrical networks (known also as “test networks”) are AC grids networks. Until recently, they included only large conventional generators characterized in steady-state operation by an active power P at specific nodes and a node voltage U (PU type node), while these generators are equipped with automatic voltage regulators designed to maintain the voltage as close as possible to a setpoint. In high and ultra-high voltage networks, this voltage maintenance is typically achieved by continuously adjusting the reactive power produced or consumed by the generator to reach the desired voltage.

Dynamic simulations in high voltage AC networks with DC links are studied in several works, e.g. [1] and [2], adding to legacy AC networks new functionalities. With the emergence of distributed generation, benchmark networks - particularly those in distribution systems - have also started to incorporate

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elements of distributed generation. Some of these elements lack the capability to adjust their reactive power Q to maintain constant terminal voltage, being characterized by fixed active power outputs P=constant at specific moments and fixed reactive power, often considered nearly zero in most of the situations.

The most important trends which require an update of benchmark grids are:

- The apparition of electrical energy storage systems;
- The need to study hybrid AC-DC networks which are trickling down architectures adapted from HV networks;
- The apparition of microgrids which can function both connected to or independent of the public network.

Among the noteworthy test / benchmark networks developed is the CIGRE one [3], presented in Fig. 1.

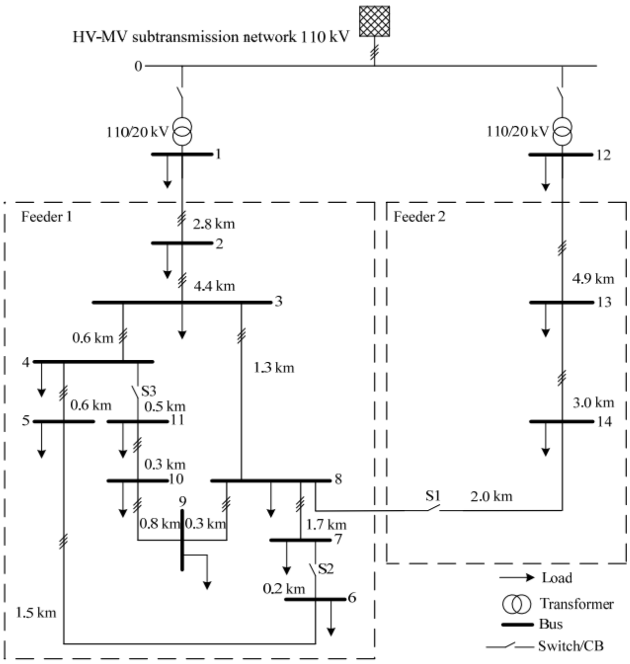


Fig. 1. CIGRE benchmark network [3]

The network presented in Fig. 1 is transformed into a hybrid AC-DC version in [4] by replacing the line between nodes 8 and 14 with a DC link.

Another noteworthy benchmark network is the 33-bus network proposed by IEEE [5], presented in Fig. 2. Being developed a long time ago, numerous papers have presented variations of it, such as extensions [5], renewable integration etc.

Due to starker integration of renewable energy sources into networks, especially at LV and MV levels, the way in which they are analyzed in terms of dynamic behavior needs to evolve. A recommended way to do this is the use of Quasi-Static Time Series (QSTS).

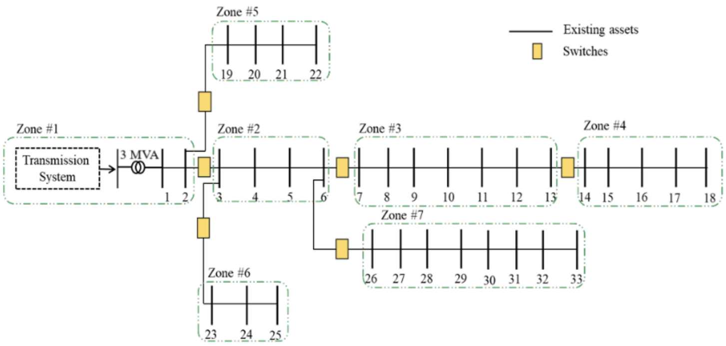


Fig. 2. IEEE 33 benchmark network [5]

QSTS is a method with which an evolutionary process can be analyzed based on a series of moments in which the process is considered to be quasi-static [6]. For electrical networks, this means that their dynamic behavior can be studied using multiple moments, situated at a fixed interval in time, in which they are considered to be in steady state. While there have been attempts to study networks based on this method [7,8, 9, 10], most of them have considered long time intervals, making each studied moment practically unrelated to the previous or future one. In order to be able to study the real dynamic behavior of a network, short time intervals (ms-s) need to be considered. Such short time data has been recorded in networks in H2020 NobelGrid [11], H2020 WEDISTRICT [12] or in H2020 SUCCES [13], where one to several seconds have been considered for electrical data recording.

In the following sections, the adaptations made to the IEEE 33-bus test network by the authors are presented, along with the novel proposed method to analyze aspects of the dynamic behavior using QSTS integrated with the help of the open-source program OpenDSS [14-16], a proven electric power distribution system simulator [17-19].

2. Implementation of a novel QSTS-based method for implementing automatization functions

Studying the dynamic behavior of a network with the help of QSTS and using short time series means that there is a link between the inputs and outputs of two consecutive moments. In traditional loadflow (LF) calculations, for the PU nodes, the reactive power of the node is calculated during the LF process of convergence, such that it is obtained the requested U in that node [20]. The LF results do not consider the dynamic process which leads to the desired node voltage U. However, in reality, this voltage is obtained through an automation which has as possible controls the P and Q injected or consumed in the node. The dynamic evolution of the node voltage until the desired set-point voltage U is reached in the node can be obtained only if the control loop of U is also part of the simulation. In this respect, PU nodes might be discarded in the load flow calculation of a steady state network and they can be replaced by PQ nodes in each moment analyzed, while the U control is implemented by changing Q or P in the node between two consecutive LF calculation corresponding to two moments in a time series until the voltage U is reached in the specific node.

By implementing a PID controller [21-25] discretized in the z-domain acting as a voltage regulator between two moments of the QSTS sequence, a PU bus can be then obtained by transforming it into a PQ node and by adapting the reactive power Q based on the deviation of the bus voltage U from the reference value of the original PU bus in the previous moment. This novel approach has two main benefits.

First, the dynamic evolution is similar to the real functioning of voltage regulators included in generators, thus bringing a better twin between simulation and real implementations. Secondly, it can include the distributed generators with flexibility in their PQ behavior in the standard PQ nodes (busses).

The way in which the PID controller behaves in a QSTS sequence is presented in Fig. 3.

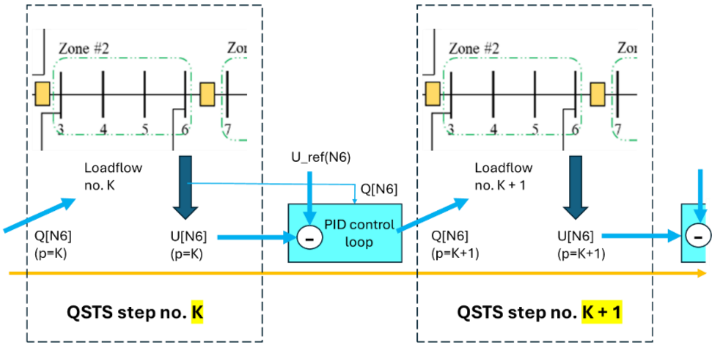


Fig. 3. PID controller loop in a network bus acting between two moments of the QSTS sequence

3. Proposed hybrid AC-DC benchmark network

Starting from the test / benchmark IEEE 33-bus network, a smaller, simpler network comprising of only 10 busses was selected, as shown in Fig. 4.

Renewable production in the form of two PV systems has been added in busses N6 and N21. The results of the steady state calculation for this situation show that two different regions appear, one with too high generation and one with too high demand. The proposed solution to this issue is to add a 10 kV DC link between buses N5 and N22, which are situated in the problematic areas, in order to improve the situation of the problem in both busses. The resulting proposed network is presented in Fig. 5.

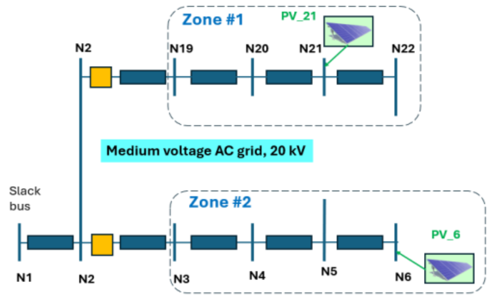


Fig. 4. Starting AC network

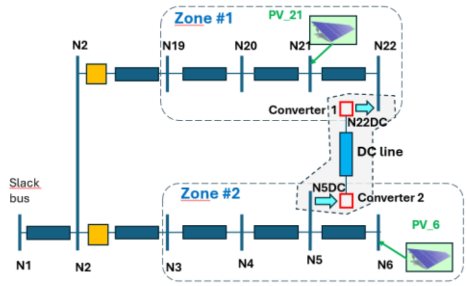


Fig. 5. Hybrid AC-DC network

4. Treatment of the DC slack bus

The power-flow on the DC line between nodes 5DC and 22DC is calculated with the same LF tool which is used as well for the AC network and needs its own slack bus in the DC network, as being one of the two DC nodes. As the power flow is from node 5DC to node 22DC, the DC slack bus has been chosen as being in the node 5DC. This means that the voltage in 5DC should be kept constant during a quasi-static moment, in order to behave as a slack bus (constant U). In our analysis, it is proposed that this constant voltage is obtained between the terminals of a capacitor which is enough big that between two moments of the QSTS evolution the voltage can be considered as being quasi-constant.

In this respect, a capacitor can be used in order to hinder the depreciation of the DC grid characteristics [26], whose electrostatic energy can emulate and take the role in a DC grid of reduction of the speed of voltage depreciation, similar to the mechanical inertia specific to AC grids, which is reducing the speed of frequency depreciation. In order to calculate the required capacitance which can ensure a quasi-constant voltage level during a time step, in our approach the voltage on the DC node acting as a slack bus is required to drop no lower than $U_{min} = 0.9\, U_N$ in $\Delta t \approx 5\, s$ for an extracted power $P_e = 1200\, kW$ from bus 5DC, as presented in eq. (1), resulting in a value of 0.63 F.

$$C = 2 * \frac{\Delta E_{El_{Cond}}}{U_N^2 - U_{min}^2} = 2 \times \frac{P_e \times \Delta t}{U_N^2 - U_{min}^2} = 2 * \frac{1200 \times 10^3 \times 5}{10000^2 - 9000^2} = 0.63\ F \quad (1)$$

If theoretically the same P_e would be possible to be kept until full energy of the capacitor is extracted, the entire energy stored in the capacitor would be consumed in $T_{tot} = \frac{C \times U_N^2}{2 \times P_e} = \frac{0.63 \times 10000^2}{2 \times 1200 \times 10^3} = 26.25\ s$, which is the electrostatic inertial constant H_{ELS} equivalent to the AC mechanical inertia constant. The ratio between the time step and the electrostatic inertial constant is 0,38%, which is small enough to consider the system quasi-static at any moment, meaning that each moment represents a steady state.

5. Algorithm of the developed QSTS method

The developed method uses the steady state load flow calculations implemented in OpenDSS. The link between the requested power P_{N22} in AC node N22 to the absorbed AC power P_{N5} from AC node N5 is presented in Fig. 6 and has been implemented in a C# environment.

The converter 1 power absorbed from the node N22DC is given by (2) and the converter 2 power absorbed from the AC node N5 is described by (3):

$$P_{N22DC_{INV}} = P_{N22_{INJ}} / \eta_1 \quad (2)$$

$$P_{N5_{CONS}} = P_{N5DC_{INV}} / \eta_2 \quad (3)$$

where η_1 and η_2 are the efficiencies of the two converters. Moreover, the following additional relations apply:

$$P_{N22DC_{GRD}} = P_{N22DC_{INV}} \quad (4)$$

$$P_{N5DC_{GRD}} = f_{LF_{DC}}(P_{N22DC_{GRD}}) \quad (5)$$

$$P_{N5DC_{INV}} = PID(\Delta U_{N5DC}) \quad (6)$$

where $f_{LF_{DC}}()$ denotes the load flow calculation on the DC grid having N5DC as slack bus, and $PID()$ denotes the use of PID control between two steps of the QSTS sequence, having as input the variation of voltage in N5DC as compared to the N5DC nominal voltage.

6. Sets of tests

According to [27], "the time-step resolution ... of the QSTS simulation should be below the fastest delay in any device with discrete controls". For voltage control, including the situation of inverter-based local voltage control - measured, updated and controlled voltage can be made e.g. at 1 second time intervals [28], with good results. In order to prove the ability of studying hybrid AC-DC networks in a dynamic evolution using QSTS, the time step between two moments has been chosen as being ΔT=0.1 s (ten times lower than in [27], such that the dynamic behavior of the network can be well described even in a faster control reaction).

Moreover, the total studied time has been chosen to be 8 s, which has been proven to be enough long to catch the dynamics of the system for the proposed scenarios.

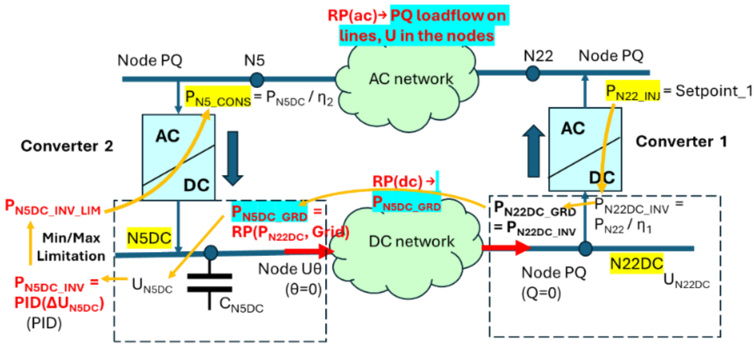
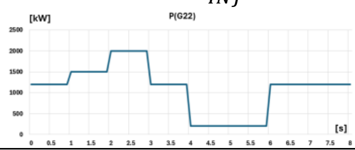


Fig. 6. Algorithm of the developed QSTS method

Two sets of tests (S1 and S2) have been considered, as per Table 1.

Table 1

Test	C_{DC} [F]	PID			P_{conv2_min} [kW]	P_{conv2_max} [kW]	Description
		Kp	K_i	K_d			
PID control of the voltage in node N5DC, with scheduled scenarios of $P_{N22_{INJ}}$ in N22							
S1.02a	0.63	50	0	0	0	3000	Evolution of $P_{N22_{INJ}}$ 
S1.02b	1.89	50	0	0	0	3000	
S1.03a	0.63	50	30	0	0	3000	
S1.03b	0.63	50	15	0	0	3000	
S1.03c	0.63	50	15	10	0	3000	
PID control of the voltage in node N5DC and P voltage control in N22 by regulating $P_{N22_{INJ}}$							
S2.01a	0.63	50	15	0	0	3000	$P_{N22_{INJ}}$ used to control U(N22) with $P_{N22_{INJ}}(0) = 1200\ kW$
S2.01b	0.63	50	15	0	0	6000	
S2.02a	0.63	50	15	0	0	6000	$P_{N22_{CONS}}$ evolution as per Figure 15a
S2.02b	0.63	50	15	0	0	6000	

where P_{conv2_min} and P_{conv2_max} are the power limits which the converter can supply in this setup.

In the first set of tests (S1.02a-03c), the transfer of active power between AC busses N5 and N22 is dictated by the requested power $P_{N22_{INJ}}$ in the AC bus N22, based on scheduled scenarios (blue line evolution Fig. 7a-11a). For this set, the effects of different values of the PID controller in the DC slack bus are studied. The main purpose of this set is to validate the developed QSTS method to analyze dynamic evolution situations of hybrid AC-DC networks.

The second set of tests (S2.01a-02b) keeps the PID controller on the DC slack bus with a set of parameters chosen in the first set of tests, while the power flow in the DC network is now calculated: 1) based on the P generation in N22 which regulate U(N22) and with an initial $P_{N22_{INJ}}(0) = 1200\ kW$ - in S2.01a/b and showing the dynamic evolution towards the voltage setpoint without disturbances on demand and 2) with dynamic change of the power demand in the AC bus N22 - S2.02a/b. In these tests, the voltage in N22 uses a second PID controller which controls the voltage in N22 to a setpoint value, by regulating it with active power $P_{N22_{INJ}}$ instead of more classical use of reactive power.

7. Results and discussion

Fig. 7-11 show the different behavior of the input power in the DC slack bus N5DC under the same requested power generation scenario in AC bus N22 depending on the tuning of the PID controller, alongside the behavior of the voltage at the slack bus 5DC. As can be seen, the powers and the voltage differ depending on the tuning, the purpose being to have an evolution of the values as smooth as possible, without oscillations and keeping the voltage of the slack bus as close as possible to its set value.

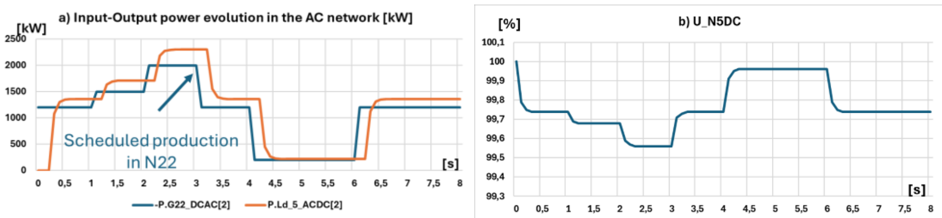


Fig. 7. Scenario S1.02a: a) Power in busses N5 (P.Ld_5_ACDC) and N22 (P.G22_DCAC[2]); b) Voltage in bus N5DC (U_5NDC)

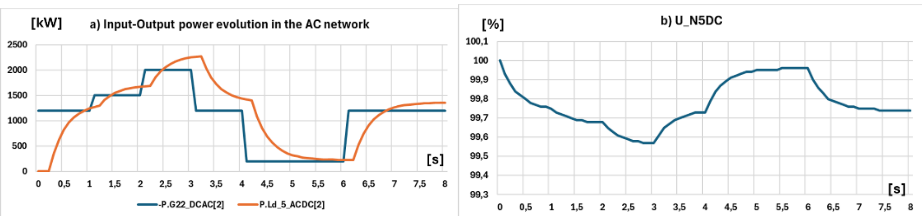


Fig. 8. Scenario S1.02b: a) Power in busses N22 (P.G22_DCAC[2]) and N5 (P.Ld_5_ACDC); b) Voltage in bus N5DC (U_5NDC)

Of notice is the fact that oscillations are produced by a too high value of the integrative constant (Fig. 9), by a too high value of the derivative factor (Fig. 11) or a combination of both (Fig. 11). Therefore, the PID controller kept for the next set of tests is only a P controller.

The results from the second set of tests further illustrate the functionality of the developed method to analyze hybrid AC-DC grids by proving the functionality even in more complex situations.

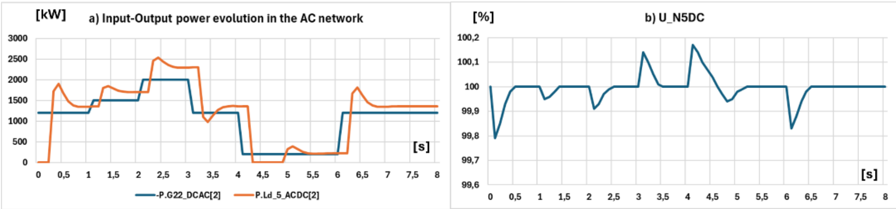


Fig. 9. Scenario S1.03a: a) Power in busses N22 (P.G22_DCAC[2]) and N5 (P.Ld_5_ACDC); b) Voltage in bus N5DC (U_5NDC)

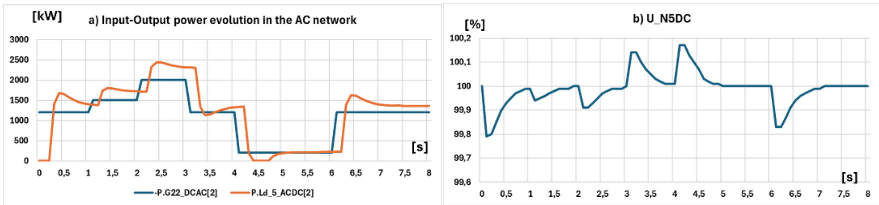


Fig. 10. Scenario S1.03b: a) Power in busses N22 (P.G22_DCAC[2]) and N5 (P.Ld_5_ACDC); b) Voltage in bus N5DC (U_5NDC)

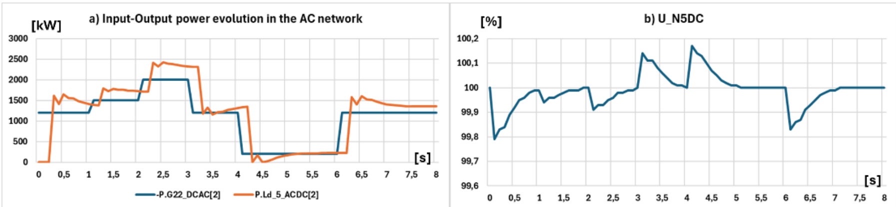


Fig. 11. Scenario S1.03c: a) Power in busses N22 (P.G22_DCAC[2]) and N5 (P.Ld_5_ACDC); b) Voltage in bus N5DC (U_5NDC)

In the following set of tests, the way in which bus N22 is set is modified. The active power production $P_{N22_{INJ}}$ is used to regulate the voltage in the AC bus N22 (U_{G22}) by the voltage controller introduced for this test and described in eq. (7), having been set only with a proportional constant with value $K_{P_U} = 1$ which can be tuned depending on the grid.

$$P_{N22_{INJ}}(t) = P_{N22_{INJ}}(t-1) + \left(U_{G22}(t) - U_{G22}(t-1)\right) * K_{P_U} \tag{7}$$

Fig. 12a illustrates for the scenario S2.01a the behavior of the voltage dynamic evolution in the AC bus N22 which is reaching $U_{99\%}$ in only 1.1 second. Fig.12.b shows the power evolution in busses N5 and N22 with a limitation of P_{conv2_max} to 3000 kW. Fig. 13 is given the evolution of the voltage in the DC slack bus N5DC, showing that the PID voltage regulator is not able to keep the DC slack bus voltage from deteriorating down to around 65%, due to long time limitation in the converter 2 power. After reaching this voltage level – at around T=6.8s, loadflow in the DC network did not converge anymore in the QSTS sequence (grey zone), showing a collapse of the DC link. For that reason, a more powerful converter would be needed at bus N22 to provide sufficient power to recover the voltage of the DC node N5DC. This adaptation is simulated in test S2.02b, where, as can be seen in Fig. 14a, the voltage in the AC bus N22 has a similar evolution as in the previous case, while in Fig. 14b, the voltage in bus 5DC can be seen that it has been recovered with the help of a higher dimensioned converter (P_{conv2_max} from 3000 kW to 6000 kW).

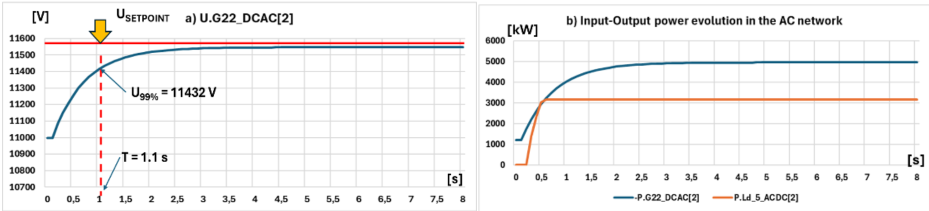


Fig. 12. Scenario S2.01a: a) Voltage in AC bus N22 (U.G22_DCAC[2]); b) Power in busses N22 (P.G22_DCAC[2]) and N5 (P.Ld_5_ACDC)

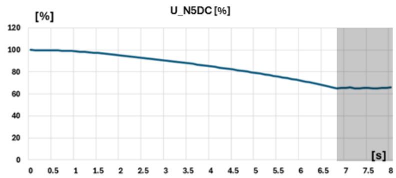


Fig. 13. Scenario S2.01a: Voltage in bus N5DC (U_N5DC - grey zone denotes non-convergent LFs)

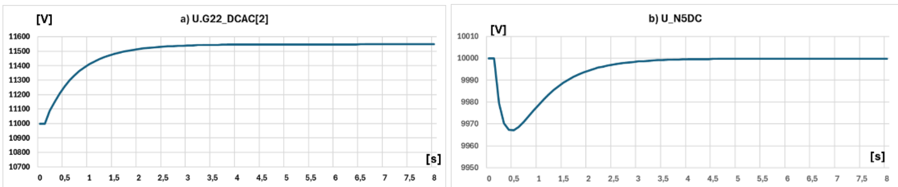


Fig. 14. Scenario S2.01b: a) Voltage in AC bus N22 (U.G22_DCAC[2]); b) Voltage in bus N5DC (U_N5DC)

The load/generation disturbance in N22 for scenarios S2.01a/b is presented in Fig. 15a, being considered a high dynamic behavior (quick changes of power).

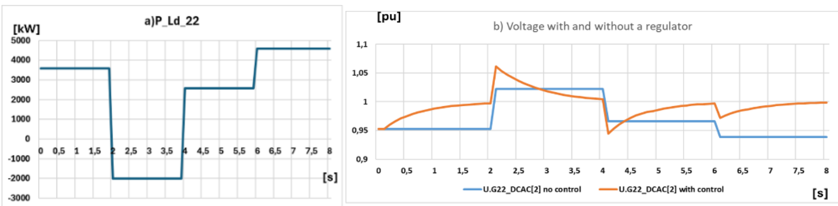


Fig. 15. S2.02: a) Load in bus N22 (P_Ld_22); b) Voltage in bus N22 (U.G22_DCAC) with and without a voltage regulator

The comparison between the behavior of the voltage in bus N22 without and with a voltage regulator can be seen in Fig. 15 b), with the differences between the average voltage in both cases being presented in Table 2, showing the effectiveness of voltage regulation of node N22 by controlling the injected active power $P_{N22_{INJ}}$.

Table 2

Average value of the voltage in bus N22

Case	Relative value	Reference value	Average deviation
Without regulator	0,969527	U_N	3,05%
With regulator	0,994346	U_N	0,57%

8. Conclusions

The paper presents and demonstrates a novel QSTS based method to analyze the dynamic behavior of hybrid AC-DC networks using existing load flow calculation software, such as OpenDSS, thus paving the way for further dynamic analysis possibilities of hybrid networks. One important result is a new benchmark network, based on the established IEEE-33 network, to simulate both AC and DC networks functioning together, with distributed renewable generation being included, an aspect which is increasingly relevant in modern grid analysis. The parameters of the proposed network has been specifically chosen to be able to analyze the grid in limit situations, where various measures need to be considered. Two sets of tests have been performed, to calibrate and verify the implemented method. Aspects of inertia in a DC network through appropriate capacitor on the DC slack bus and checking dynamic evolution of essential electrical means have also been proven. An essential contribution relies in demonstrating the ability of QSTS combined with load-flow calculation to be able to analyze various dynamic evolutions of a hybrid AC/DC network, while implementing control algorithms between QSTS time steps, thus being able to contribute to existing dynamic evolution methods of studying power networks.

Further research of the authors will include expanding the benchmark grid into a more complex one on the DC side, including flexible bidirectional power flow on the DC networks, islanding possibilities on AC network while still having a DC connection, introducing FACDS and storage possibilities and introducing a third type of interconnected network using the energy vectors natural gas and hydrogen.

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