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MODELING AND DESIGN OF VOLTAGE CONTROL SYSTEMS FOR THE ENERGY TRANSITION

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VOLTAGE AND REACTIVE POWER CONTROL IN TRASMISSION SYSTEMS

The power systems are undergoing significant changes, due to the massive increase in the exploitation of renewable power sources. Moreover, the global warming issue is leading to a massive decarbonization action, which is applied in power systems also by means of the progressive shut off of coal-fired power plants. The changes in electrical power systems are making more difficult for the actual voltage control system to maintain voltage control in all operative conditions. Given this premises, the actual Italian 3 level hierarchical control, which consist of Primary Voltage Regulation (AVR), Secondary Voltage Regulation (SART, Voltage control areas, pilot nodes) and Tertiary Voltage Regulation (OPF), may be undergo into a structural revision.

PRELIMINARY STUDIES ON SECONDARY VOLTAGE CONTROL'S AREAS AND PILOT NODES

Fig. 1: Italian Trasmission Network (380 kV only)

A preliminary study has been carried out on IEEE 39 Buses (Fig.2) to identify the most influential parameters on Zoning (i.e. the determination of the voltage control areas) and pilot nodes (PNs) selection. The results highlighted the unsuitability of voltage control based on adaptive nodes clustering only, due to the progressive decrease of nodes electrical decoupling and the progressive reduction in pilot nodes short circuit power (which indicates their capability of affecting the voltage of the other nodes). Thus, efforts are focused on finding new kind of voltage control approaches that allow the buses' voltage regulation without relying on the rationale of voltage control areas and PN.

Voltage regulation for Italian Transmission Network (ITN) (Fig.1) is the main topic.

GOAL: figure out a solution for voltage control on ITN considering

- Decarbonization
- Renewable energy resources
- Decrease in buses' short circuit power
- Decrease of buses decoupling

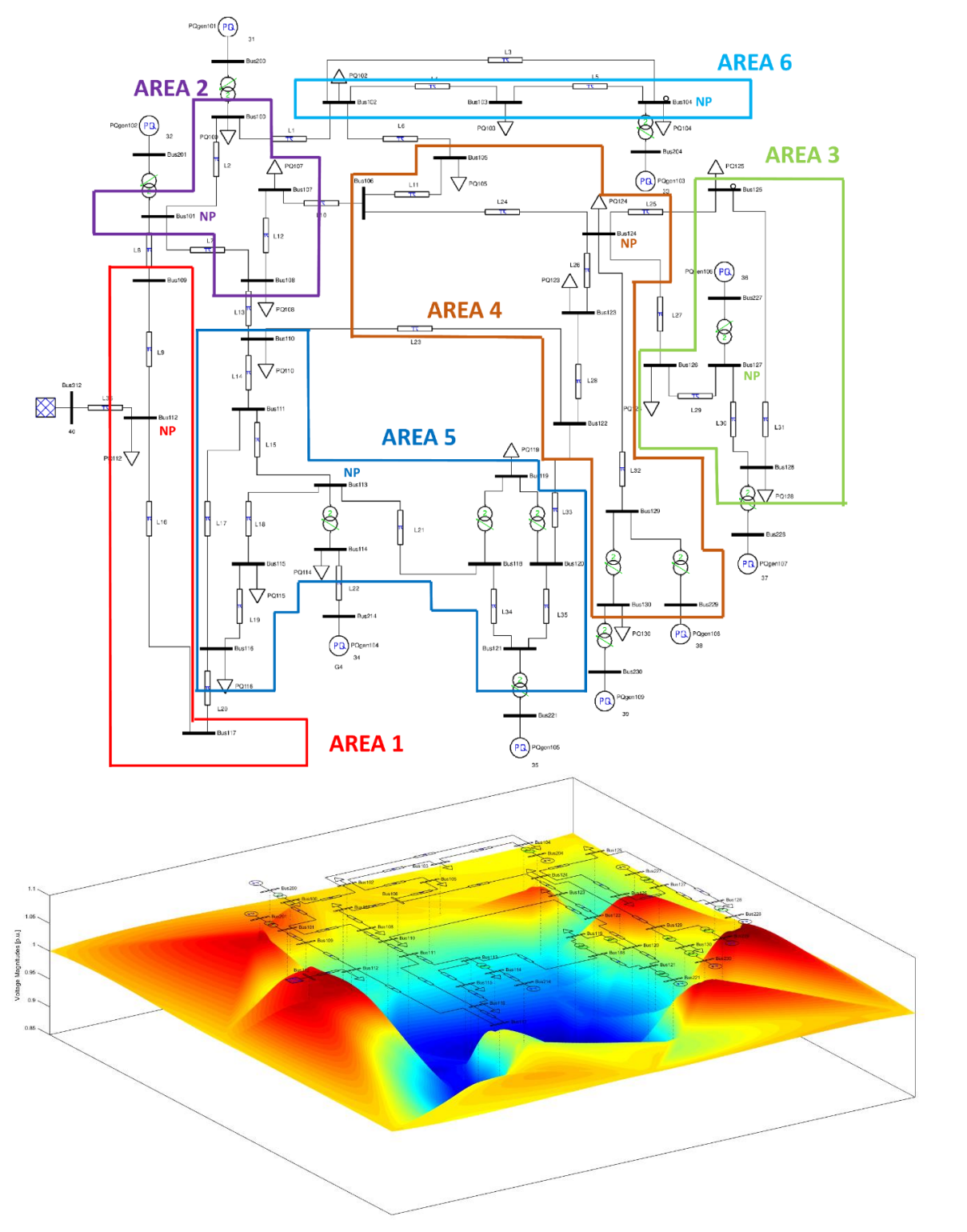

Fig. 2: IEEE 39 Bus Test Network (above) and the respective result of PF (below)

DESIGN OF NEW VOLTAGE CONTROL ARCHITECTURES

In the framework of voltage control, the transmission network can be modelled as a MIMO system. Thus, MIMO systems control approaches are here studied and tested.

DECOUPLING CONTROL

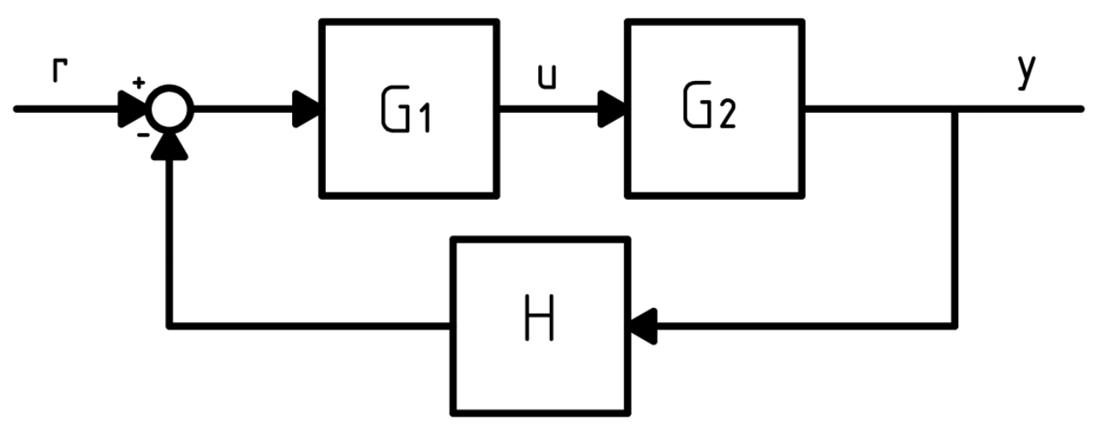

Fig. 3: Decoupling Control general scheme

The Decoupling Control [2] concept (Fig. 3) is based on the definition of a reference transfer matrix capable of decoupling the input-output behaviour of the system, making it possible to act on each output variable separately (managed like independent SISO systems).

The control law results: $G_1(s) = G_2^+ \, G\,(s)$ where *G(s)* is a diagonal non singularity matrix ($^+$:represent the pseudo-inverse operator)

The decoupling control requires that control signals are at least equal in number to the controlled outputs. A reduced number of selected nodes are here called Controlled Nodes (CNs), because are used to provide feedback to the control system, thus being conceptually similar to the actual PNs. Simulations (Fig. 4) were performed using a model of real Italian transmission network portion.

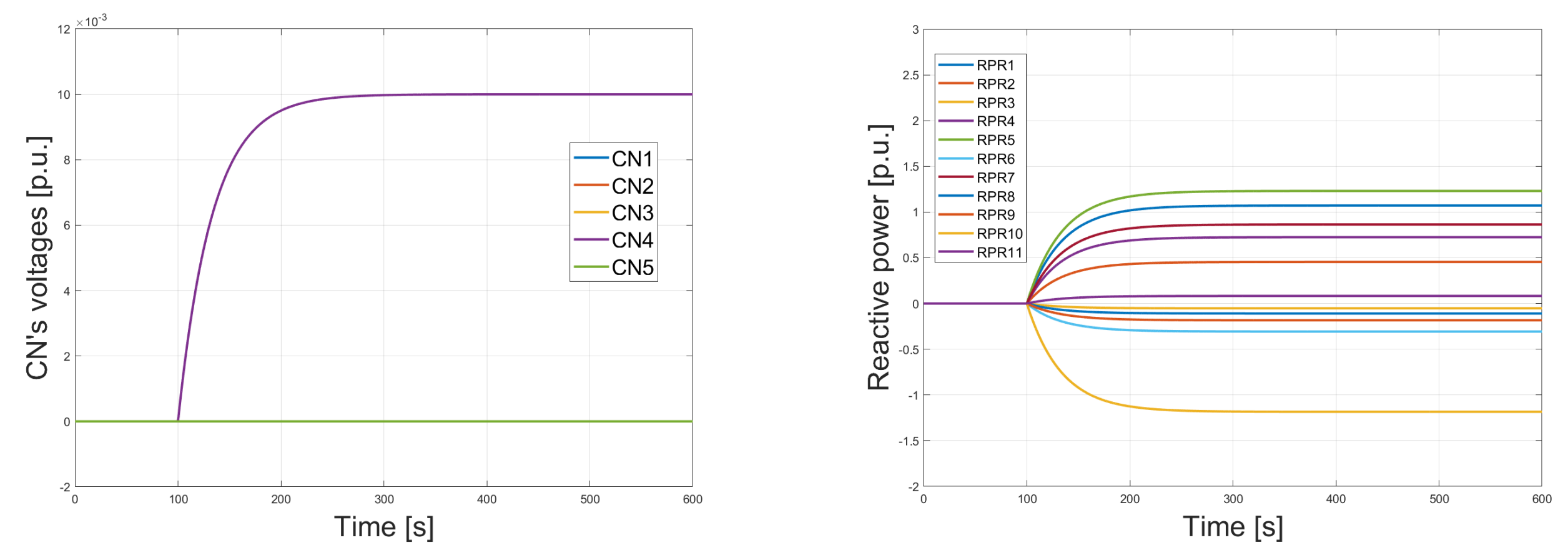

Fig. 4: Decoupling Control simulation results: voltages (left), reactive powers (right)

LQRI CONTROL

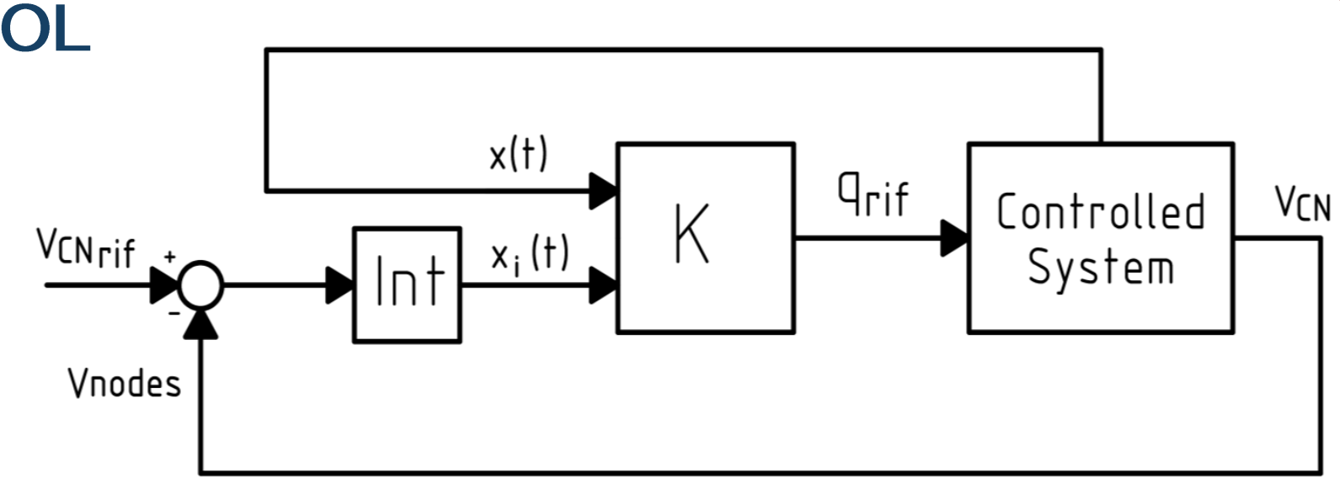

Fig. 5: LQRI control general scheme

LQRI (Fig. 5) is a MIMO state-feedback controller whose coefficients are calculated following an optimization process. Considering a generic dynamic system in its standard state-space representation $\dot{x} = Ax + Bu,$ where *x* is the state array and *u* is the control input, with a quadratic cost defined as:

$J(u) = \sum_{n=0}^{\infty} \{z^T Q z + u^T R u + 2 z^T N u\}$, thus the feedback control law that minimizes the value of the cost is $u = -Kx$, where *K* is given by $K = R^{-1}(B^T P + N^T)$ and *P* is the Riccati equation's solution.

By implementing LQR approach as secondary voltage controller, the nullification of the CNs voltage error is needed, thus an integral action is added to the system's output [3][4]. Simulations (Fig. 6) were performed using a model of real Italian transmission network portion.

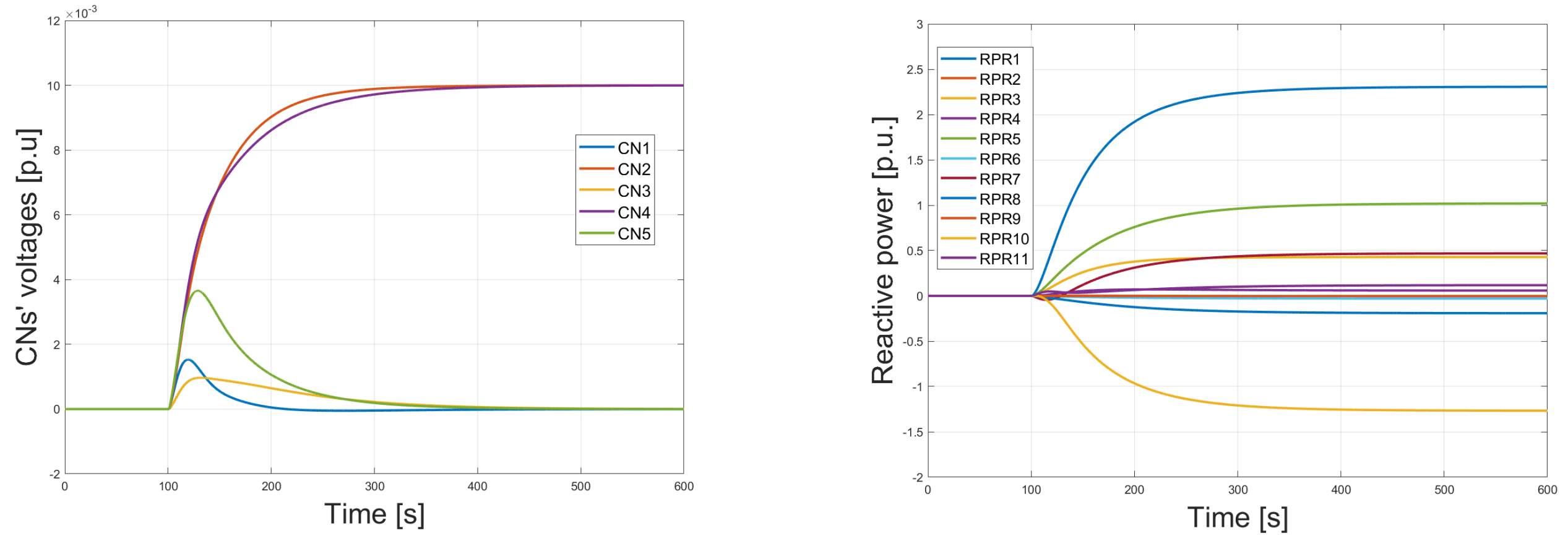

Fig. 7: LQRI control simulation results: voltages(left), reactive powers (right)

DYNAMIC PERFORMANCE COMPARISON

Both the control approaches require the determination of the power system's operative state (transfer function for the decoupling control, state space representation for the LQRI) for calculating the control parameters (decoupling matrix and state feedback gain matrix for LQRI). This implies the need of recalculating the control parameters when the power system's operating state changes (e.g., due to loads' reactive power variation, lines' opening/closing, power plants' connection/disconnection, etc.).

What about inherent stability (or adaptivity) during the dynamic state recalculation?

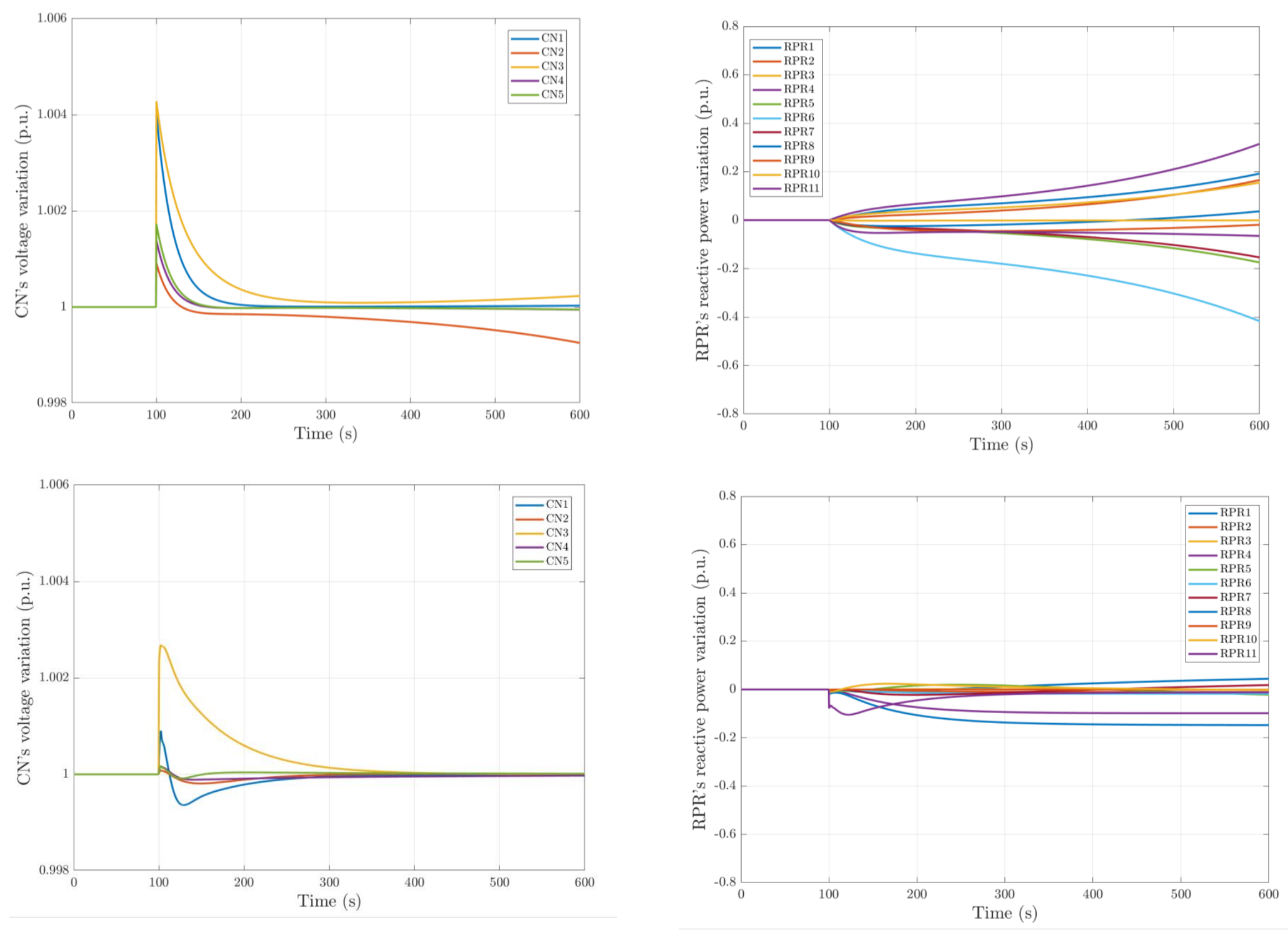

Fig. 7: Reactive load variation response of decoupling (above) and LQRI (below)
(voltages: left , reactive powers: right)
approaches with control matrices calculated on a different working point

LQRI CONTROLLER IMPLEMENTATION FOR HARDWARE IN THE LOOP TESTS

The first issue which must be solved to design such voltage regulator is the determination of the set of system states to be fed back to the controller for ensuring its correct operation. This requires identifying the variables that are directly measured in a transmission system and determine if they can be useful for the LQRI state feedback. The results of [4] turns up in the following state calculation formula: $v_{MTeq} = v_{AT} + x_{Teq} \cdot q_{AT}$, since it can be demonstrated that the state feedback is the RPR (Reactive power Resources) Thevenin equivalent's medium voltage (see Fig. 9).

The second issue to be solved is that power plants can be connected and disconnected, or their remote reactive power control function can be enabled and disabled. Therefore, the system's actuator number changes over time. This peculiar problem of LQRI control application to SVC in a power system has been addressed, by means of a bumpless control transfer method (Fig 9) that avoid abrupt K matrix change. Results of its application are depicted in Fig. 10.

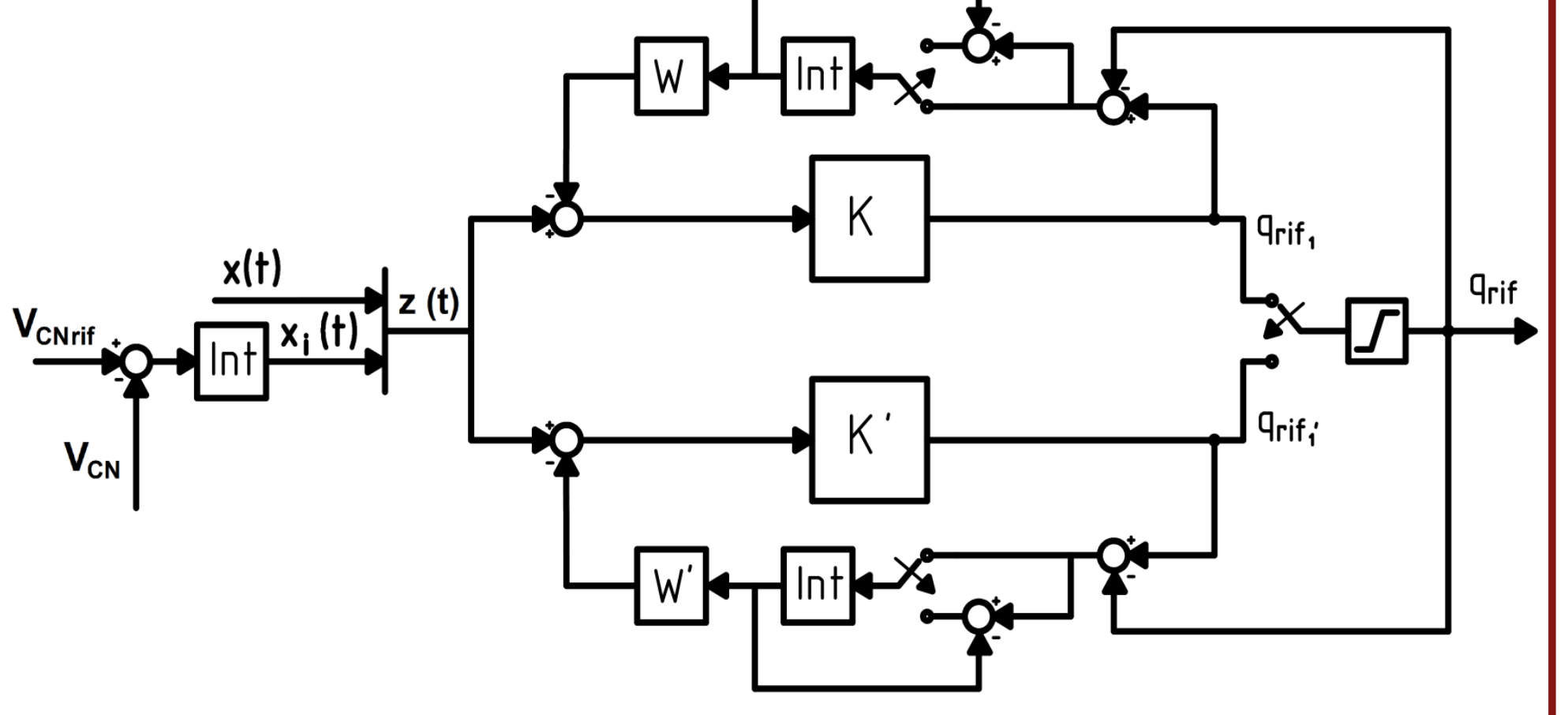

Fig. 9: Bumpless transfer scheme for LQRI control in a MIMO system, application to SVC)

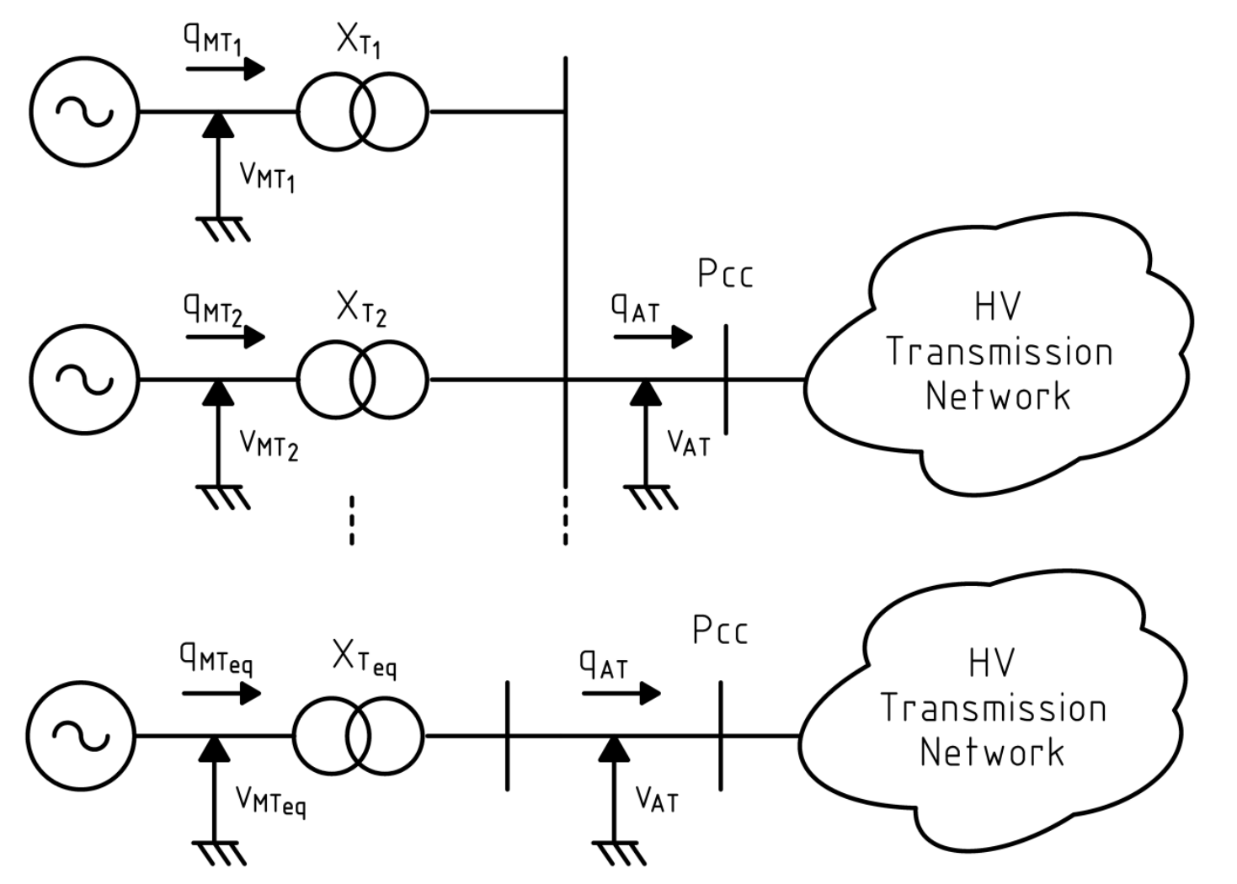

Fig. 8: Notional representation of an RPR composed by multiple generators/sources, with the significant measured variables highlighted: multi-generator (above) system, equivalent single generator model (below)

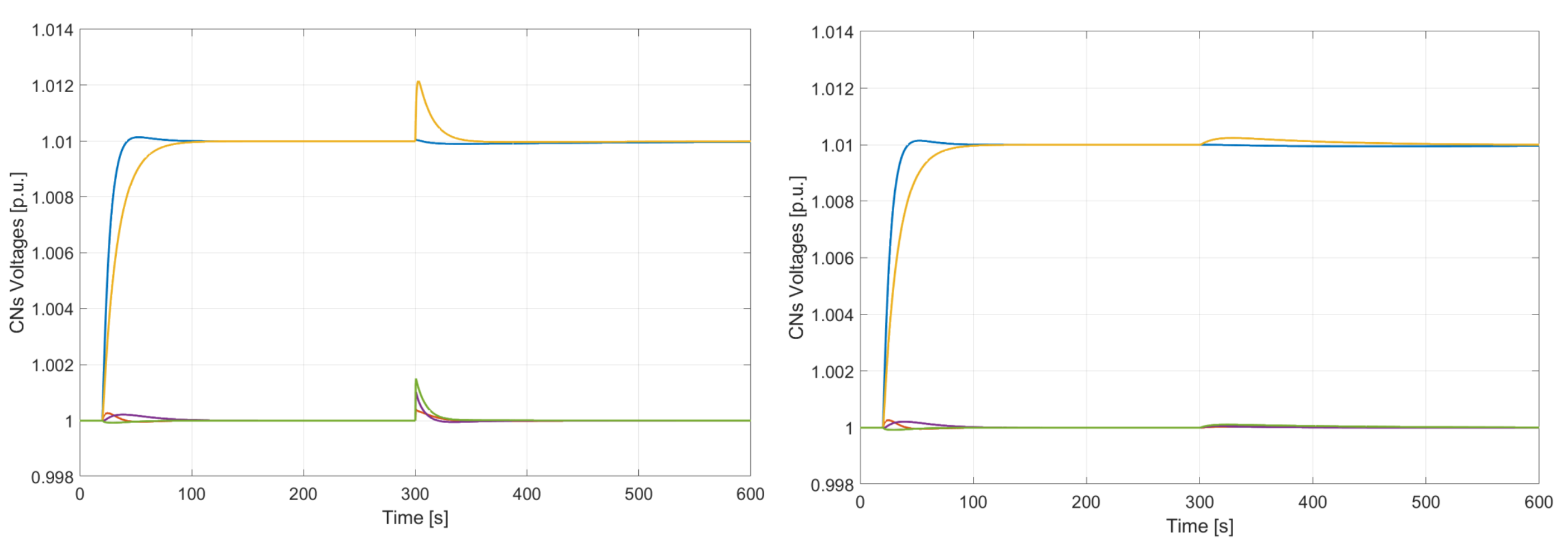

Fig. 10: Change in voltage reference without (left) and with (right) bumpless transfer logic

PUBLICATIONS

[1] F. Marzolla et al., "Study on zoning procedures for Secondary Voltage Regulation," 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 2020, pp. 1-8 (personally presented)
[2] G. Sulligoi et al., "Reactive Power Resources Management in a Voltage Regulation Architecture Based on Decoupling Control," 2021 AEIT International Annual Conference (AEIT), 2021, pp. 1-6 (personally presented)
[3] A. Vicenzutti, F. Marzolla, et al, "Reactive Power Resources Management in a Voltage Regulation Architecture Based on LQRI Control," 2022 IEEE International Conference on Environment and Electrical Engineering (EEEIC / I&CPS Europe), Prague, Czech Republic, 2022, pp. 1-6. (personally presented)
[4] A. Vicenzutti, F. Marzolla, et al, "Study on the State Feedback Selection and Measurement for the Application of an LQRI Secondary Voltage Regulator to a Transmission System," 2022 20th International Conference on Harmonics & Quality of Power (ICHQP), Naples, Italy, 2022, pp 1-6. (personally presented)