Study on the State Feedback Selection and Measurement for the Application of an LQRI Secondary Voltage Regulator to a Transmission System

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***Abstract*— The electrical power system is being significantly affected by the climate change mitigation actions. The power generation, originally centralized, is transitioning towards a more decentralized paradigm due to the coal-fired power plants shut off and the increase in renewable power. Issues in transmission system's voltage control may arise, if the voltage regulation architecture is not modified accordingly. To this aim, in this paper it is investigated the use of a Linear Quadratic Regulator with Integral action (LQRI) for the secondary voltage regulation, aimed at exploiting several reactive power sources as actuators. Being the LQR class of regulators requiring the system state to correctly operate, and being a transmission system a complex system, a critical investigation must be done. In particular, it is needed to identify the variables that are directly measured in a real system, determine if they can be useful for the LQRI state feedback, and finally study the effect of the different possible feedback selection on the regulation performance.**

Keywords*— *transmission network, secondary voltage control, LQRI, state feedback, reactive power management

I. INTRODUCTION

The regulations and policies aimed at mitigating the climate change are promoting both an increase in renewable energies exploitation and the shutting-off of coal fired power plants. This is gradually shifting the electric energy production from a limited number of high-power plants to a significant amount of distributed low-power sources. In this evolutionary scenario, maintaining voltage control on the transmission system may become critical. Voltage regulation (i.e., keeping the voltage in a determined range at loads supply terminals) is an important part of Power Quality, and is achieved using a multi-layered hierarchical approach [1]. In particular, short-term regulation is concerned with fast dynamic transients (up to 1 second of equivalent time constant), and exploits the voltage control loops of the generators and sources that are participating in local voltage control. This is the primary voltage control regulation, and in the past was quasi-exclusively obtained through the Automatic Voltage Regulators (AVRs) installed on synchronous generators (as well as synchronous compensators and variable tap transformers). Medium-term regulation is achieved through Secondary Voltage Control (SVC), which coordinates several generators and sources in an area of the transmission network to keep constant the voltage of a set of significant nodes. The involved dynamic is slower than the previous one (equivalent time constant of tens of seconds), to allow the dynamic decoupling with the primary voltage control. Traditionally, the SVC function has been appointed to a reduced number of high-power plants, whose effect on the transmission network was sufficient for guaranteeing the expected regulation performances. Finally, the third voltage control layer is a non-dynamic one, concerned with calculating, on the basis of the solution of an Optimal Reactive Power Flow problem, the best set of voltage references for the nodes controlled by SVC.

The above-mentioned evolutionary scenario is leading to the shut-off of several power plants that were used for SVC, making it necessary to integrate and coordinate in such hierarchical control layer new Reactive Power Resources (RPR). The latter can be big renewable plants, STATCOMs, synchronous compensators, and HVDC links with voltage source converters interfaces [2]. It is relevant to notice that a single RPR can be composed by different generators/sources, which are aggregated, controlled together, and connected to the transmission network in a single point to provide reactive power and SVC ancillary services. To ensure the correct coordination of these varied RPRs as actuators for voltage regulation, new control architectures may be required [3]. In this paper a Linear Quadratic Regulator with Integral action (LQRI) [4] is selected for the SVC on the transmission grid. Several issues must be solved to design such voltage regulator, among which there 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, determine if they can be useful for the LQRI state feedback, and finally study the effect of the different solutions on the regulation performance. In this regard, the focus is here made towards solutions that can be applied at short/medium-term, thus considering as much as possible the present voltage control architecture and the underlying measurement and communication infrastructure [5]. Moreover, a specific effort is made towards solutions that do not need the implementation of complex state estimation systems, to avoid increasing the complexity of the control system design and implementation.

The paper is structured as follows: Section II presents the LQRI control approach, its application to the SVC for a transmission system, and the issues related with the state-feedback selection in the present power system regulation architecture; Section III discusses the system's mathematical modeling, its state feedback selection, and the possible uses of measured variables for implementing an LQRI controller in the present power system; in Section IV the effect on system regulation performance of the different variables used for the state-feedback is assessed using simulations, and the results are discussed; Finally, Conclusions are given.

II. LQRI FOR SECONDARY VOLTAGE CONTROL AND THE STATE FEEDBACK SELECTION PROBLEM

The LQRI (Linear Quadratic Regulator with Integral action) is an LQR control system using a set of integrated variables as additional inputs [4][6]. The latter allows nullifying the steady-state error of such variables (in respect to a given reference), which may be useful in some applications.

A generic LQR is designed starting from the standard state-space representation of a continuous time-invariant system:

$$\dot{x}(t) = Ax(t) + Bu(t)$$

where $x(t) \in \mathbb{R}^n$ is the system state, $u(t) \in \mathbb{R}^m$ is the input (control) signal, A (dim = $n * n$) is the state matrix, and B (dim = $n * m$) is the input matrix of the system.

The LQR controller applies a linear state-feedback to the system control input, defined as follows:

$$u(t) = -Kx(t)$$

where K (dim = $m * n$) is the feedback control gain matrix.

The matrix K is designed in order to provide a control signal that minimizes the following quadratic cost function:

$$J = \int_0^\infty \left[x^T(t)R_{xx}x(t) + 2x^T(t)R_{xu}u(t) + u^T(t)R_{uu}u(t)\right] dt$$

where the state is weighted relative to the amount of control action in $u(t)$ through the state weighting matrix R_{xx}, the control weighting matrix R_{uu}, and the cross-weighting matrix R_{xu}.

In particular, the feedback control gain matrix K is equal to:

$$K = R_{uu}^{-1}(R_{xu}^T + B^T S)$$

where S is the solution of the algebraic Riccati equation:

$$SA_r + A_r^T S + (R_{xx} - R_{xu}R_{uu}^{-1}R_{xu}^T) - SBR_{uu}^{-1}B^T S = 0$$

with $A_r = (A - BR_{uu}^{-1}R_{xu}^T)$.

There are several requirements to be met for ensuring that such controller can be correctly designed, but are outside the scope of the paper (please refer to [4] for an in-depth mathematical description of the LQR control).

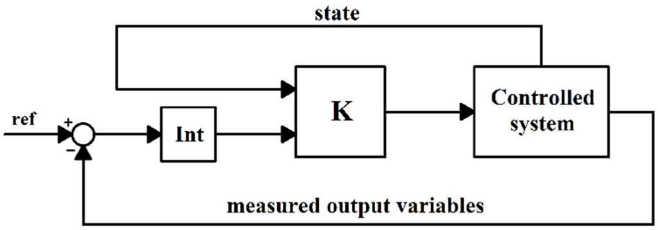


Fig. 1. LQRI controller applied to a generic system, Int: integrators; ref: reference values for the measured output variables

By adding an integral action to a set of system's output variables and using them as additional inputs for the above defined LQR controller, it is possible to build the so-called Linear Quadratic Regulator with Integral action. A notional representation of the LQRI controller is shown in Fig. 1. The integrated feedback allows cancelling the error in the measured output variables, while at the same time increasing the design complexity. Indeed, the integrators in the control system are equivalent to an increase in the number of total states to be managed by the controller, with a related increase in the dimension of the K matrix. The design of an LQRI can be made using the same approach of the above-described LQR, starting from a system's state-space representation that already includes the additional integral feedback.

In this paper, the LQRI controller is applied to the secondary voltage control system of a transmission network, specifically to the regulator that ensures the most significant nodes in the network (i.e., the Control Nodes - CNs) are kept close to their reference values (provided by tertiary voltage control). Such regulator takes as inputs both the voltage error on the CNs and the system state, providing at its output the reactive control signals for each RPR (i.e., the actuators for the SVC). In particular, the integral feedback of the LQRI is used on the voltage measurements coming from the CNs, to ensure they are kept at the reference values, while the linear state feedback is used to keep the system asymptotically stable and minimize (together with the integral feedback) the cost of the above J equation.

The selection of the state variables to be fed back to the controller is critical, because in a complex system there are a huge number of states and using all of them may be impractical (or even impossible). However, choosing to ignore some states (which means applying simplifying hypotheses on the standard state-space representation of the system used for designing the LQRI) may result in poor control performance. Moreover, even if the LQRI designed on the simplified model provides acceptable results, the chosen states may still be unusable for the feedback, being them not available in the specific application (because they are not measured, or even are not measurable). To solve such issue, it is possible to add a new set of sensors to the controlled system for measuring a non-measured state, or introduce a state estimator for obtaining the state on the basis of the available measures. However, this means adding cost and complexity to the system. Therefore, it is interesting to evaluate if the variables that are presently measured in a transmission system (in regards to the scope of secondary voltage control) can be used, either directly or through a simple signal conditioning approach.

III. STATE FEEDBACK FOR A LQRI SVC REGULATOR IN A TRANSMISSION NETWORK

A. Controlled system mathematical modeling and resulting states

The simplest approach for defining the feedback states for an LQRI regulator is to take the *x* state array from the controlled system's state space representation. Indeed, it is sufficient to build the mathematical model of the system, then convert it into its state-space form (if it has not been directly built in such form) for obtaining the list of the feedback signals to be routed to the controller. Such list can be also inferred from other forms of mathematical model. As an example, in block diagram form it is possible to use as states the output signals of the integrator blocks (although this requires manipulating the model equations to use only integrations in the model, and never derivations). However, the determination of the *A* and *B* matrices of the state space representation is critical for the controller design, as shown in the previous section, thus building the system model in such form is considered a required step.

The goal in this paper is the design of an SVC regulator for a transmission system. Thus, the system to be controlled is composed by:

- Loads (aggregated loads at HV/MV substations)
- HV transmission network (lines, transformers, etc.)
- Generators/reactive power sources
- Primary voltage control systems of each RPR
- Reactive power control system of each RPR
- Tertiary voltage control (providing references for the SVC)

Given the bandwidth/dynamic usually considered for secondary voltage control on transmission network (equivalent time constants of tens of seconds), it is possible to apply some simplifying hypotheses to the system's mathematical modeling.

The system is operating in an equilibrium point, with constant loads and the generators/sources have already reached the correct active and reactive power sharing between them. Therefore, the system can be linearized in such equilibrium point, and loads variations (as well as other events) can be modeled as disturbances to the linearized system. Moreover, generators/sources that are not used for SVC have fixed power injections or voltages, depending on their control mode.

The dynamic behavior that is required to be considered is the one pertaining secondary voltage control (transients with time constants in the order of seconds/tens of seconds). Thus, all the dynamic that is either faster or slower can be ignored. This in turn means that: the HV network is a passive network made of algebraic impedances (electric transients are neglected); the generators and reactive power sources are already in steady-state (thus modeled as gains); primary voltage control systems are in steady-state (thus modeled as gains); the reactive power control systems' dynamics is retained; tertiary voltage control provides constant references. Moreover, being the system in study a high voltage transmission one, the Carpentier hypothesis [7] (active power – frequency and reactive power – voltage channels are separated) is valid, thus the frequency and active power components can be ignored in the model for SVC and the passive part of the transmission system (lines, transformers, switchboards, etc.) can be modeled through its sensitivity matrix *S*, whose elements are defined as follows:

$$S_{ij} = dv_i / dq_j$$

where v_i is the voltage of *i*-th bus, and q_j is the reactive power injected/absorbed in the *j*-th bus.

The network passive matrix is subjected to the reactive power injections from the RPRs, as well as to all the other disturbances (reactive power and voltage variations due to both the loads and the sources not contributing to SVC).

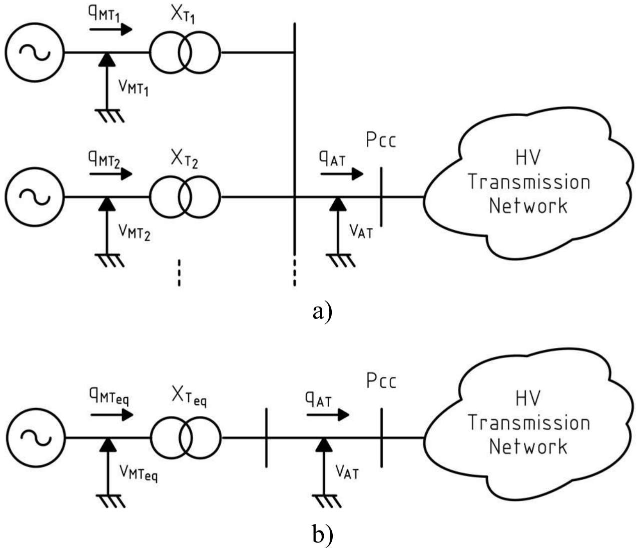
For what it concerns the RPRs reactive power loops, it is possible to use different modeling approaches, depending on the level of detail that is sought during the SVC regulator design. The coarsest approach is using a first order transfer function for the dynamic part. Then, the reactive power injected by the RPR in the HV transmission network can be calculated using a set of simple algebraic equations, on the basis of the reactive power reference signal received from the LQRI controller and the voltage on the network node to which the RPR is connected. More detailed models can be used, depending on the specific needs. However, the more detailed the models are, the more complex becomes the overall system mathematical model.

By applying the above simplifications, it is possible to build a state space representation of the system, to be used as a base for designing the LQRI controllers (following the theory presented in Section II).

B. Availability of the state feedback for the LQRI regulator

The LQRI resulting from the previous sections hypotheses uses the voltage of the CNs for the integral feedback. Such variables are measured either through a SCADA system, or through a more modern PMU-based system [8]. In this paper, the latter is considered, and this specific feedback section is kept constant in all the different simulations (presented in the following section).

Concerning the state feedback, from a mathematical point of view and given the above-depicted simplifying hypotheses, the system's state array to be fed back to the LQRI is composed by the RPRs reactive power loops output signals (i.e., the signal at the output of the integral part of its PI regulator). Such choice is taken as a base in this paper for comparing the other solutions presented in the following. While being the best solution due to its complete coherency with the mathematical definition of the LQRI controller, using the reactive power loops output signals as the set of states for the feedback is not possible. Indeed, such signals are not made available to the SVC controller at present, since no previous requirement was set in regards to their measurement and transmission to the secondary voltage control layer. Thus, it is required an overhaul of the voltage control system in order to use them, which includes changes in the transmission operator systems, in the data communication infrastructure, and in the control and measurement system installed in each RPR. An often-applied solution to this issue is the design of state observers, for inferring the required states from the available measures, through Kalman estimators or other



a)

b)

Fig. 2. Notional representation of an RPR composed by multiple generators/sources, with the significant measured variables highlighted: a) multi-generator system, b) equivalent single generator model

approaches [9][10]. However, the simplification hypotheses depicted in the previous section make it possible to achieve a simple model, whose complexity mainly lies in the significant dimension of the related matrices for a transmission system (where hundreds of nodes and tens of RPRs are present). Thus, with the aim of avoiding either the complete overhaul of the voltage regulation architecture, or the design of complex state estimators, it is interesting to evaluate if measures that are already sent to the current SVC system can be used for the feedback to the new LQRI regulator. Indeed, these may be used as a direct substitution of the required state, or may be used to provide the state estimation through simple algebraic equations.

C. *Available measures that can be used for the state feedback to the LQRI regulator*

At present, there are several measured variables that are sent from each RPR to the transmission network operator for control and management purposes. These signals are exchanged through a SCADA system, with specific limitations in terms of measurement and transmission performance (e.g., sampling times of about 2-4 s). Such performance may increase in the future (e.g., sampling rate up to 0.02 s), through the introduction of PMU-based measurement and communication systems for the most significant variables, like it is done at present for the voltage of the CNs.

Among the several measured variables, the following have some usefulness for the scope of this paper:

- Voltage at HV (network) terminals of the RPR (v_{AT});
- Voltage at MV terminals of each generator/source of the RPRs (v_{MT1}, v_{MT1}, etc.);
- Reactive power injected by the RPR in the HV transmission network (q_{AT});
- Reactive power of each generator/source of the RPRs (q_{MT1}, q_{MT1}, etc.).

These variables are depicted in Fig. 2.a, where a generic RPR is shown. The RPR is connected to the HV transmission network in the point of common coupling (*Pcc*), and is composed by several generators/sources. The latter are endowed with their primary voltage control loops and transformers (x_{T1}, x_{T2}, etc.), and are coordinated in order to provide the required reactive power to the network.

Being the RPRs considered in the mathematical model only the ones that are used for the secondary voltage control, the first control loop of interest is the primary voltage one. This means that the voltage at terminals of the source is directly regulated, and the reactive power follows from the interaction of such voltage with the HV network. Therefore, the first approach here applied is to investigate if the measured voltages can be used as substitutes for the required state feedback. In the above-depicted mathematical system model, the voltage at MV terminals is proportional to the reactive power loop output signals, i.e., the mathematically defined state. This is because primary voltage control systems and generators/sources are in steady-state, thus modeled as constant gains. Thus, it should be possible to use the MV voltage measures as the feedback for the LQRI controller. However, such measure is not constituted by a single signal, but by multiple ones if the RPR is made up by several generators/sources. Consequently: a) the MV voltage signal array for each RPR must be properly conditioned, for obtaining a single value that is representative of the entire RPR as a whole (i.e., building its single-generator equivalent model, as shown in Fig. 2.b; b) the MV voltage signal array can be used as it is, leading to a rise in complexity (system order and matrices size) in the LQRI controller design.

The second approach involves using the voltage at HV terminals of the RPR, which already takes into account the entire set of generators/sources as an aggregated equivalent one. However, such measurement point is separated by transformers from the generators/sources, thus it provides a signal with an offset in respect to the MV one. Although the dynamic is partially preserved, the presence of voltage drops on the transformers that are variable with the reactive power flow may lead to a reinforcement or dampening of some transients.

Using the reactive power injected by the RPRs in the transmission network can be considered as the third solution, but it presents some criticalities. In fact, in a transmission system the reactive power flows are a consequence of the voltage differences between the network nodes. Thus, both the single generator/source reactive power and the overall aggregated RPR's one depend on the interaction of the voltage at the terminals of the generator/source with the voltage of the network node to which the RPR is connected. Thus, reactive power is proportional not only to the state of the single RPR, but also to the state of all the other RPRs in the network. This makes it difficult to directly use the reactive power as a substitute for the state feedback for the LQRI SVC regulator, due to the presence of mixed dynamic that is not considered during the LQRI design process. Using the reactive power of each single generator/source or the aggregated reactive power of the entire RPR does not make any difference for this purpose, being the latter nearly equal to the sum of the former (the power measured on the HV side includes the transformers reactive power, which can be considered constant given the system operation at voltages that are close to the rated ones).

A fourth approach can be proposed, which uses a combination of most of these available measures to both make available the required state feedback signal, and solve the issue of using additional signal conditioning for providing the voltage of the equivalent generator/source from the several separated signals sent by each RPR. In particular, it is possible to use the measures that already consider the RPR as a single source (i.e., the HV ones), to evaluate the equivalent MV voltage of the aggregated source. This can be made using the following equation:

$$v_{MTeq} = v_{AT} + x_{Teq} \cdot q_{AT}$$

where v_{MTeq} is the voltage at MV terminals of the equivalent generator/source for the RPR, v_{AT} is the measured voltage at HV (network) terminals of the RPR, x_{Teq} is the equivalent reactance of the MV/HV transformers of the RPR, and q_{AT} is the aggregated reactive power of the RPR.

In the following section, all these approaches are tested by means of simulations, and the results are presented, discussed, and compared with the mathematical defined state.

IV. EFFECT OF THE STATE FEEDBACK SIGNAL SELECTION ON THE REGULATION PERORMANCE

To evaluate the effect of using different signals for achieving the state-feedback in the LQRI controller, a mathematical model of a section of the Italian transmission network has been chosen as case study. Such section, encompassing approximatively 26 thousand square kilometers, is made by 65 HV buses, with 11 RPRs and 5 nodes selected as CNs. The model of the system is mainly based upon the Section III.A assumptions, but presents complete controllers for the RPRs' reactive power loops, and the assemble of each primary voltage control loop and generator/source is modeled with a delay plus a gain. Such a choice allows to test if the significant simplifications done for designing the LQRI controller are still valid when the system to be controlled is more complex. The model is built in relative units (i.e., per unit) using the same base values, while in a real application suitable base change must be introduced. All the simulations are done with the same LQRI controller, designed using the simplified mathematical model in state-space representation discussed in Section III.A. The results shown in the following are obtained in response to a 1% variation in the SVC voltage references for two CNs, with the other three kept constant. Simulations with load variation have been done providing similar results, thus, are not shown here. Finally, in order to remove the effect of multiple parameters, the simulations here presented are done with all the measurement signals sampled at PMU-based performance level. However, simulations have been made also with a mixed solution, related to the present system condition (CNs voltage measured with PMU and state measured and sent through SCADA). No significant difference is found, besides the presence of small steps in the resulting traces due to the piecewise input signals.

The first result concerns the system response while using the state feedback defined through the mathematical modeling approach (i.e., the set of reactive power loops output signals). This result is used as a benchmark for evaluating the other solutions. The Fig. 3 depicts the CNs voltages, which reach the expected reference values with smooth transients and limited coupled dynamics. Being such result obtained with a simulation of a system model that is more complex than the one used for designing the LQRI, it is demonstrated that the simplifications presented in Section III.A do not impair the controller design, while reducing its complexity.

The results in terms of CNs' voltages for the controller using the RPRs' MV as feedback are shown in Fig. 4. Specifically, the model here used for the simulation presents a single generator/source for each RPR, in the hypothesis of having already done the proper conditioning on the measures for achieving a single signal from the multiple MV voltages coming from the field. By comparing the Fig. 3 and Fig. 4 results, it is evident that the MV voltage is a suitable substitute for the system state, being the results equal (provided that the correct base changes for the per unit representation are used).

By using the voltage measured on the HV side of the RPRs, the Fig. 5 results can be obtained. These are similar to the previous results, although the presence of the voltage drop on the transformers leads to a slightly higher overshoot for the green voltage trace (clearly visible by comparing Fig.4 and Fig. 5 magnifications). It is expected that a more appreciable difference will arise in presence of significant reactive power variations, where the transformers voltage drop becomes higher, but such event cannot be evaluated with the linearized model here used.

Simulations made using the reactive power as state feedback showed significant issues with the system control, being the reactive power signals dependent on both the single RPR's and the rest of the system's behavior. After introducing a gain (experimentally determined) for adapting the reactive signals range to the voltages one, the results show the unsuitability of such feedback (voltage oscillations and increased cross-coupling between the CNs' transients, shown in Fig. 6).

Finally, Fig. 7 shows the results obtained using the feedback obtained by means of the fourth approach of Section III.C (i.e., calculating the MV equivalent voltage for each RPR by using the reactive power and voltage measured on the HV side). The results show that the proposed algebraic state calculation, made on the basis of the available measures, is a feasible solution for implementing the LQRI SVC. Indeed, the comparison of Fig. 7 with Fig. 3 shows equal transients, in both shape and magnitude. Thus, this solution allows obtaining the required performance while removing the need of a complex state observer.

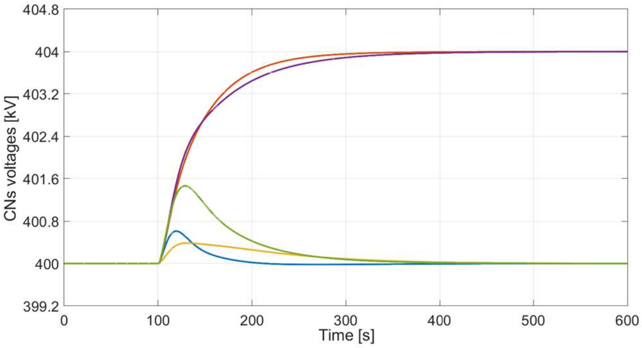


Fig. 3. CNs voltages, LQRI controller with the state feedback defined using the mathematical model of the system

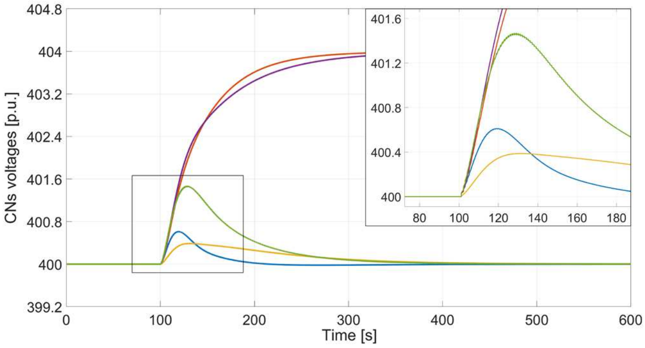


Fig. 4. CNs voltages, LQRI controller with the measured MV voltage of the RPRs used as state feedback

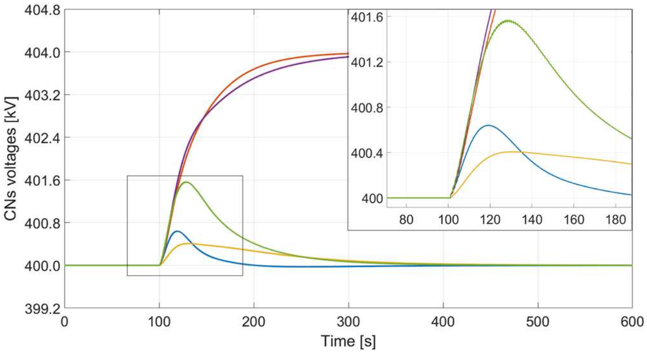


Fig. 5. CNs voltages, LQRI controller with the measured HV voltage of the RPRs used as state feedback

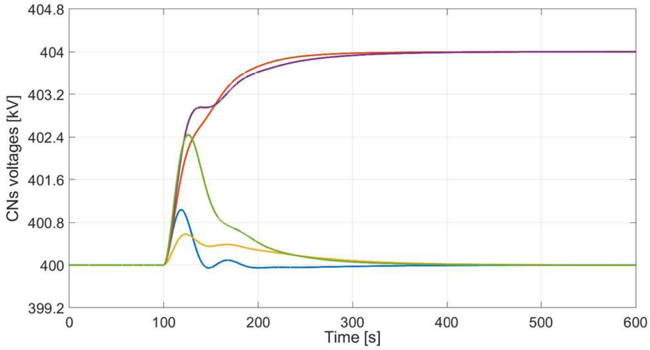


Fig. 6. CNs voltages, LQRI controller with the reactive power of the RPRs used as state feedback (with proper scaling)

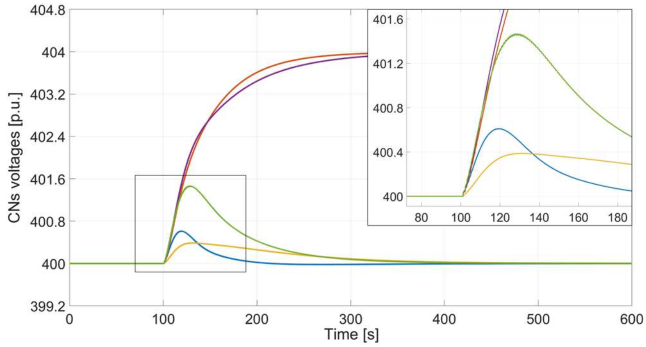


Fig. 7. CNs voltages, LQRI controller with the calculated MV voltage used as state feedback (with proper scaling)

V. CONCLUSION

The evolutionary scenario for the electrical power system will require a change in present voltage regulation architecture, to correctly integrate new distributed reactive power resources into it. In this paper a Linear Quadratic Regulator with Integral action (LQRI) is selected for the secondary voltage control of the transmission grid, using as actuators high-power non-renewable plants, high-power renewable resources, and synchronous compensators. The specific issue of determining the signals to be used for the state-feedback section of the LQRI controller is detailed and analyzed in this paper, with the aim of finding a set of already measured variables for such a purpose (thus avoiding a costly and time-consuming measurement and communication infrastructure overhaul). Among the several variables considered in this paper, the voltage at terminals of the generators/sources and the state reconstructed using simple algebraic equations (from the voltage at HV terminals and reactive power injected into the grid) both provide promising results in terms of voltage regulation performances, being very similar to the real state-feedback ones. Specifically, the second solution seems to be more suitable for the scope, being the first more complex in terms of controller design (due to the need of considering separately the state of each generator/source, or the need to determine an approach to calculate the equivalent aggregated source state from the several measures).

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