Reactive Power Resources Management in a Voltage Regulation Architecture Based on LQRI Control

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Abstract— **The Italian transmission system's voltage control is based on its subdivision into decoupled control areas, where a hierarchical regulation architecture is applied. However, the structure and the voltage regulation of the electrical power system are being significantly impacted by the actions being taken to limit climate change. The increase in renewable energy sources exploitation is leading to a more-distributed and converter-based energy production. In addition, the forthcoming coal-fired plants shut-off will force the shift from providing regulation capability with a small number of big power plants, towards using a big number of smaller resources. Thus, in the near future a decrease in the effectiveness of the present voltage control architecture is expected. To solve such issue, a new voltage control architecture is needed, involving the more-distributed and converter-based energy production systems, as well as no longer relying on physically decoupled control areas. Therefore, in this paper a coordinated LQRI secondary voltage control is presented, able to use each grid-available reactive power source as an actuator. Furthermore, a bumpless transfer technique is proposed to solve the problem of managing a varying number of actuators (due to the reactive power resources' connection and disconnection).**

Keywords— secondary voltage control, reactive power management, LQR control, LQRI control, bumpless transfer

I. INTRODUCTION

The implementation of new laws and policies to fight global warming is encouraging widespread use of distributed Renewable Energy Sources (RESs) in electric power systems as well as the gradual phase-out of coal-fired power plants. Due to their precedence in dispatch, RESs (such as photovoltaic and eolic) are progressively substituting standard power plants in today's energy production. The importance of including more Reactive Power Resources (RPRs) in the automatic voltage control architecture increases in the context of voltage control as RES presence increases in place of conventional power plants. Along with RESs, RPRs must also include synchronous compensators, STATCOM devices, and VSC interfaced HVDC links, collecting all the available means to provide reactive power and voltage regulation ancillary services to the transmission grid.

RPRs can fulfill different roles in the Italian transmission system's voltage control architecture, either exclusively or in a combination. These roles can be easily represented using the present Italian voltage regulation architecture structure, which is subdivided in three hierarchical control tiers [1]. Primary Voltage Control (PVC) keeps regulated the voltage at the output terminals of the single power source. It is obtained through the Automatic Voltage Regulator (AVR) devices, controlling the excitation systems of generators, and the voltage control loop of converter-interfaced systems. RESs have been traditionally operating in this layer, using a grid-following paradigm (the source voltage output is the same as the grid one, to limit as much as possible its effect on the latter). The Secondary Voltage Control (SVC) layer is made up of a system that is partially installed in each power plant (the generator's reactive power control loops, which perform as actuators for the SVC by means of the so-called SARTs), and partially installed in each regional control center of the transmission system operator (the actual secondary voltage controller, also called regional voltage regulator). Some high-power RES power plants are starting to implement this function, to help in grid voltage regulation. The remote-control signal sent by the secondary voltage regulator to the SARTs is represented by a reactive power level (*livq*) request, formulated as a percentage of the single generator's reactive capability [2]. SVC aims to achieve voltage regulation of a group of pilot nodes in each of the transmission system's divided regions. The network's subdivision into different voltage control areas (one or more for each region, each presenting one pilot node) is called zoning, and there are numerous approaches and methods that can be used to find the optimal clustering. [3][4]. Pilot nodes have the highest short-circuit power in a given region, thus being capable of influencing the voltage of all the other surrounding nodes. By controlling their voltage profile through reactive power injection by RPRs, it is possible to keep all the nodes in the region in the correct voltage range. The reference profile for the pilot nodes voltage is determined by the Tertiary Voltage Control (TVC), using specific optimization methods [5].

The above control architecture has been conceived when the RPRs were rotating machines only, fully controlled by the transmission system operator. However, in the present power system new RPRs have been installed (and additional ones will be in the future) and must be used for providing voltage regulation. Most of these are converter-based sources, providing very different performance and transient behavior in respect to conventional rotating machines. This makes it necessary to carefully consider how to properly incorporate them into the voltage control, and how the voltage control itself must be changed in order to take advantage of them. As an example, a particularly evident issue is the need of managing several different distributed RPR's in place of a single big power plant, being the power size of these new sources smaller in respect to the latter. Moreover, in the long term it is expected that conventional power plants will be phased out completely, thus making it necessary to prepare for the shift towards a more distributed voltage regulation.

Given these premises, the best approach is to completely redesign the voltage control architecture, rather than adapting the existing one for the new task. Thus, in this work a step towards a new voltage control architecture is done, considering a secondary voltage controller based on LQRI control [6], capable of sending to each actuator its specific command signal (reactive power reference).

During the system's operation, the sources 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 optimum control application to SVC in a power system is here specifically addressed, by means of a bumpless control transfer method.

The paper is structured as follows: Section II presents the LQRI control and discusses how it applies to a transmission power system. In Section III, the problem of LQRI control in a system with actuators that change in number is presented, and the bumpless transfer method that is employed to ensure proper control system operation is addressed. Section IV applies to a case study the LQRI control and its bumpless transfer approach. The paper conclusion is in Section V.

II. LQRI CONTROL FOR SECONDARY VOLTAGE REGULATION

A. *LQR background*

The transmission system's voltage control is a multiple input multiple output (MIMO) system control task. Indeed, the meshed grid architecture leads to an interdependence between the voltages of the buses and the reactive power flows in the lines. This makes it necessary to separate the input-output behavior by means of specific control approaches, where the variation of a single output can be achieved through the action on most (if not all) the inputs. Several different approaches have been conceived for controlling MIMO systems [6]. Among them, the Linear Quadratic Regulator (LQR) has been selected for being applied here. Some works can be found in the literature that deal with LQR control applications in power systems, but they mostly deal with frequency regulation [7][8] or voltage stability [9] rather than voltage regulation.

To provide a brief background on LQR, it is possible to consider a generic time-invariant dynamic system in its standard state-space representation:

$$\dot{x}(t) = Ax(t) + Bu(t); \quad x(t=0) = x_0 \qquad (1)$$

where $x(t) \in \mathbb{R}^n$ is the system state, and $u(t) \in \mathbb{R}^m$ is the input (control) signal.

The goal of the LQR controller is to define a control signal $u(t)$, which minimizes the following quadratic cost function:

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

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}.

The selection of the weighting matrices allows to penalize (with high values) or promote (with low values) specific feedbacks. As an example, choosing a high-gain R_{uu} means penalizing intense control actions, due to the presence of the term $u^T(t)R_{uu}u(t)$ into the cost function to be minimized.

If the following assumptions are also valid:

- the whole state vector $x(t)$ is available for feedback (either measured or estimated);
- the (A,B) couple is stabilizable and the $(A,R_{xx}^{1/2})$ couple is detectable;
- R_{xx}, R_{xu} are R_{uu} symmetrical and positive definite;

then:

- the linear quadratic controller is the following unique, optimal, full state linear feedback control law that minimizes the J cost:
  $$u(t) = -Kx(t) \quad \text{with} \quad K = R_{uu}^{-1}(R_{xu}^T + B^TS) \qquad (3)$$
- S is the unique, symmetrical, positive semidefinite solution of the algebraic Riccati equation:
  $$SA_r + A_r^TS + (R_{xx} - R_{xu}R_{uu}^{-1}R_{xu}^T) - SBR_{uu}^{-1}B^TS = 0 \qquad (4)$$
  where $A_r = (A - BR_{uu}^{-1}R_{xu}^T)$;
- The closed-loop dynamics can be calculated as:
  $$\dot{x}(t) = [A - BK]x(t) \qquad (5)$$
  and K guarantees its asymptotical stability.

B. *Considerations for the application of an LQR controller to the transmission power system's SVC*

In the SVC frequency bandwidth (time constant in the order of tens of seconds), the transmission network can be modeled as a system having as output the voltage on the controlled network nodes, and input (control variables) the reactive power injections provided by the RPRs that have the SVC function enabled. The other sources, as well as the loads, are disturbances to the system. In this scenario, the LQR controller design requires using the system's mathematical model, which represents the relevant dynamic behavior occurring into it.

However, it is possible to make some considerations to simplify the system in study, and significantly reduce its order. The reduction in the amount of state variables of (1) is beneficial. In fact, not only it limits the number of feedback signals to the LQR controller, but also it reduces the size of all the matrices in (2), thus making it easier to determine K.

In terms of the transmission system, it is well known that a generic transmission line's dynamic behavior can be categorized as an electromagnetic phenomenon due to its rapid nature (time constants in the order of milliseconds). Therefore, it is possible to state that the transmission line response is not relevant for the SVC dynamic, being dynamically decoupled from it. Likewise happens for RPRs voltage dynamic (i.e., the rotating machine or the converter internal dynamic, plus the AVR), while RPRs reactive power control loop must be retained, because it presents a dynamic response with a time constant in the order of seconds. As a result, the sensitivity matrix S, whose components are defined below in equation (6), can be used to model the passive component of the transmission system (lines, transformers, switchboards):

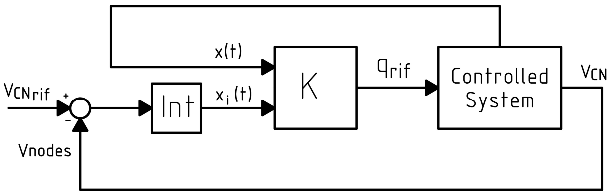

Fig. 1. General scheme of a system controlled by an LQRI controller

$$S_{ij} = dv_i \,/\, dq_j \tag{6}$$

where v_i is the voltage of *i-th* bus, and q_j is the reactive power injected/absorbed in the *j-th* bus. Notably, using the sensitivity matrix requires the linearization of the system in a suitable operating point, with an impact on matrices' calculation but no impact on control concept design. The network passive matrix is then subjected to the reactive power injections of 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).

To perform the SVC on a transmission network, it is crucial to select some specific nodes to be regulated. controlled nodes (CNs) is the name given to these buses in this paper, because they are utilized to send voltage data back to the secondary voltage controller. They are similar in function to the present pilot nodes, but are defined without following the concept of area subdivision (taking into account a future scenario where transmission network is significantly coupled and most high-power plants are dismissed in favor of distributed RESs). The selection of the CNs is outside the scope of this paper.

Concerning the other elements needed to model the whole transmission network voltage control, the reactive power loops of the RPRs have been modelled by means of a first order transfer function that provides the dynamic, and a set of algebraic equations. The latter allows calculating the reactive power injected by the RPR in the transmission network, on the basis of the reactive power reference signal q_{rif} received from the LQR controller and the voltage on the network node at which the RPR is connected.

Given these simplifying hypotheses, the system state array is constituted by the RPRs reactive power loops output signals only. For this paper's work purposes, such array is assumed to be fully available and measurable (thus no state observer is here applied).

C. LQR with integral action

Being the goal of the SVC the cancellation of the CNs' voltage steady state error, an integral control part must be added to the LQR (whose control matrix K is only capable of providing proportional feedback). The resulting regulator is the so-called LQRI (Linear Quadratic Regulator with Integral action), whose notional representation is shown in Fig. 1 for the application in study in this paper. Specifically, while the system state variables are fed back using the conventional LQR proportional gain, the error in the CNs' voltages (i.e., the difference between the reference voltage provided by the TVC and the measured one) is integrated prior to be fed in the LQR. The introduction of a new set of integrators (one for each CN) can be considered as an expansion in the transmission system's state array, which is mathematically obtained by simply appending x_i to the system's state feedback's array x:

$$z(t) = [x, x_i] \tag{7}$$

Denoting with s the number of RPRs and with c the number of CNs, the signals represented in Fig. 1 have the following dimensions:

- v_{CNrif}, v_{CN} , $x_i(t) \in \mathbb{R}^c$
- $x(t) \in \mathbb{R}^s$
- $z(t) \in \mathbb{R}^{s+c}$
- $K \in \mathbb{R}^{s+c,\ s}$

The determination of the feedback control gain matrix K for the LQRI follows an approach that is similar to the one depicted in Section II.A, but considers the expanded state and system model (which includes the integral part).

Given the absence of studies in literature, the choice of R_{xx}, R_{xu}, R_{uu} for the LQRI control has been done through simulations, aimed at obtaining a dynamic response comparable with the one shown by the present SVC system.

D. Issues in applying LQRI control to the transmission system

The determination of the feedback control gain matrix K is based on the determination the system's state-space representation matrices, and on the solution of the Riccati equation (as shown in Section II.A). The methods to determine S, A, B, C, their refresh rate, and the assessment of the effects in calculation errors are all topics for future works. However, it is relevant to notice that the application of an LQRI to the transmission system SVC is effective as long as the system (1): does not change in structure, does not change in parameters, works in an operating point that is not so far from the original one (i.e., the one used for the calculation of the Riccati equation solution S). If these constraints are violated, the equation model (1), the matrix S, and consequently the control gain matrix K must be determined again. It should be noted that changes may occur not only in magnitude of the matrices, but also in their dimensions.

One of the operations causing a change in the system structure is the enabling or disabling of the SVC function in the RPRs, which can be mathematically seen by the (1) system as a change in the number of system states and input signals, and by the controller as a change in the number of the actuators. This makes it necessary to recalculate a new feedback control gain matrix K, which has a different size and values in respect to the previous one, and to apply the control signals to the new RPRs' set. (It is important to notice that RPRs can have the secondary voltage control function enabled or disabled, provided that the constraints on system's controllability given in Section II.A are verified, i.e., the number of RPRs must not be lower than the number of CNs). K doesn't have a dynamic because it is a matrix of algebraic gains. Thus, any alteration in its value causes an immediate shift in the reactive power reference signals transmitted to the RPRs. The results showed in Section IV demonstrate that the outcome is an undesirable transient on both the reactive powers and voltages of all nodes. As a result, the LQRI controller must have a bumpless transfer function to reduce the voltage transient that occurs after the control system change caused by the enabling or disabling of the RPR's SVC function. Such function can be designed to face both programmed and unexpected events, providing the best results in the former case, and an acceptable behavior in the latter case. In this paper only the base design is considered, taking into account programmed variations. The function performance and its possible required changes to face unusual occurrences (e.g., a power plant's abrupt disconnection) will be evaluated as part of further work.

III. BUMPLESS TRANSFER FOR A LQRI CONTROLLER USED IN TRANSMISSION SYSTEM'S SVC

As previously explained, a change in feedback control gain matrix *K* (and a variation in RPR's number, depending on the specific event considered) is required when the system changes its structure, or change its parameters, or works in an operating point that is far from the original one. Such change can be considered as a complete control system switch, from the controller with the *K* matrix to a new one with the newly calculated *K'* matrix. This change can be managed using a proper bumpless transfer technique, whose task is to guarantee smooth transients and continuity of the control signals when switching from a controller to another. Several proposals are available in literature for obtaining the bumpless transfer. Some of them are based on H_∞ [10], other are based on Model Predictive Control [11], and there are even techniques capable of providing anti-windup function for controllers with integral elements [12]. In [13] the technique proposed in [12] has been chosen and improved for a decoupling PI regulator applied to the transmission network SVC. Thus, in this paper the same technique has been selected, and properly modified and improved, for solving the switching issue related to an LQRI control.

The base idea of the technique here used is to provide a conditioning signal to the controller that needs to be activated, on the basis of the output of the controller that needs to be deactivated. Such conditioning signal must prepare the new controller for the switch over, ensuring a limited impact of the discontinuity on the system. In Fig. 2 is depicted the bumpless transfer scheme here applied, which allows to switch between two properly dimensioned LQRI controller, identified by means of the two feedback control gain matrices *K* (the former one) and *K'* (the entering one). Before the controller switch, the system is controlled by the upper branch (by applying q_{rif1} to the output), while after the switch the control is taken by the lower branch (by applying $q_{rif1'}$ to the output). The output of the new controller must be initialized as closely as possible to the output of the old one in order to prevent a discontinuity in qrif when shifting the controller, by means of a conditioning signal based on the error between the actual control output towards actuators (q_{rif}), and the controller output (q_{rif1} or q_{rif2}). Using the output error between the controllers allows not only the conditioning signal to force them to be equal, but also ensures that the conditioning signal is automatically disabled when the controller takes action (its output and the signal to actuators becomes equal).

Being the technique here used based on the equality between the two controller outputs, an integral component is required. Differently to what has been done in [13], where the PI controllers where capable of nullify the input error, here additional integrators (marked as *Int* in Fig. 2) must be added, being the LQRI integral action applied only on the CNs voltage feedback. Although such new integrators allow the bumpless switch between the two controllers, they introduce a new issue. I.e., they cause an offset in the system feedback for the new controller, leading to a variation in the controller response in respect to the design one. Thus, additional feedback must be added to the integral function, to ensure the integrator unloading after the controller switching. The gain of the integrator unloading feedback can be selected freely, on the basis of the desired system response. In general, selecting a high gain ensures fast recovery of the state feedback offset, but causes an appreciable transient on the system output (which can reach the same magnitude of a switch between the controllers without the bumpless function). Conversely, selecting a very low gain ensures negligible transients in the system at controllers' switch and in the following period, but keeps the states offset for long time and thus makes the controller work outside its design point. In this paper, a feedback gain equal to 0.1 has been selected using simulations. As stated in [12] and [13], the primary feedback of this bumpless transfer technique double as anti-windup compensators, if saturations are present in the control signals (Fig. 2).

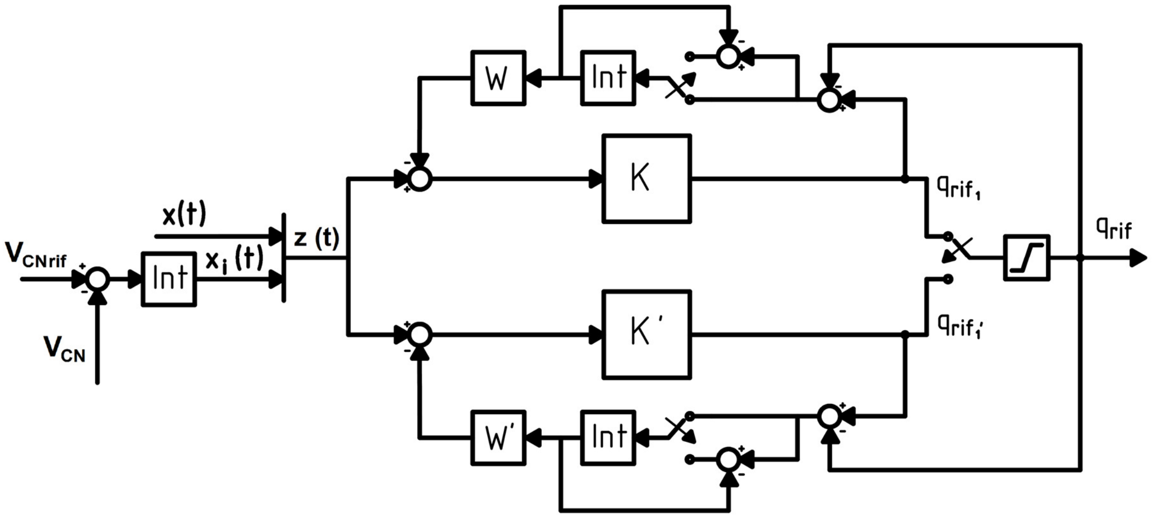

Fig. 2. Bumpless transfer scheme for LQRI control in a MIMO system, application to SVC

Besides the integral action on the controllers' output error, the conditioning section must also ensure the proper size of the feedback signals array, as well as their physical and mathematical coherence with the states used by the LQRI controller. In fact, there are several issues that make it impossible direct feedback of the integrator output to the state. First, the size of the system state array $z(t)$ and the size of the controller output to actuators array q_{rif} are different. Second, if the switch between controllers is initiated by a change in RPRs number, the two controllers also have diverse output array dimension to each other (q_{rif1} vs. q_{rif2}). Third, the output to actuators is proportional to reactive power, while the input state is proportional to different physical variables depending on the chosen states to be fed-back to the controller. For the latter, in this paper the feedback from RPRs is the output of their reactive power loops, thus being proportional to a voltage, while the integral part feedback is the output of the CNs voltage error integrators, thus being proportional to a reactive power. Thus, the conditioning section must apply three steps to ensure the correct feedback. Step one: the q_{rif} linked to the RPRs that are not used for the SVC are constrained to zero. Step two: the controllers' output error linked to the same RPRs is removed from the feedback. Step three: the collection of reactive power reference errors that results is multiplied by a suitable matrix, represented by W and W' in Fig. 3, to ensure mathematical and physical coherency.

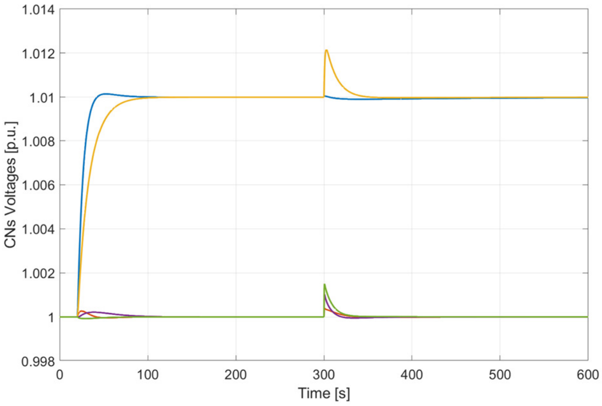

Fig. 3. CNs' voltages with LQRI control without bumpless transfer

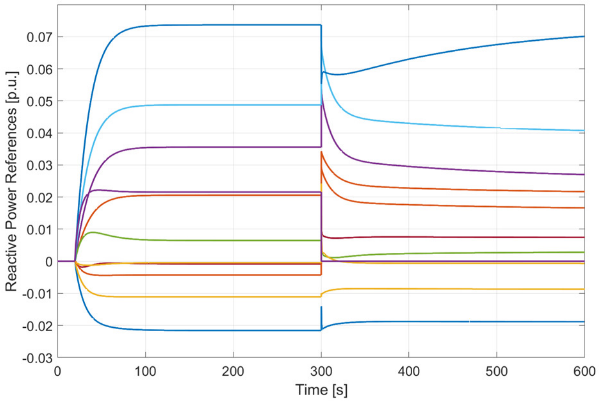

Fig. 4. Reactive power references variation of RPRs with LQRI control without bumpless transfer

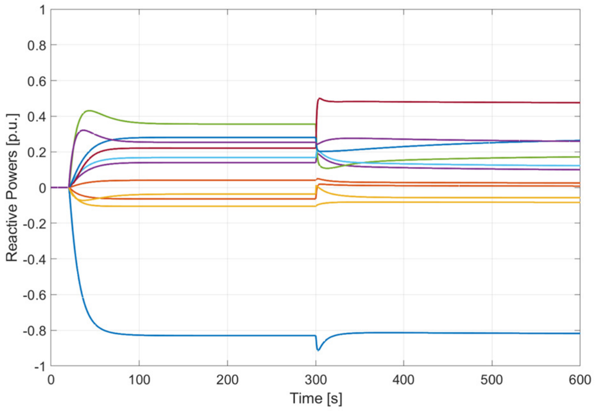

Fig. 5. Reactive power variation of RPRs with LQRI control without bumpless transfer

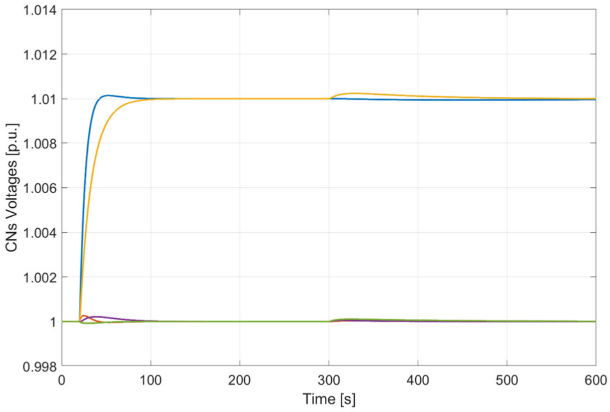

Fig. 6. CNs' voltages with LQRI control with bumpless transfer

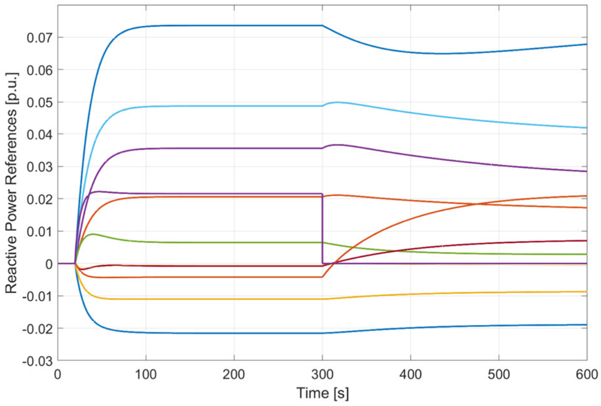

Fig. 7. Reactive power references variation of RPRs with LQRI control with bumpless transfer

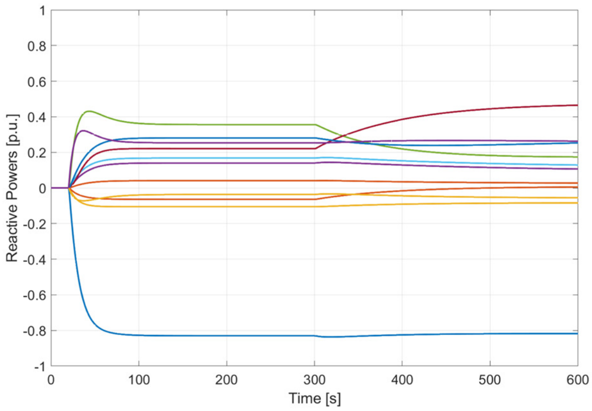

Fig. 8. Reactive power variation of RPRs with LQRI control with bumpless transfer

The latter are calculated as follows:

$$W = (K)^{-1} \tag{8}$$

$$W' = (K')^{-1} \tag{9}$$

where the matrix inversion operation is substituted with the Moore-Penrose pseudoinverse when required (i.e., for all the cases in which K or K' are not square matrices).

In Fig.2, the operations on the signals arrays to match the dimensions are not shown, to retain readability.

IV. CASE STUDY AND RESULTS

In order to test the effectiveness of the above described bumpless transfer technique, a part of the Italian transmission network of almost 26.000 km^2 was selected as case study. It composed of 65 buses and 11 RPR. In such a network, 5 buses have been selected as CNs. As described in Section II.B, the system is modelled using the network's sensitivity matrix S and the RPRs' first order dynamic. The S matrix is determined fixing a standard network's working point and solving the load flow problem. The scheduled deactivation of the SVC function in one RPR perturbs the system. This is accomplished by cutting off the RPR's q_{rif} input signal while maintaining a constant level of the reactive power it was injecting into the grid. The simulation results for a secondary voltage controller with (Figs. 3, 4, and 5) and without (Figs. 6, 7, and 8) the bumpless transfer function are described in the sections that follow. Being the model linearized, all CNs' initial voltages are set to 1 *p.u.* although having a reactive power equal to *0 p.u* (the simulations evaluate the variations in respect to the operating point). It is relevant to notice that the reference values sent to the RPRs (Figs. 5 and 8) are different from the reactive power injected into the network (Figs. 4 and 7), because the latter depend also on the voltages on the network, and thus on the reactive power of the loads and all the other RPRs.

At time equal to *20 s,* two CNs' voltage reference is changed (from *1* to *1.01 p.u.*), with the aim of demonstrating the LQRI control's effectiveness in managing system voltage and reactive power. Figures 3 and 6 clearly show that the LQRI control allows reaching the desired setpoints for all the CNs (two reach a new setpoint, while the others are kept at a constant level). This is obtained by adjusting the reference point for reactive power (Figs. 4 and 7), and subsequently the reactive power injected into the network (Figs. 5 and 8), of all the RPRs.

At time equal to *300 s,* the SVC function in one RPR is disabled leading to the need of changing the feedback control gain matrix K to K'. As a consequence, the reactive power reference of chosen RPR has been set to zero and it stops following the reactive power command from the LQRI regulator (Figs. 4 and 7, purple trace), and its reactive power injected into the grid only follows voltage variations in the adjacent nodes (Figs. 5 and 8, purple trace). The modification of matrix K occurs concurrently. As a result of the latter, the system without a bumpless transfer function experiences undesirable CNs voltages dynamics (Fig. 3) since all reactive power references changed abruptly (Fig. 4). On the other hand, the system with the bumpless transfer function shows extremely little voltage variation (Fig. 6) because it requires the controller output to match the entering controller output before the switching instant. The effect of the integrator unloading in the conditioning signal section of the bumpless transfer scheme is also visible in Figs. 6-8, with the reactive powers that slowly change towards their correct steady-state values (the ones presented also by the system without the bumpless transfer function), and limited voltage variations.

V. CONCLUSION

In this paper the secondary voltage regulation of a transmission network by means of an LQRI controller is presented, proposing a solution to address the variability in system structure and number of actuators (reactive power resources) that is common in such application. Using a bumpless transfer control technique, it has been possible to address the changes in the feedback control matrix gain and size, as well as in the measurement and remote actuation signal arrays. The result, demonstrated by simulation on a case study, is a negligible variation in the controlled nodes voltages at the variation time instant, coupled with smooth reactive power transients.

Future work on this topic will address controller determination on the basis of the available system state and response to emergency actions following unexpected events.

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