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

Giorgio Sulligoi
Dept. of Engineering and Architecture
University of Trieste
Trieste, Italy
gsulligoi@units.it

Andrea Vicenzutti
Dept. of Engineering and Architecture
University of Trieste
Trieste, Italy
avicenzutti@units.it

Massimiliano Chiandone
Dept. of Engineering and Architecture
University of Trieste
Trieste, Italy
mchiandone@units.it

Fabio Marzolla
Dept. of Engineering and Architecture
University of Trieste
Trieste, Italy
fmarzolla@units.it

Enrico Maria Carlini
Head of Dispatching and Operation
Terna
Rome, Italy
enricomaria.carlini@terna.it

Giorgio Maria Giannuzzi
Head of security, defence and system protection
Terna
Rome, Italy
giorgio.giannuzzi@terna.it

Roberto Zaottini
Head of stability and network calculations
Terna
Rome, Italy
roberto.zaottini@terna.it

Cosimo Pisani
Stability and network calculations
Terna
Rome, Italy
cosimo.pisani@terna.it

Abstract—The actions for limiting the climate change are significantly affecting the electrical power system. Indeed, the increase in renewable power sources and the progressive shut off of coal-fired power plants are transitioning the generation from a centralized to a decentralized paradigm. The latter may cause issues in a grid that was originally designed taking as granted the presence of several big power plants to be used as actuators for the system control. Considering voltage control, the actual control architecture is based on a hierarchical structure applied to a given set of rigidly subdivided control areas. Although such architecture is currently capable of maintain voltage control on the grid, the increase in converter interfaced generators (due to renewables exploitation) and the decrease of the buses short circuit powers (due to high power plants shut-off) may decrease its effectiveness in the future. To this aim, in this paper a coordinated decoupling voltage control is proposed, capable of using all the available reactive power sources on the grid as actuators. The issue of controlling a system with a variable number of actuators (due to generators connection and disconnection) is taken into account, proposing a suitable solution for avoiding transients during the switch between controllers having different output dimension. A brief discussion about communication (among actuators and controller) performances required for implementing the proposed control in the power system is also given.

Keywords— secondary voltage control, reactive power management, decoupling control, bumpless transfer, communication and control requirements

I. INTRODUCTION

The emission of regulations and policies aimed at addressing the climate change at first promoted the extensive exploitation of renewable energy sources in electric power systems, and now are actively pushing towards the elimination of coal fired power plants. Thus, a great amount of energy production nowadays is coming from renewable resources, like photovoltaic and wind, which are gradually replacing the traditional power plants (considering also their priority in dispatching). Within the context of voltage control, the more the presence of renewables increases at the expenses of conventional power plants, the more critical the need of involving new Reactive Power Resources (RPR) in automatic voltage control becomes. The latter include not only renewables, but also synchronous compensators, STATCOMs, and HVDC links with voltage source converters interfaces.

The actual voltage control architecture used in the Italian Transmission System is performed through three hierarchical control levels [1]. Primary Voltage Control, through the Automatic Voltage Control (AVR), aims at regulating the single generator voltage. The Secondary Voltage Control (SVC) consists of the reactive power control loops of each power station generator, closed by local (one for each power plant) voltage and reactive power regulators, called SARTs (Automatic System for Voltage Regulation). The latter receive from the regional voltage regulators a reactive power level (livq) request, expressed in percentage of the single generator reactive capability, and acts on the AVRs to provide such reactive power to the transmission network [2]. The goal of SVC is to obtain the voltage regulation of the Pilot Nodes (PN), which are nodes with large short-circuit power and are thus capable of affecting the voltage of all the neighboring nodes. By controlling the PN voltage, all the nodes belonging to its area of influence result in suitable voltages. The network subdivision into areas is called zoning, and there are several procedures and methods to determine their optimal splitting [3][4]. Finally, tertiary voltage control defines the optimal PN voltage reference on the basis of optimization algorithms that aim at maximizing the generators reactive power margin and minimizing the transmission lines losses, while considering the network structural limits (i.e., solving the optimal reactive power flow problem [5]).

In order to correctly integrate the new RPRs in voltage control, it is needed to consider their peculiarities. The above-mentioned new RPRs usually have static converter interfaces, thus presenting higher dynamic performance in respect to rotating machines. Therefore, it is required to specifically design the control system to take advantage of such benefit, for improving the voltage regulation performance. However, the bandwidth separation between the several controllers must still be guaranteed, to avoid overlapping dynamics (e.g., rotating machines AVRs and static converters reactive power regulators) that could cause stability issues. The RPRs reactive power contribution is also difficult to manage, since the single source power size is in most of the cases smaller than conventional power plant's one, and its reactive power production capability is strictly tied to the interface converter technology and control. It is clear that the voltage control architecture requires a revision in order to allow not only the correct coexistence of new RPRs with conventional power plants, but also their best use in a future scenario where conventional power plants may be totally phased out. A step towards such revision is presented in this paper, where an architecture based on decoupling control [6] is considered for the SVC. Being the RPRs number variable during the system operation (due to the sources connection and disconnection, or simply their enabling and disabling of the SVC function), the application of the decoupling approach to power system SVC leads to the peculiar issue of managing a system with a variable number of actuators. This is here addressed by means of a bumpless control transfer method.

The paper is organized as follow: in Section II the decoupling control is presented and its application to a transmission power system is discussed. Section III presents the issue of decoupling control in a system with a variable number of actuators, discussing the bumpless transfer technique used to enable the correct control system operation. In section IV decoupling control and bumpless transfer are applied to a case study. A brief argument about communication among actuators and controller, and its performance is given in section V. Finally, Section VI leads to the conclusions.

II. DECOUPLING CONTROL FOR SVC

Controlling the voltage of a power system at transmission level is basically a MIMO (multiple input multiple output) system control task. The meshed nature of the high voltage power grid makes the change in a bus voltage affecting the reactive power flowing in all afferent lines, thus modifying also the voltage of all the other buses. One of the characteristic properties of MIMO systems is that the input–output behavior is coupled, i.e., a change in one input affects several outputs, and the change of a single output can be achieved only by acting on several inputs at the same time. The decoupling control concept is based on the definition of a reference transfer matrix capable of decoupling the input-output behavior of the system, making it possible to act on each output variable separately (without affecting the other outputs). Therefore, it becomes possible to define a set of input–output pairs for the overall decoupled system, which can be managed like independent SISO (single input single output) systems.

A. Decoupling control general approach

In Fig. 1 is depicted a generic MIMO dynamic system, composed by the controlled system, the controller, and a suitable control feedback.

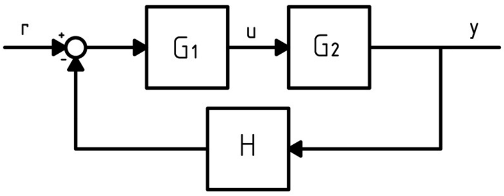

Fig. 1. General scheme of Decoupling Control

The figure shows:

- u, array of control signals (dimension m);
- y, array of output signals (dimension t);
- r, array of input signals, which are the references for the control system (dimension t);
- H, transfer function of control feedback transducers, here assumed to be diagonal (dimension txt);
- G_2, transfer function of the dynamic system to be controlled (dimension mxt);
- G_1, transfer function of the control system (dimension t$x$$m$).

The G_1 transfer function must be defined in such a way to obtain the above-mentioned decoupling between r and y arrays. If this is achieved, each input signal affects only one output, by means of a coordinated set of control signals. In the Fig. 1 system, this can be achieved by defining a suitable diagonal non-singular matrix G as follows:

$$G_2 G_1(s) = G(s) \tag{1}$$

The non-singularity of G implies that G_2's rank must be t and, consequently, it must result that $m \geq t$ (control signals are at least equal in number to the controlled outputs, i.e., the system is completely controllable).

By assuming $m=t$ (which can be achieved in the completely controllable system by using only a subset of the available control signals), all the involved matrices become square. Thus, G_1 can be determined as:

$$G_1(s) = G_2^{-1}\, G\,(s) \tag{2}$$

where G_2^{-1} is the inverse matrix of G_2 and G is the above mentioned diagonal non-singular matrix. The latter can be chosen accordingly to the system input-output desired behavior (as an example, it can be a diagonal matrix of PI regulators).

Conversely, if $m>t$ (all the available control signals are used to control the system), G_2 is a rectangular matrix. Thus, G_1 can be determined as:

$$G_1(s) = G_2^{+}\, G\,(s) \tag{3}$$

where G_2^{+} is the Moore-Penrose pseudo-inverse matrix of G_2.

In either case, the control system with the decoupling approach applied is constituted by one control (G) and one decoupling (G_2^{-1} or G_2^{+}) matrix.

B. Application to the transmission system's SVC

In the context of SVC, a general transmission network can be considered as a MIMO system, where the output is the set of voltages in the network and the control signal is the set of reactive powers injected in the system by the RPRs. Both loads and sources not contributing to SVC can be considered as a disturbance to the system. In such a case, the system's transfer function G_2 is the one that represents all the dynamic behavior that occurs between these two sets of variables.

The dynamic response of a transmission line is an electromagnetic phenomenon, presenting a very fast dynamic (time constants in the order of milliseconds). These pertain to the electrical transients domain, and are dynamically decoupled from the SVC dynamic (time constants in the order of tens of seconds). Similarly happens for RPRs internal dynamics, which have fast dynamic in respect to SVC one (this is true for both rotating machines and the much faster static interfaced power sources). By the same reasoning, primary voltage control dynamic (time constants in the order of one second) can also be ignored. Therefore, the transfer function of the transmission system for the SVC becomes a matrix of real coefficients matrix (i.e., a constant transfer function), relating reactive power and voltages in all the network nodes. Being the transmission system a meshed one, such relationship can be easily determined by means of power flow calculation tools. Therefore, the transmission system can be modeled with its sensitivity matrix S, whose elements are defined as follows:

$$S_{ij} = dv_i/dq_j \tag{4}$$

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 use of the S matrix implies the linearization of the system in an equilibrium point, which affects matrices calculation, but not control concept definition.

The decoupling control requires that $m \geq t$, i.e., that control signals are at least equal in number to the controlled outputs. Therefore, a reduced number of network nodes, at most equal to RPRs one, needs to be selected for the SVC. These 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. Several methods can be used to this aim: use of the electrical distance concept [7], use of short circuit power [8] [9], use of sensitivity among nodes [10], mixed methods [11]. Once the CNs have been selected, the overall S matrix can be reduced by taking into account only the nodes that either pertain to the CN set or have an RPR connected, leading to the definition of the S_{red} matrix, whose dimension is mxt.

Referring to Fig. 1 general scheme, it is then possible to set a series of correspondences with the specific SVC application. The array of references r is the array of CNs voltage references v_{rif}. The array of control signals u is the array of reactive power references q_{rif} (i.e., the output of the centralized secondary voltage regulator). The control action is applied to the system by means of the RPR, which are the actuators for the SVC and are modeled by means of the transfer functions $F_1, F_2, \ldots, F_n$. The latter model the reactive power control loop dynamic of the sources. Finally, the output array y is the set of CNs' voltages v_{nodes}.

The application of the decoupling control to this system can be achieved by setting the G_1 control's transfer function as explained in the previous section. In particular, here the reference transfer matrix that decouples the system is calculated as S_{red}^+, ignoring the actuators dynamic, and by setting G as a simple diagonal matrix of PI regulators. Fig. 2 represent the final block scheme of the decoupling control applied to a transmission network.

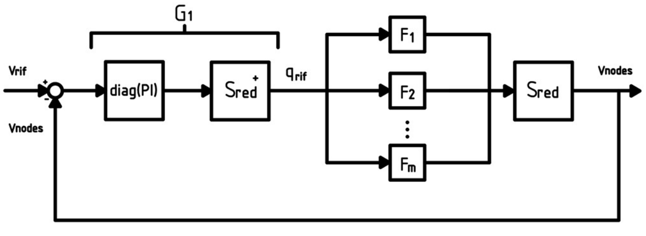

Fig. 2. Decoupling Control applied to a transmission grid

C. Issues in applying decoupling control to the transmission system

The application to the transmission system of the control equation (3) is effective as long as its structure does not change, and its operating point does not drift too far from the equilibrium point used in the S matrix determination. If the operating point of the transmission system or its structure (in terms of connection between nodes) changes, also the matrix S changes and the control law must be modified as consequence. The methods to determine S, its refresh rate, and the assessment of the subsequent errors are all topics for future works. Another significant issue is related to the enabling or disabling of the SVC function in the power sources. This is equal to a change in the number of RPRs, i.e., a change in the number of actuators used by the system to perform the voltage control. Thus, the control system must recalculate the new decoupling matrix S_{red}^+ and apply the resulting set of reactive power references to the remaining RPRs. (This works until the number of RPRs becomes equal to the number of CNs, then a reduction in the latter must also be applied. This case is not considered here.)

Being S a matrix of algebraic gains, it has no dynamic. Thus, any change in it leads to a subsequent step change in the values of the derived S_{red}^+ matrix, which in turn causes a sudden change in the reactive power reference signals sent to the RPRs. The result is an unwanted transient on both reactive powers and voltages of all nodes, as it is shown in the Section IV case study results. Therefore, a bumpless transfer function needs to be added to the decoupling control, to limit the voltage transient that follows the control system change caused by RPRs SVC function enabling/disabling. In this paper only programmed variations are taken into account, while emergency actions following unexpected events (e.g., the sudden disconnection of a power plant) will be addressed in the future.

III. BUMPLESS TRANSFER FOR DECOUPLING CONTROL OF TRANSMISSION SYSTEM'S SVC

The objective of bumpless transfer techniques is to ensure continuity in the control signals and smooth transients at, and immediately following, the switching instant. There are several techniques to obtain a bumpless transfer. Some of them are based on H_∞ [12], other are based on Model Predictive Control [13], and there are even bumpless transfer techniques that provide also an anti-windup function [14]. Having chosen a matrix of PI regulators for the SVC system in this paper, the latter is here used for solving the issue highlighted in the previous section.

The base idea is that the required changes in S_{red}^+ and in RPR's number can be considered as a complete control system switch, from the former controller to a new one. Therefore, the [14] approach can be applied to the decoupling SVC of Fig. 2, leading to the Fig. 3 control structure. In particular, in the figure the system is controlled before the change by the upper branch (by applying q_{rifG1} to the output), while the control after the change is done by the lower branch (by applying $q_{rifG1'}$ to the output). The system reduced sensitivity matrix is S_{red} for the former and S_{red}' for the latter.

In Fig. 3, G_1 represent the retiring controller and G_1' the incoming one. G_1 includes the decoupling matrix S_{red}^+ calculated for the system before the change, while in G_1'

includes the decoupling matrix S_{red}^{+}' calculated for the system after the change. To avoid sudden modification in q_{rif} when shifting the controller, the output of the new one must be initialized as close as possible to the output of the former one. This can be obtained by applying a proper input signal to the incoming controller before performing the switch, to force the equality of both outputs. Such a function is achieved by the additional $\mathrm{q_{rif}}$ feedbacks added to each controller, clearly visible in Fig. 3. These allow assessing the error between the q_{rif} signal applied to the system and each controller output, and generating a correcting action if this is not null. If saturations are present in the control signals, as shown in Fig. 3, the feedbacks double as anti-windup compensators. While in [14] such approach was used for a SISO system, in the application of this paper the system is a MIMO one. This is enabled by the use of the decoupling control concept, which allows managing the input-output system relations as multiple SISO ones.

A peculiarity of the issue here addressed is that the number of CNs and RPRs is generally not equal, thus making the size of the input and output signals of the controller different in size. Moreover, the two controllers also have different output array size among them, due to the change in RPRs number. Thus, the q_{rif} error feedback must be properly transformed to allow the correct bumpless transfer system operation. This is achieved through several steps. First, the components of the q_{rif} signal related to the RPRs that are not applying the SVC function are forced to zero. Second, the q_{rif} error related to the above RPRs is removed from the feedback. Third, the resulting set of reactive power reference errors is multiplied by the matrix S_{red} or S_{red}', depending on the specific controller section, to obtain the required bumpless corrective signal.

The mathematical reason for the latter step is that the transfer function that makes the q_{rif} array comparable with the v_{rif} one is the sensitivity matrix of the controlled network, as per (3) definition.

IV. CASE STUDY AND RESULTS

A 65 buses transmission network section, lying on an area of approximatively 26 thousand square kilometers, has been chosen as case study. Among the buses, 11 have an RPR installed, and 5 have been selected as CNs. To this paper aims, only the network's sensitivity matrix S is required, which has been calculated by means of a load flow problem solution on a typical operating point for such network.

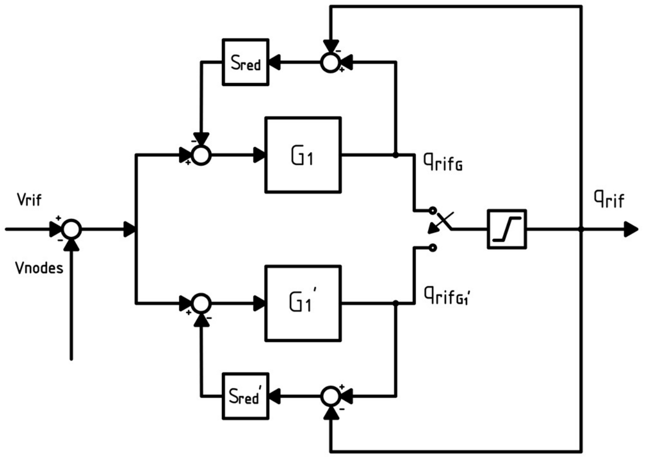

Fig. 3. Bumpless transfer scheme for decoupling control in a MIMO system

The assumed perturbation is the planned disabling of SVC function in one RPR (as mentioned above, other events are planned for future work). This is achieved on source-side by disconnecting its input q_{rif} signal and keeping the same reactive power level that was present prior to the event. Such behavior is also the one applied as starting point in the procedure for the disconnection of a source from the grid. Control side, since the specific RPR is not anymore using the q_{rif} signal, the latter is set equal to zero (to avoid issues in case of a sudden re-enabling of the SVC function for the source).

The simulation of the Fig. 2 system when such disturbance is applied are presented below, considering the control system without (Fig. 4, 5, and 6) and with (Fig. 7, 8, and 9) the bumpless transfer function enabled. Since the model is a linearized one, the starting voltage of all CNs is equal to 1 *p.u.* despite having a reactive power equal to *0 p.u.*

At $t_1 = 20\ s$ a change in voltage reference from *1* to *1.01 p.u.* of two CNs is driven, to demonstrate the effectiveness of the decoupling control. As clearly visible from Fig. 4 and 7, in both cases the decoupling control is capable of driving the two CNs to their new setpoints, without affecting the others. This is achieved by changing the reactive power reference point of all the RPRs (Fig. 5-6, and 8-9), as expected in a MIMO system.

At $t_2 = 100\ s$, the planned disabling of SVC function in one RPR occurs. The affected RPR keeps its reactive power level (Fig. 6 and 9, violet curve), while its reference is set to zero by the control system (Fig. 5 and 8, violet curve). At the same time the change of the decoupling matrix is performed. The latter cause undesired transients in the CNs voltages for the system without the bumpless transfer function (Fig. 4), while the system where the function is enabled shows very limited voltage variation (Fig. 7). The voltage transient in the first system is caused by the sudden change in reactive power references shown Fig. 5, which in turn is due to the abrupt change in the decoupling matrix (from S_{red}^{+} to S_{red}^{+}'). This requires the overall PI regulators to intervene (with their time constants) to recover the correct CNs voltages. Conversely, the bumpless transfer function forces the incoming controller output to be equal to the outcoming one, during a time 30 seconds timeframe before the effective switch. Therefore, the new controller q_{rif} signal is very close to the already present one at the switch time (Fig. 8), and very little voltage transient is present (Fig. 7). The latter can be further reduced by extending the adaptation timeframe above 30 seconds.

V. ICT REQUIREMENTS FOR APPLYING THE CONTROL

The control here presented requires the feedback of the measurements of m nodes and the communication of t correction values to the actuators. These data transmissions take place over a rather large regional area, as above-stated, making the control system sensitive to transmission delays and any communication error.

In electrical systems, different communication protocols are used, and at level 1 of the ISO model many physical media are under consideration. Currently there is a convergence among all operators in the use of protocols based on TCP/IP (IP-based) both on local [15] and regional networks [16]. Considering level 1, hardwired and wireless implementations are under consideration, the latter more for distribution grids [17]. At layer 3, the connectionless datagram service known as the IP protocol introduced in 1974 [18] represents the standard de facto on which the several protocols traditionally used in electrical systems are based. In [19] the various applications concerning the management and transmission of electrical energy are listed with their specific requirements. In the case considered in this work, both the communication of the voltage value of the CNs, and the communication of the q_{rif} to the RPRs, have the following characteristics:

- each is a continuous monodirectional flow;
- the repetition of values in cases of non-receipt or receipt of incorrect values has no practical advantage.

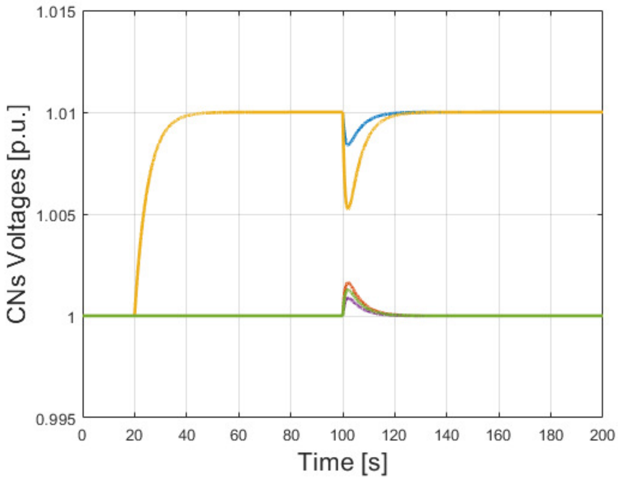

Fig. 4. CNs' voltages with decoupling control without bumpless transfer

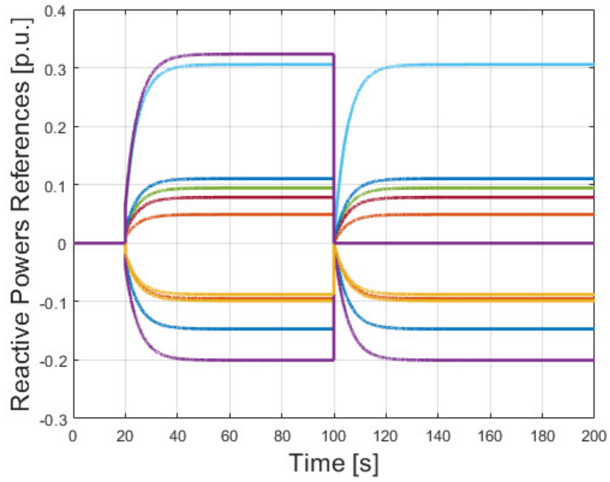

Fig. 5. Reactive power references of RPRs with decoupling control without bumpless transfer

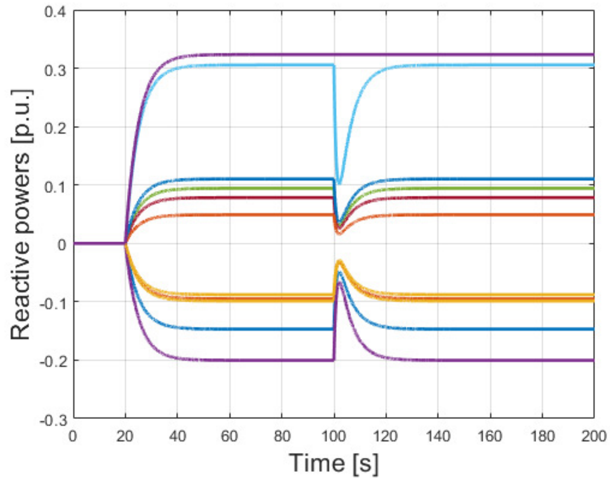

Fig. 6. Reactive power provided by RPRs with decoupling control without bumpless transfer

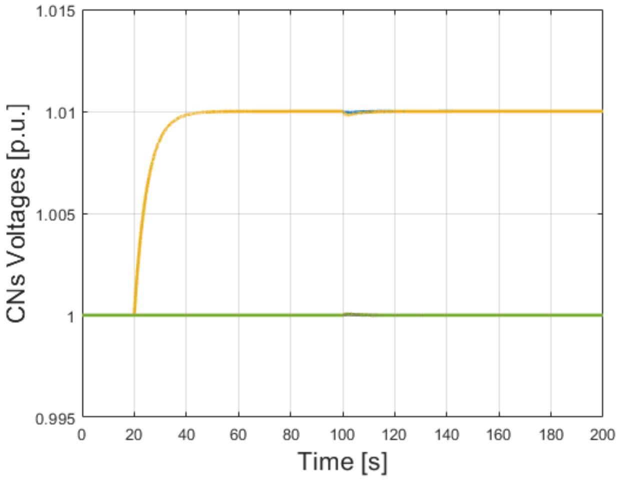

Fig. 7. CNs' voltages with decoupling control with bumpless transfer

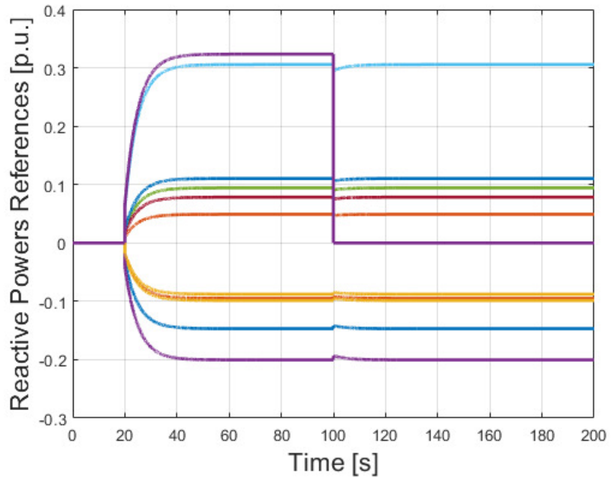

Fig. 8. Reactive power references of RPRs with decoupling control with bumpless transfer

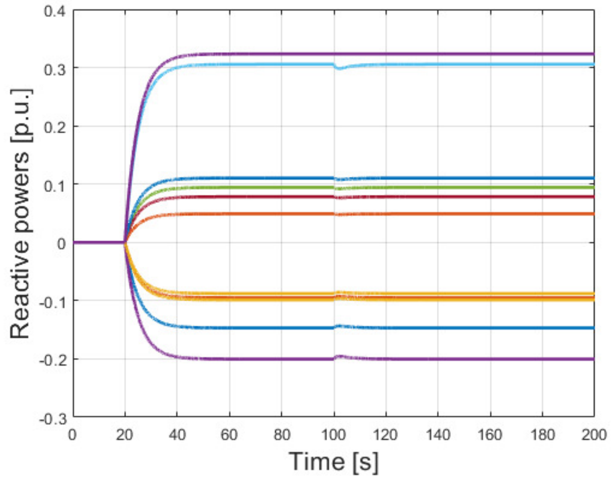

Fig. 9. Reactive power provided by RPRs with decoupling control with bumpless transfer

Communications therefore have typical characteristics of data streaming, where the correction of any transmission error should be done discarding the incorrect values at the application level (e.g.~~,~~ by the regional controller and the RPRs), no retransmission is implemented (dropping packets is preferable to waiting for delayed packets), and handshaking protocols should be limited as much as possible.

Communication requirements can be deduced from common practice rules in digital control system design, as in [20], considering the effect that delays have on the control performance [21]. For a control that requires a bandwidth of the order of 0.1 rad/s, the sampling period can be between 0.5 and 3 s. Assuming as a rule of thumb that a limit on delay can be one tenth of the sampling time, a rough limit on the delay is in the order of a hundred of milliseconds. This requirement seems to be compatible with a wide area distributed real time control system based on the TCP/IP standard [22] [23].

User Datagram Protocol (UDP), one of the core protocols of IP networks, is suitable considered that it has no handshaking dialogues and error checking and correction can be implemented at the application level. Unlike the polling mechanisms normally used in SCADA systems, the communication of values can be implemented with single messages, avoiding both handshaking at the TCP level and other handshaking mechanisms at the application level.

Further investigations will be made on how to apply the necessary security mechanisms while limiting the overhead in transmission.

VI. Conclusion

This paper addressed the application of a decoupling control to the secondary voltage control of a transmission network, presenting a solution for the issue of controlling a MIMO system with a variable number of actuators (the reactive power resources – RPRs). By considering the RPRs SVC function enabling and disabling (required for their correct connection and disconnection) equal to a complete controller change, it becomes possible to apply bumpless transfer techniques to avoid the reactive power and voltage transients caused by the abrupt change in the decoupling matrix. The results of an application to a case study demonstrate the effectiveness of the proposed approach for both achieving a decoupled voltage control in a meshed transmission system, and allowing the RPRs management with negligible impact to the system's voltages. Due to the physical extension of transmission systems, the application of the proposed approach requires dedicated communication channels for measuring the controlled nodes' voltages and communicating the reactive power references to the RPRs. This is feasible with actual communication technologies, without needing specific protocols to be developed.

Further research will be done regarding decoupling matrices determination following system structure and operating point variations, and control response to emergency actions after unexpected events.

References

[1] S.Corsi, M. Pozzi, C. Sabelli, & A. Serralli "The Coordinated Automatic Voltage Control of the Italian Transmission Grid—Part I: Reasons Of The Choice And Overview of the Consolidated Hierarchical System", Ieee Trans. On Power System, 19(4), Pp. 1723-1732, 2004.

[2] G. Sulligoi, M. Chiandone and V. Arcidiacono, "NewSART automatic voltage and reactive power regulator for secondary voltage regulation: Design and application", 2011 IEEE Power and Energy Society General Meeting, 2011, pp. 1-7.

[3] Daher, N. A., I. Mougharbel, M. Saad, e H. Y. Kanaan. "Comparative study of partitioning methods used for secondary voltage control in distributed power networks". In 2013 IEEE International Conference on Smart Energy Grid Engineering (SEGE), 1–7, 2013.

[4] 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.

[5] H. W. Dommel and W. F. Tinney, "Optimal Power Flow Solutions," in IEEE Transactions on Power Apparatus and Systems, vol. PAS-87, no. 10, pp. 1866-1876, Oct. 1968.

[6] W. S. Levine, "Control System Advanced Methods, The Control Handbook", Second Edition, CRC Press, 2011.

[7] Shaaban, M. "Improved regional coordination of generation voltage control". In 2008 IEEE 2nd International Power and Energy Conference, 175–79, 2008.

[8] V. Arcidiacono, "Automatic Voltage and Reactive Power Control in Transmission Systems", Symposium 39-83, Florence, 1983.

[9] Hernandez, B., C. A. Canizares, J. M. Ramirez, B. Hu, e M. Liu. "Secondary and Tertiary Voltage Regulation Controls Based on Regional Optimal Power Flows". In 2018 Power Systems Computation Conference (PSCC), 1–7, 2018.

[10] Omar H. Abdalla, Hady H. Fayek, Abdel Ghany M. Abdel Ghany, "Secondary and Tertiary Voltage Control of a Multi-Region Power System", Journal Electricity, 2020.

[11] Sun, H., Q. Guo, B. Zhang, W. Wu, e B. Wang. "An Adaptive Zone-Division-Based Automatic Voltage Control System with Applications in China". IEEE Transactions on Power Systems 28, n. 2 (may 2013).

[12] Y. Zhao and J. Zhao, " H_∞ Reliable Bumpless Transfer Control for Switched Systems With State and Rate Constraints," in IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 50, no. 10, pp. 3925-3935, Oct. 2020.

[13] T. C. S. Wibowo and N. Saad, "Steady-state bumpless transfer MPC using external feedback of Manipulated Variables," 2010 International Conference on Intelligent and Advanced Systems, 2010, pp. 1-6.

[14] Youbin Peng, D. Vrancic and R. Hanus, "Anti-windup, bumpless, and conditioned transfer techniques for PID controllers," in IEEE Control Systems Magazine, vol. 16, no. 4, pp. 48-57, Aug. 1996.

[15] Kwok-Hong Mak and B. L. Holland, "Migrating electrical power network SCADA systems to TCP/IP and Ethernet networking," in Power Engineering Journal, vol. 16, no. 6, pp. 305-311, Dec. 2002.

[16] R. Amiri and O. Elkeelany, "An embedded TCP/IP hard core for Smart Grid information and communication networks," Proceedings of the 2012 44th Southeastern Symposium on System Theory (SSST), 2012.

[17] A. Angioni et al., "Coordinated voltage control in distribution grids with LTE based communication infrastructure," 2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC), 2015, pp. 2090-2095.

[18] V. Cerf and R. Kahn, "A Protocol for Packet Network Intercommunication," in IEEE Transactions on Communications, vol. 22, no. 5, pp. 637-648, May 1974.

[19] Kuzlu, Murat, Manisa Pipattanasomporn, e Saifur Rahman. "Communication network requirements for major smart grid applications in HAN, NAN and WAN". Computer Networks 67,2014, pp. 74–88.

[20] Astrom, K. J. and B. Wittenmark, "Computer Controlled Systems, Theory and Design", Prentice-Hall, 1984.

[21] P. Albertos and M. Olivares, "Time delay limitations in control implementation," 1999 European Control Conference (ECC), 1999, pp. 1288-1293.

[22] G. Sheng, Y. Liu, D. Duan, Y. Zeng and X. Jiang, "Secondary voltage regulation based on wide area network," 2009 IEEE Power & Energy Society General Meeting, 2009, pp. 1-7.

[23] C. Gomez, M. Catalan, D. Viamonte, J. Paradells and A. Calveras, "Internet traffic analysis and optimization over a precommercial live UMTS network," 2005 IEEE 61st Vehicular Technology Conference, 2005, pp. 2879-2884 Vol. 5.