Automatic voltage and reactive power control in distribution systems: dynamic coupling analysis

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***Abstract*—The paper focuses on the dynamic response of a secondary voltage control scheme for distribution networks. The proposed control is based on a hierarchical architecture and is similar to the hierarchical voltage control implemented in some countries in high voltage transmission systems. The objective of the paper is to show a possible undesired dynamic coupling of different reactive power control loops of network generators. The effect of an algebraic decoupling matrix of the secondary voltage control as well as its effects simulated on a real-world case study are also duly discussed.**

***Index Terms*—Distribution network, hierarchical voltage control, reactive power control.**

I. INTRODUCTION

During the last decade, electric power grids have been facing a deep restructuring process. The power supply is moving towards a distributed generation approach. This change is mainly due to the large penetration of renewable energy sources (RES). While power plants based on RES are typically connected to MV and LV grids there is also a considerable number of plants that are connected directly to the HV transmission system. In this paper, we consider a hierarchical secondary voltage control of RES.

Special regulations and policies are being defined for RES power plants connection to the grid: in Europe, a process of harmonization coordinated by ENTSO-E led to the publication of new European grid codes [1] - [3]. Reference [4] provides an outline of the rules that are expected to be implemented in Europe. Research activity on the matter results in several proposals for voltage control of RES power plants [5]-[8].

The present work focuses on the voltage control of a cluster of RES power plants consisting of multiple interconnected generators. The generators form a local MV network that is connected to the system through a single point of delivery (POD). Such a point can be either in MV or HV. For these particular RES configurations, the paper analyses the application of a hierarchical control strategy based on a control scheme similar to that traditionally implemented in HV transmission systems [9].

The paper is organized as follows. Section II describes the architecture of the proposed hierarchical voltage control. Section III discusses the dynamic coupling of reactive power control loops acting on different power plants. Section IV shows, through simulations based on a real-world system, the effect of such a coupling. This section also discusses the implementation of decoupled control to be included in the hierarchical voltage and aimed at improving the dynamic response of the overall system. Section V draws conclusions and outlines future work directions.

II. PROPOSED CONTROL STRATEGY

The proposed control strategy is based on the hierarchical controller that has been successfully implemented in some countries in HV networks [10][11]. Such a control scheme consists of an external and a cluster of internal controllers, as follows. To control the voltage of a selected pilot bus (such as the point of connection), a central control unit coordinates the reactive power of each generator. This control unit implements the reactive power regulators (RPR) of the Secondary Voltage Regulation (SVR) [12] (for the transmission grid a similar device is called SART [13] in the Italian Grid Code). Figure 1 shows a synoptic scheme of the proposed control system.

The proposed control regulator receives the voltage reference from the TSO or DSO (depending on the voltage of the POD). The pilot bus (as defined in SVR) is the POD of the RES generation plant. Then, an external voltage control loop, implemented by the Busbar Voltage Regulator (BVR) in Figure 1, computes a reactive power level q_{lev} (between -1 and +1) [12], which is then multiplied by each generator reactive power limit. The result is a vector of reference reactive powers, namely Q_{ref}. Every value of this vector is compared with the actual value of each generator reactive power. The vector of errors is multiplied by the Dynamic Decoupling (DD) matrix [14] and sent to the GRPRs (Generator Reactive Power Regulators). The GRPRs resulting control signals are the reference of every generator (in Figure 1 these generators are represented as Static Frequency Converter SFC and Synchronous Generators AVR-G). It is also possible to

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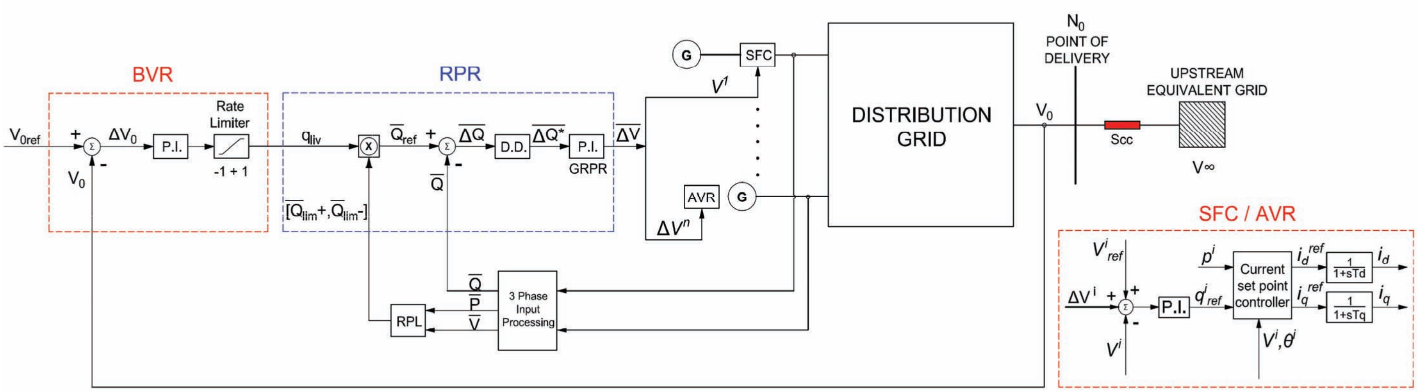


Figure 1. Synoptic schema of the secondary voltage control.

exclude the external voltage control loop and send a q_{lev} reference signal directly to the reactive power control loop.

As demonstrated in [15] - [17], this control technique can be applied to different kinds of generation plants connected to HV networks (cluster of hydro power plants, wind and PV farms) coordinated by a TSO voltage regulation. Moreover, the application of a common control system for both traditional power plants and RESs allows standardizing the dynamic response of all types of generators of the network. The distributed generators have been modelled in terms of a simple model in dq-axis coordinates and a set of PI controllers to regulate active and reactive powers [18]. This model is adequate to study the transient stability of the proposed hierarchical voltage control coupled with a simplified RES model.

The proposed control scheme shows several advantages, as follows. It is characterized by a fast response and shows a perfect tracking of both the pilot bus voltage and RES reactive powers. As it will be shown in section IV, even in case of dissymmetrical disturbances, this control ensures a stable operation, thanks to the decoupling action implemented by the matrix DD. Each generator equally shares a quota of the reactive power requested by the coordinating unit. Furthermore, the proposed control strategy is easy to implement, as there is a single control signal q_{lev}, and has already been successfully implemented for conventional power plants. The latter feature makes it attractive for TSOs.

III. COUPLING OF LARGE RES POWER PLANTS

A. Definition and calculation

Large RES power plants that are connected to the HV transmission system are typically composed of a set of generators connected through a MV distribution network and having a single POD at HV level. For the sake of example, Figure 4 in section IV shows the topology of a real-world cluster of hydroelectric power plant. The MV distribution network can be described, for the generic node k, by the well-known power flow equations, as follows:

$$\begin{cases} P_k = \sum_{i=1}^{n} V_k \cdot V_i \cdot Y_{ki} \cdot \cos(\theta_k - \theta_i - \gamma_{ki}) = P_{ko} \\ Q_k = \sum_{i=1}^{n} V_k \cdot V_i \cdot Y_{ki} \cdot \sin(\theta_k - \theta_i - \gamma_{ki}) = Q_{ko} \end{cases} \quad (1)$$

Where:

- P: active power at node;
- Q: reactive power at node;
- V: node voltage magnitude;
- Y: magnitude of admittance coefficients;
- θ: phase angle of node voltage;
- γ: phase angle of admittance coefficients;
- n: number of nodes of the network;
- P_{ko}: active power fixed at the generic node k;
- Q_{ko}: reactive power fixed at the generic node k.

Linearizing (1) at a given operating point leads to the following matrix form:

$$\begin{bmatrix} [\Delta P] \\ \\ [\Delta Q] \end{bmatrix} = \begin{bmatrix} \left[\frac{\partial P}{\partial V}\right] & | & \left[\frac{\partial P}{\partial \theta}\right] \\ - & & - \\ \left[\frac{\partial Q}{\partial V}\right] & | & \left[\frac{\partial Q}{\partial \theta}\right] \end{bmatrix} \cdot \begin{bmatrix} [\Delta V] \\ \\ [\Delta \theta] \end{bmatrix} \quad (2)$$

where the partial derivatives matrices $\left[\frac{\partial P}{\partial V}\right], \left[\frac{\partial P}{\partial \theta}\right], \left[\frac{\partial Q}{\partial V}\right], \left[\frac{\partial Q}{\partial \theta}\right]$ constitute the Jacobian matrix and represent the link between the active and reactive power with the module and bus voltage phasors. Matrix coefficients embed information about the characteristic parameters of the transmission lines of the network. For the purposes of voltage control, active power variations are neglected ($[\Delta P] = 0$) and only reactive power sources are utilized as actuators [19], thus equation (2) can be simplified as:

$$[\Delta Q] = \left[\left[\frac{\partial Q}{\partial V}\right] - \left[\frac{\partial Q}{\partial \theta}\right] \cdot \left[\frac{\partial P}{\partial \theta}\right]^{-1} \cdot \left[\frac{\partial P}{\partial V}\right] \right] [\Delta V] \quad (3)$$

Setting a working point of the system (i.e. fixed generators active power produced, generator power factors and voltage of the infinite power upstream equivalent network - V_∞) and solving the problem of power flow, it is possible to obtain the equations describing the linearized system:

$$[\Delta Q] = [A] \cdot [\Delta V] \quad (4)$$

where $[\Delta Q]$ and $[\Delta V]$ are the vectors of the reactive power (n,1) and voltage variations (1,n), respectively, and $[A]$ is a (n,n) matrix that defines the electric coupling between reactive powers and voltage magnitudes. Hence, generators are electrically coupled according to the matrix coefficients $\left[\frac{\partial Q}{\partial V}\right] - \left[\frac{\partial Q}{\partial \theta}\right] \cdot \left[\frac{\partial P}{\partial \theta}\right]^{-1} \cdot \left[\frac{\partial P}{\partial V}\right]$.

Note that we assume that [A] is full rank, as it is in most practical applications. The discussion of idiosyncratic cases where [A] is singular is out of the scope of this paper.

B. Decoupling matrix

Starting from the inverse of the electric coupling matrix, it is possible to calculate the dynamic decoupling matrix, as follows:

$$[DD] = [A]^{-1} \quad (5)$$

[DD] is composed by the coefficients $\frac{\partial V}{\partial Q}$ and is defined by the following equations:

$$[\Delta V] = [A]^{-1} \cdot [\Delta Q] \Rightarrow [\Delta V] = [DD] \cdot [\Delta Q] \quad (6)$$

Note that the coefficients above can also be calculated through a numerical sensitivity analysis, as discussed in [20].

IV. CASE STUDY

This section illustrates the effect of the secondary voltage control scheme through time domain simulations. With this aim, we consider three networks, each shows a different power plant topology and, hence a potentially different behavior when coupled with the secondary voltage controller. The configuration under study are depicted in Figures 2, 3 and 4.

Table I provides a legend of the symbols used in the schemes of the figures above, while the notation of cable technologies is given in Table II.

TABLE I. LEGEND OF SYMBOLS USED

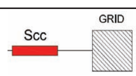
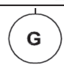
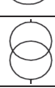
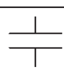
Graphic symbols	Description
	Short-circuit impedance of the upstream network
	Generator
	Transformer
	Load
	Line/Cable
	Bus
	Capacitor

TABLE II. CABLE TECHNOLOGIES AND DATA

Line Type	Graphic symbol	R	X	c
		[Ohm/ Km]	[Ohm/ Km]	[µF/ Km]
Type 1 L-AER-01 1x148,51mmq		0,219	0,339	0,0106
Type 2 L-AER-02 1x307,7mmq		0,106	0,316	0,0114
Type 3 ARG7H1OR 3x(1x150mmq)		0,206	0,110	0,25
Type 4 RG7H1R 3x(3x1x300mmq)		0,060	0,100	0,35
Type 5 RG7H1OR 1x(3x240mmq)		0,075	0,090	0,37
Type 6 RG7H1OR 4x(3x95mmq)		0,193	0,100	0,26

We first calculate the sensitivity coefficients (∂V/∂Q) that combine the POD N0 to all other nodes of the grid. Table III, IV and V show, for the three examples, the influence on the POD voltage variations of each generator. The higher the sensitivity, the more a generator participates to the voltage regulation. Clearly, if sensitivity values have similar magnitudes, then all generators of a given power plants effectively participate to the voltage regulation proportionally to their capacity.

TABLE III. SENSITIVITY COEFFICIENTS - PLANT A

∂V/∂Q	N0
C-01	0,777
C-02	0,777

TABLE IV. SENSITIVITY COEFFICIENTS - PLANT B

∂V/∂Q	N0
C-01	0,634
C-02	0,610
C-03	0,593

TABLE V. SENSITIVITY COEFFICIENTS - PLANT C

∂V/∂Q	N0
GEN 1	0,0717
GEN 2	0,0714
GEN 3	0,0675
GEN 4	0,0680
GEN 5	0,0680
GEN 6	0,0689
GEN 7	0,0657

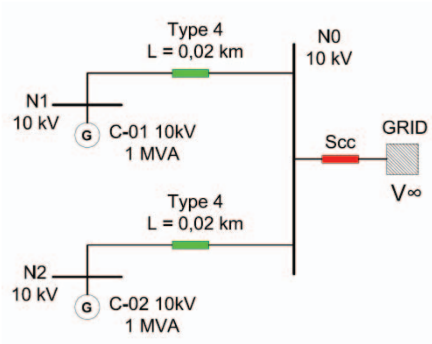


Figure 2. Topology of plant A

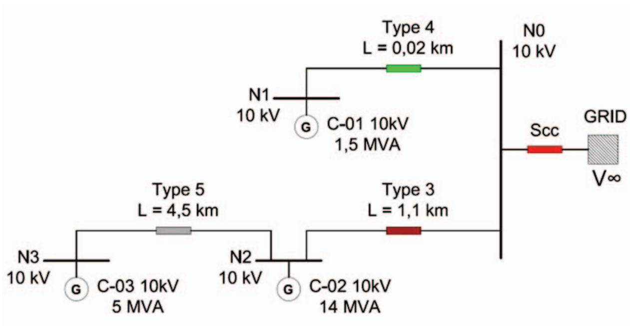


Figure 3. Topology of plant B

For each power plant of Figures 2 to 4, regulator coefficients and time constants are chosen to ensure stability and a dynamic response with time scales comparable to those of traditional power plants. The internal voltage loop (AVR or SFC) is characterized by fast time scale, i.e., in the order of tenths of a second; the RPR has a time constant of few seconds; and the external voltage loop (BVR) time constant is of the order of 10 s.

The first simulation has been conducted considering the topology of plant A in Figure 2. In this case, two generators with same capacity are connected to a common bus bar and we assume that their reactive power production is different [21]. At time $t = 50$ s, the SVR is switched on. The purpose of the SVR is to balance the reactive power production of the two generators. Without the decoupling matrix, the SVR introduces reactive power oscillations. Figure 5 shows such oscillations (all reactive power plots are in per unit of 100 MVA), which are in counterphase, thus indicating a reactive power loop between the generators. Note that reactive power loops should be avoided as they mechanically stress alternators, increase losses, interfere with voltage protections, and are seen as voltage disturbances by loads electrically close to the generators.

It should be noted that, although the topology of the network and starting conditions has been chosen to emphasize the coupling phenomenon, such asymmetric perturbations happens every time the system is started up or whenever a generator is inserted alone into the cluster. Figure 6 shows the effect of applying the same perturbation to the system but considering the effect of the proposed decoupling matrix. In this case, as expected, the transient evolution of reactive powers and, thus, bus voltages do not show oscillations.

Similar results are obtained with the power plant topologies B and C. In particular, Figures 7 and 8 show the step response of the voltage reference for the network topology B respectively without and with the inclusion of the decoupling matrix [DD]; while Figures 9 and 10 show the transient response for the same scenarios for the topology C. The transient evolution of reactive powers in Figures 8 and 10 confirms the expected stabilizing effect of the proposed decoupled control scheme: no reactive power loop, in fact, occurs among generators. It is worth noting that such phenomena does not appear merely observing the dynamic evolution of bus voltage magnitude alone. It is thus necessary to measure and control the reactive powers.

V. CONCLUSIONS

The paper presents a study on the dynamic coupling of

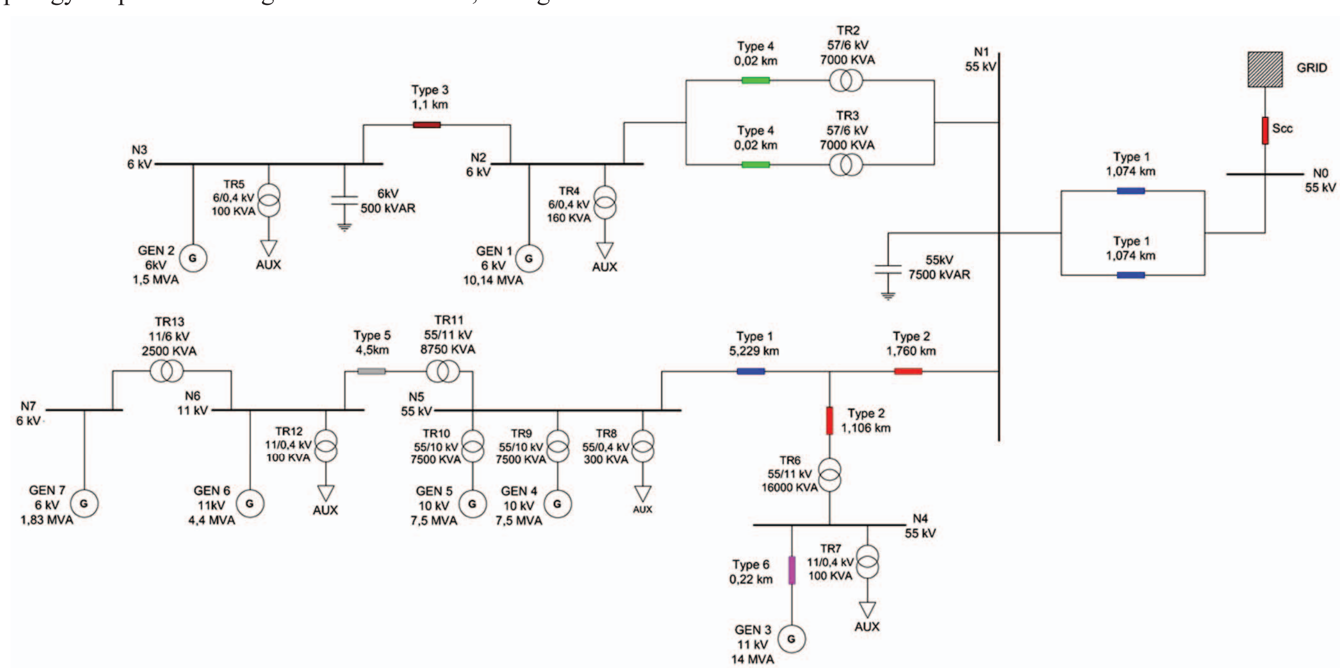


Figure 4. Topology of plant C

secondary voltage controllers of RESs connected into a dedicated subnetwork with a single POD. Such a coupling effect causes undesirable reactive power loops among the generators that belong to the same cluster. To prevent that, the paper proposes a secondary voltage control scheme with inclusion of a dynamic decoupling block that has been already successfully implemented in some conventional large power plants connected to HV transmission networks. Simulation results, based on different power plant topologies, show that the proposed scheme successfully remove reactive power oscillations and considerably improves the dynamic response of the overall power plants.

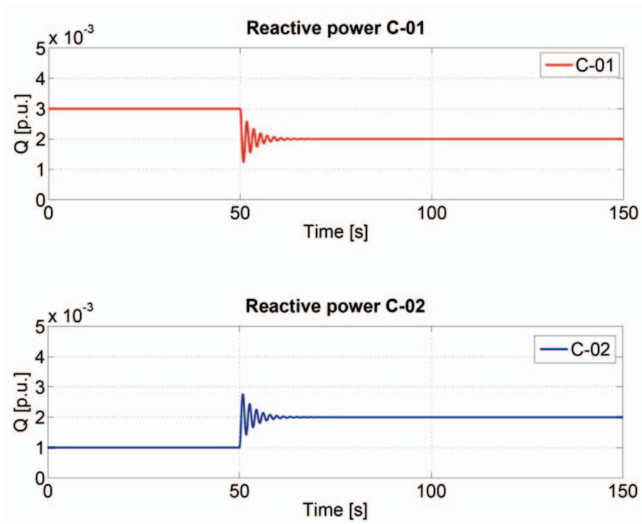


Figure 5. Reactive power response without dynamic decoupling.

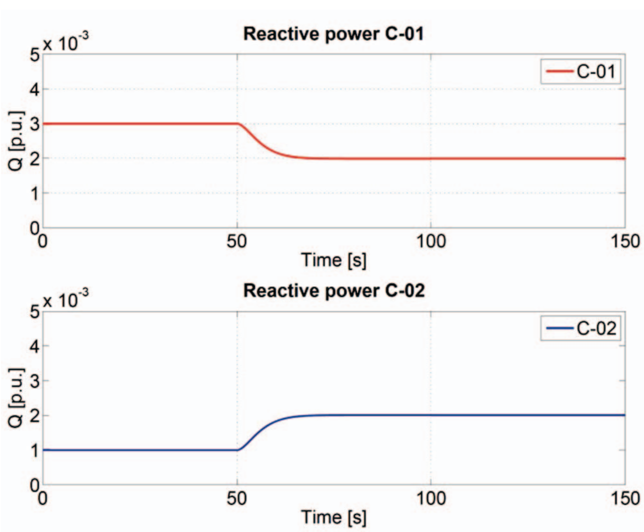


Figure 6. Reactive power response with dynamic decoupling.

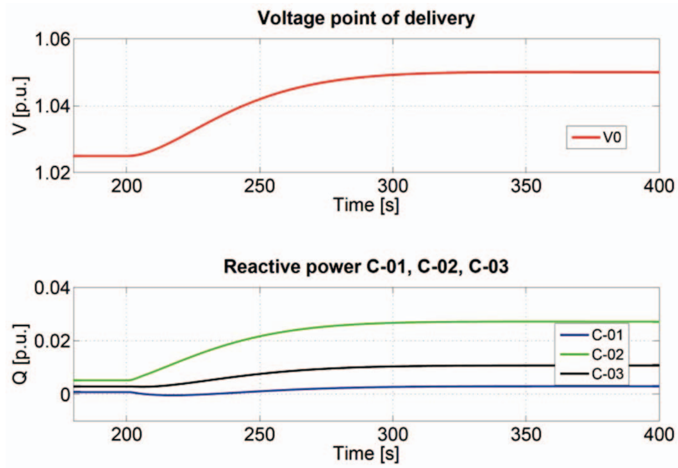


Figure 7. Voltage and reactive power response for a step in reference voltage without the decoupling matrix: network B

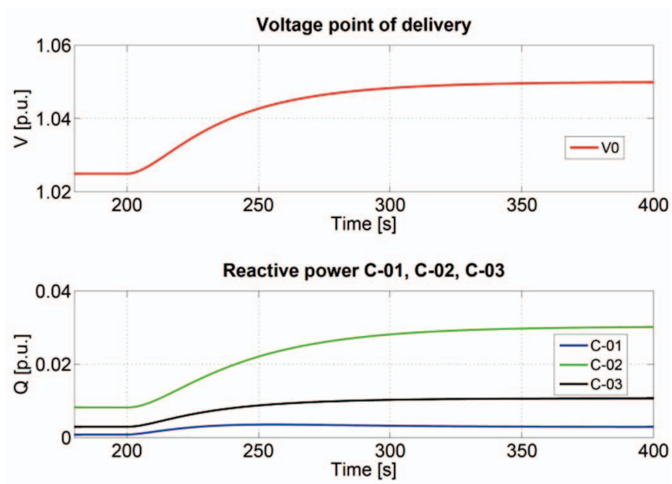


Figure 8. Voltage and reactive power response for a step in reference voltage with the decoupling matrix: network B .

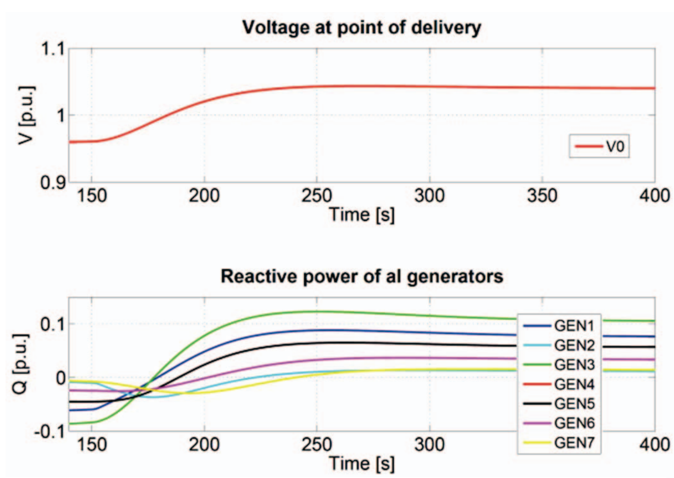


Figure 9. Generators reactive powers and voltage response in network C without decoupling matrix

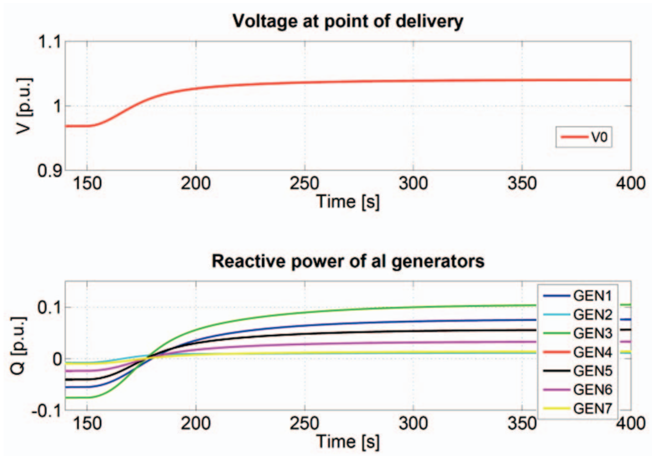


Figure 10. Generators reactive powers and voltage response in network C with decoupling matrix.

The utilization of a decoupling matrix based on the well-known modal analysis of the power flow Jacobian matrix can solve this issue. Future work will focus on the study of the dynamic response of secondary voltage regulation schemes that coordinate different RESs as well as conventional power plants.

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