ACTA IMEKO
ISSN: 2221-870X
December 2024, Volume 13, Number 4, 1 - 6

Measurement-driven load change compensation for robust secondary voltage regulation

Francesco Bonavolontà[1], Pasquale Di Palma[2], Annalisa Liccardo[1], Fabio Mottola[1], Domenico Villacci[2]

[1] *Dept. of Electrical Engineering and Information Technology, University Federico II of Naples, Via Claudio 21, 80125, Naples, Italy*
[2] *Dept. of Industrial Engineering, University Federico II of Naples, Via Claudio 21, 80125, Naples, Italy*

ABSTRACT
Voltage regulation ensures the reliable and efficient operation of power systems by maintaining voltage levels within specified limits despite changing load conditions. Modern grids integrating renewable energy sources face new challenges. These sources, such as wind and solar power, cause rapid power fluctuations. Furthermore, high-demand loads like electric vehicles could also result in very fast power variations. This paper explores an advanced control strategy related to the integration of Flexible AC Transmission Systems (FACTS) devices within an improved Secondary Voltage Regulation (SVR) based on an optimal linear quadratic control. The control strategy can compensate the effects of fast load variations, by exploiting the information provided by the Phasor Measurement Units (PMUs). The PMUs are, however, affected by non-idealities, which can reduce the compensation's efficiency. In the paper, the performance of the regulation strategy is assessed according to the two main PMU's characteristics: the report rate and the accuracy associated with the measurement results. The paper thus provides a walkthrough to properly select the characteristics and, thus, the cost of the PMU, according to the desired voltage regulation's performance.

Section: RESEARCH PAPER

Keywords: Secondary voltage regulation; FACTS devices; PMU report rate; PMU uncertainty

Citation: F. Bonavolontà, P. Di Palma, A. Liccardo, F. Mottola, D. Villacci, Measurement-driven load change compensation for robust secondary voltage regulation, Acta IMEKO, vol. 13 (2024) no. 4, pp. 1-6. DOI: 10.21014/actaimeko.v13i4.1923

Section Editor: Francesco Lamonaca, University of Calabria, Italy

Received August 5, 2024; **In final form** November 20, 2024; **Published** December 2024

Funding: This work was supported by the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 - Call for Tender No. 341 dated 15.03.2022 of Ministero dell'Università e della Ricerca (MUR); funded by the European Union – NextGenerationEU. Project code PE0000021, Concession Decree no. 1561 of 11.10.2022 adopted by Ministero dell'Università e della Ricerca (MUR), CUP E63C22002160007, Project title "Network 4 Energy Sustainable Transition – NEST", Spoke 7 – "Smart Sector Integration"

Corresponding author: Annalisa Liccardo, e-mail: annalisa.liccardo@unina.it

1. INTRODUCTION

Voltage regulation is essential for ensuring the reliable and efficient operation of power systems. It involves maintaining voltage levels within specified limits despite changes in load conditions. Traditional voltage regulation techniques, which

include primary and secondary control mechanisms, have been effective in maintaining voltage stability. Primary voltage regulation provides an immediate response to local disturbances, while secondary voltage regulation (SVR) aims to restore the voltage to its nominal value over a longer period, ensuring system-wide stability.

The modern power grid is increasingly complex, incorporating renewable energy sources and distributed generation. These advancements have introduced new challenges in maintaining voltage stability. Renewable energy sources like wind and solar power are intermittent and unpredictable, causing rapid fluctuations in power generation. Additionally, high-demand loads such as electric vehicles can lead to fast load variations. These challenges necessitate advanced control strategies that can quickly and effectively manage voltage stability in the face of these fluctuations.

Optimal linear quadratic control logic is a feedback control strategy that minimizes a cost function representing the deviation of system variables from their desired values. It is well-suited for voltage regulation due to its ability to balance performance and robustness. The linear quadratic regulator (LQR) is a common implementation, which optimally adjusts control actions based on the current system state, providing a dynamic response to fast load variations.

Studies such as those by [1] and [2] demonstrate the effectiveness of LQR in managing voltage levels under varying load conditions. LQR provides a systematic approach to design control laws for optimal performance in multivariable systems, as highlighted in [3], making it an attractive option for secondary voltage regulation.

Flexible AC Transmission Systems (FACTS) devices, including Static Synchronous Compensators (STATCOMs), Static VAR Compensators (SVCs), and Unified Power Flow Controllers (UPFCs), are crucial for enhancing voltage stability. These devices offer rapid and flexible control of power system parameters, making them ideal for compensating fast load variations. Studies by [4] and [5] emphasize the role of FACTS devices in improving voltage profiles and reducing power losses in transmission systems.

The integration of FACTS devices with advanced control algorithms further enhances their performance. Model predictive control (MPC) and adaptive control techniques have been explored in conjunction with FACTS devices to improve voltage regulation and system stability. For instance, [6] applied MPC to STATCOMs, resulting in better voltage control and system resilience.

Despite the advancements in voltage regulation techniques, several limitations and weaknesses persist. One significant limitation of the optimal linear quadratic control logic is its dependency on accurate system models. The performance of LQR relies heavily on the precision of the mathematical model representing the power system. Inaccuracies in modelling can lead to suboptimal control actions and reduced effectiveness in voltage regulation.

The implementation of FACTS devices, although beneficial, involves high costs and complexity. The installation and maintenance costs of FACTS devices can be prohibitive, especially for smaller or less economically developed power systems. Moreover, integrating FACTS devices with existing infrastructure requires meticulous planning and coordination to avoid compatibility issues and ensure seamless operation.

Coordination between multiple control strategies and devices in large and complex power systems presents another challenge. Multiple voltage regulation mechanisms operating simultaneously can lead to conflicts and inefficiencies. Effective coordination strategies, such as hierarchical control frameworks and multi-agent systems, are necessary to harmonize the actions of various controllers and devices [7].

The main drawbacks which could affect the traditional SVR strategies in modern power systems can be overcome if a data-driven approach involving measurements data coming from Phasor Measurement Units (PMUs) are exploited to feed FACTS devices for voltage regulation. At this purpose, the regulation strategy presented in [8], where the SVR is combined with a FACTS device to compensate for the effects of rapid load changes on voltage regulation, is taken into account in this paper, and it is studied how the report rate of the PMUs influences the efficiency of compensation.

The paper is organized as follows: in Section 2 the control strategy of the improved SVR supported by the FACTS for fast load changes compensation is briefly recalled; in Section 3 a numerical application is shown and the effect of the PMUs on the compensation strategy is examined; concluding remarks are given in Section 4.

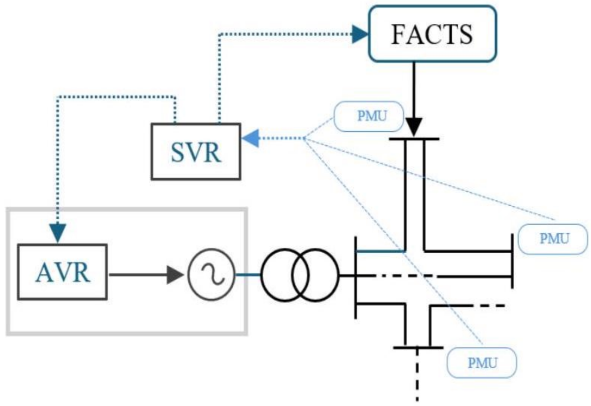

Figure 1. SVR supported by FACTS devices

2. SECONDARY VOLTAGE REGULATION SUPPORTED BY LOAD CHANGES COMPENSATION

In Figure 1, the basic scheme of the SVR integrated by the functionalities of the FACTS is shown. It can be noticed that the SVR controls the automatic voltage regulators as usual and, in addition, controls the FACTS devices thanks to the support of the PMUs, which are able to catch in real time the fast load variations. In particular, the scheme of the SVR is reported in Figure 2.

The SVR of Figure 2 includes the regulator based on the linear quadratic integral (LQI) control proposed in [9] and the contribution of the FACTS which injects reactive power, Δq_{f}, at the pilot bus to compensate the fast load variations. The proposed approach is based on the consideration that the active and reactive powers of the loads can be described in terms of dynamic stochastic Ornstein-Uhlenbeck (OU) processes. Their parameters are estimated based on the measurement available through the PMUs. This allows us to represent the improved SVR as an augmented state space model [8]:

$$\begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{x}}_{\mathbf{H}} \end{bmatrix} = \begin{bmatrix} \mathbf{A}' & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_{\mathbf{H}} \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \boldsymbol{\mu} - \mathbf{x}_{\mathbf{H}} \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ \mathbf{0} \end{bmatrix} \mathbf{u} + \begin{bmatrix} \mathbf{0} \\ \mathbf{B}_{\mathbf{H}} \end{bmatrix} \mathrm{d}\mathbf{w} \tag{1}$$

where $\mathbf{x}$ is the state variable vector, including the voltage variation at the generator buses, and the state variable related to the integral action:

$$x_i = \int_0^{+\infty} \left(\Delta v_{\mathrm{p,r}} - \Delta v_{\mathrm{p}} \right) \mathrm{d}t \,, \tag{2}$$

which refer to the deviation between pilot voltage variation, Δv_p, and its reference, $\Delta v_{p,r}$. In (1), $\mathbf{u}$ is the vector of variation of the reference stator voltages of the generators, $\mathbf{A}'$ is given by:

$$\mathbf{A}' = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ -\mathbf{C}_{\mathbf{v}} & \mathbf{0} \end{bmatrix}, \tag{3}$$

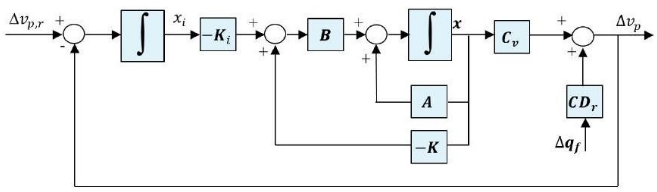

Figure 2. Improved SVR with load variation compensation.

where the diagonal matrices $\mathbf{A}$ and $\mathbf{B}$ are made by the generators' time constants of the primary regulation. Regarding $\mathbf{C_v}$, it is given by $\mathbf{CC_r}$, being $\mathbf{C}$ a matrix able to identify only the elements corresponding to the pilot bus (i.e., all terms of $\mathbf{C}$ are zero except those with indices including the number of the pilot bus) and $\mathbf{C_r}$ obtained through a proper partitioning of the network Jacobian matrix:

$$\Delta q_{\mathrm{g}} = \mathbf{A_r}\, \Delta\mathbf{v_g} + \mathbf{B_r}\, \Delta\mathbf{q_l} \tag{4}$$

where Δq_{g} and Δq_1 are the reactive power variations at the generator and load buses, respectively, as well as $\Delta\mathbf{v_g}$ and $\Delta\mathbf{v_l}$ are the voltage variations at the generator and load buses, respectively. In [9], the reference values of the generator voltage, $\Delta\mathbf{v_{g,r}}$, are then evaluated according to the feedback law:

$$\mathbf{u} = -[\mathbf{K} \quad \mathbf{K_i}]\mathbf{x} \tag{5}$$

In order to consider the fast variations of the active, $\mathbf{p}$, and reactive, $\mathbf{q}$, powers at the load buses, the augmented state variable vector, $\mathbf{x_H}$, is introduced in (1) to account for the OU multivariate process:

$$\begin{aligned} \dot{\mathbf{p}} &= \boldsymbol{\vartheta}_p\left(\boldsymbol{\mu}_p - \Delta\mathbf{p}\right) + \boldsymbol{\sigma}_{\Delta_\mathrm{p}}\, \mathrm{d}\mathbf{w_p} \\ \dot{\mathbf{q}} &= \boldsymbol{\vartheta}_q\left(\boldsymbol{\mu}_q - \Delta\mathbf{q}\right) + \boldsymbol{\sigma}_{\Delta\mathrm{q}}\, \mathrm{d}\mathbf{w_q} \end{aligned} \tag{6}$$

where $\boldsymbol{\mu_p}$ and $\boldsymbol{\mu_q}$ are their mean values, $\boldsymbol{w_p}$ and $\boldsymbol{w_p}$ the corresponding Wiener processes. Based on (6), $\mathbf{x_H}$ is then given by:

$$\dot{\mathbf{x}}_\mathbf{H} = \mathbf{A_H}(\boldsymbol{\mu} - \mathbf{x_H}) + \mathbf{B_H}\, \mathrm{d}\mathbf{w} \tag{7}$$

with

$$\mathbf{x_H} = \begin{bmatrix} \mathbf{p} \\ \mathbf{q} \end{bmatrix} \tag{8}$$

$$\mathrm{d}\mathbf{w} = \begin{bmatrix} \mathrm{d}\mathbf{w_p} \\ \mathrm{d}\mathbf{w_q} \end{bmatrix} \tag{9}$$

$$\mathbf{A_H} = \begin{bmatrix} \boldsymbol{\vartheta}_p & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\vartheta}_q \end{bmatrix} \tag{10}$$

$$\mathbf{B_H} = \begin{bmatrix} \boldsymbol{\sigma}_{\Delta p} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\sigma}_{\Delta q} \end{bmatrix} \tag{11}$$

$$\boldsymbol{\mu} = \begin{bmatrix} \boldsymbol{\mu}_\mathrm{p} \\ \boldsymbol{\mu}_\mathrm{q} \end{bmatrix}. \tag{12}$$

The augmented state space model (1) allows considering for a proper power to be injected into the network, within the SVR control action, aimed at compensating for the fast load variations. The estimated power can be injected in load buses by FACTS devices. Focusing on the reactive power, in Figure 2 the power supplied by the FACTS to the network is $\boldsymbol{\Delta q_\mathrm{f}}$. Assuming just one device connected to the pilot bus, according to (4), the injected reactive power $\boldsymbol{\Delta q_\mathrm{f}}$ contributes to the SVR through the matrix term $\mathbf{CD_r}$. Regarding the value of power to be injected, $\boldsymbol{\Delta q_\mathrm{f}}$, it is based on the estimation of the load variations, which has been assumed varying according to the OU multivariate process. This process is driven by the following stochastic differential equation [10]:

$$\mathrm{d}\mathbf{x_H} = -\mathbf{A_H}(\mathbf{x_H} - \boldsymbol{\mu})\, \mathrm{d}t + \mathbf{B_H}\, \mathrm{d}\mathbf{w} \tag{13}$$

which can be integrated as:

$$\begin{aligned} \mathbf{x}_{\mathbf{H}_{\mathbf{t}+\Delta\mathbf{t}}} &= (\mathbf{I} + e^{-\boldsymbol{\vartheta}\Delta t})\boldsymbol{\mu} + e^{-\boldsymbol{\vartheta}\Delta t}\mathbf{x}_{\mathbf{H}_{\mathbf{t}}+} \\ &\quad + \int_t^{t+\Delta t} e^{\boldsymbol{\vartheta}(u-\Delta t)}\, \mathbf{B_H}\, \mathrm{d}\mathbf{w}_u \end{aligned} \tag{14}$$

where $\mathrm{d}\mathbf{w_u}$ is the vector of independent normally distributed random variables with covariance $\mathbf{I}\, \mathrm{d}t$. Eq. (14) can be written in a more compact form by using the exponential matrix of the mean regression rates as:

$$\boldsymbol{\Lambda} = e^{\boldsymbol{\lambda}\,\Delta t} \tag{15}$$

along with the covariance matrix $\boldsymbol{\Sigma}$. The compact form of (14) can then be written as:

$$\mathbf{x}_{\mathbf{H}_{t+\Delta t}} = (\mathbf{I} - \boldsymbol{\Lambda})\, \boldsymbol{\mu} + \boldsymbol{\Lambda}\, \mathbf{x}_{\mathbf{H_t}} + \sqrt{\boldsymbol{\Sigma}}\, \mathbf{w_t}. \tag{16}$$

In the cases of our interest, the estimation of the OU parameters is performed based on a set of sample data which corresponds to the power measurements provided by the PMUs. In other words, the observations of the process are given by the data available from the PMUs located at the load buses. Thus, with reference to a set of N samples of data, the estimation of $\boldsymbol{\mu}$ is derived as:

$$\hat{\boldsymbol{\mu}} = \frac{1}{N}\sum_{n=1}^{N} \mathbf{x}_{\mathbf{H_n}} \tag{17}$$

with $\mathbf{x}_{\mathbf{H_n}}$ representing the nth sample. Regarding the process $\mathbf{x_H} - \boldsymbol{\mu}$, it is a zero-mean process characterized by the exponential matrix $\boldsymbol{\Lambda}$ and covariance matrix $\boldsymbol{\Sigma}$. Their estimates are evaluated on the basis of the matrices $\mathbf{T_1}$, $\mathbf{T_2}$, and $\mathbf{T_3}$ which are sufficient statistics for $\boldsymbol{\Lambda}$ and $\boldsymbol{\Sigma}$ [10]:

$$\hat{\boldsymbol{\Lambda}} = \mathbf{T_2}\, \mathbf{T_3^{-1}} \tag{18}$$

$$\hat{\boldsymbol{\Sigma}} = \frac{1}{N}\left(\mathbf{T_1} - \mathbf{T_2}\, \mathbf{T_3^{-1}}\, \mathbf{T_2^T}\right) \tag{19}$$

where, by assuming $\mathbf{X} = \mathbf{x_H} - \boldsymbol{\mu}$, matrices $\mathbf{T}_i$, with $i = 1, 2, 3$ are given by:

$$\mathbf{T_1} = \sum_{n=1}^{N-1} \mathbf{X}_{n+1}\, \mathbf{X}_{n+1}^T \tag{20}$$

$$\mathbf{T_2} = \sum_{n=1}^{N-1} \mathbf{X}_{n+1}\, \mathbf{X}_n^T \tag{21}$$

$$\mathbf{T_3} = \sum_{n=1}^{N-1} \mathbf{X}_n\, \mathbf{X}_n^T. \tag{22}$$

Once the estimations $\hat{\boldsymbol{\mu}}$, $\hat{\boldsymbol{\Lambda}}$, and $\hat{\boldsymbol{\Sigma}}$ have been evaluated, the reactive power that FACTS has to supply, $\boldsymbol{\Delta q_\mathrm{f}}$, is then derived as that able to compensate the estimated load variation $\hat{\mathbf{x}}_\mathbf{H} - \hat{\boldsymbol{\mu}}$, that is:

$$\boldsymbol{\Delta q_\mathrm{f}} = -(\hat{\mathbf{x}}_\mathbf{H} - \hat{\boldsymbol{\mu}}). \tag{23}$$

The injection of $\boldsymbol{\Delta q_\mathrm{f}}$ allows reducing the voltage variation around the current operation point. Moreover, it allows improving the control action of the SVR, since through the estimation $\hat{\boldsymbol{\mu}}$, the operation point used for the linearization can be found in a more accurate way.

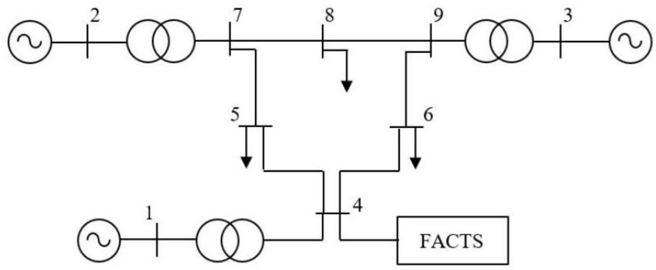

Figure 3. Scheme of the test network.

3. NUMERICAL APPLICATIONS

3.1. Case study

The proposed SVR strategy including the fast load compensation is applied to the to the WSCC 9-bus test network reported in Figure 3 at 230 kV, 60 Hz [11]. Line parameters of the test network are reported in Table 1 (100 MVA base power). Three synchronous generators are considered:

1) bus #1: 247.5 MVA rated power connected to the network (bus #4) through a transformer having v_{cc}=5.76 %;
2) bus #2: 192 MVA rated power connected to the network (bus #7) through a transformer having v_{cc}=6.25 %;
3) bus #3: 128 MVA rated power connected to the network (bus #7) through a transformer having v_{cc}=5.86 %.

Three loads are connected to the network:

1) bus #5: 125 MW and 50 MVAR;
2) bus #6: 90 MW and 30 MVAR;
3) bus #8: 100 MW and 35 MVAR.

The FACTS device is supposed to be connected to the pilot bus (bus #4).

The stochastic modelling of the three loads is defined according to the assumed values of the following the matrices:

$$\mathbf{A_H} = \begin{bmatrix} -0.03 & 0 & 0 \\ 0 & -0.03 & 0 \\ 0 & 0 & -0.03 \end{bmatrix} \tag{24}$$

$$\mathbf{B_H} = \begin{bmatrix} 5\cdot10^{-6} & 6\cdot10^{-7} & 7\cdot10^{-7} \\ 6\cdot10^{-7} & 1.8\cdot10^{-6} & 4.2\cdot10^{-7} \\ 7\cdot10^{-7} & 4.2\cdot10^{-7} & 2.45\cdot10^{-6} \end{bmatrix}. \tag{25}$$

Regarding the estimations, which are not reported here for the sake of conciseness, the maximum errors are equal to $4\cdot10^{-3}$ for the elements of $\mathbf{A_H}$ and 8.1$\cdot10^{-7}$ for the elements of $\mathbf{B_H}$

3.2. Analysis of the effect of PMU specifications on regulation efficacy

Several tests are being conducted on the simulated network in order to assess the efficacy of secondary voltage regulation with respect to the non-idealities of the measurement instruments involved in the secondary regulation.

The simulated scenario takes into account fast variations of reactive power; the variations regard the load buses and the corresponding stochastic OU process are described by the aforementioned matrices $\mathbf{A_H}$ and $\mathbf{B_H}$. As for the control strategy of the generator, the approach described in [9] has been implemented and applied; the reactive power compensation is then carried out by the FACTS connected on the bus #4 thanks to a suitable power injection. The corresponding value is real-time defined and controlled, according to the estimated matrices $\mathbf{A_H}$ and $\mathbf{B_H}$.

Table 1. Line parameters.

From bus #	To bus #	Resistance in p.u.	Reactance in p.u.	Susceptance in p.u.
4	5	0.0100	0.085	0.176
4	6	0.0170	0.092	0.158
5	7	0.0320	0.161	0.306
6	9	0.0390	0.170	0.358
7	8	0.0085	0.072	0.149
8	9	0.0119	0.101	0.209

Compensation for load changes is performed by exploiting the measures of active and reactive power provided by the PMU [12]. Thus, assessing the efficiency of the load compensation according to the PMU metrological characteristics is mandatory [13]-[15].

In particular, authors have taken into account the two main characteristics of a PMU: the report rate and the uncertainty. As regards the report rate, it can be expected that the higher the PMU report rate, the better the regulation efficacy in compensating fast load variations. However, it should be advisable to not jam the communication lines with an excessive number of messages exchanged among the PMUs and the control centre where the equations are running. So the right trade-off between the conflicting demands has to be found. The following values of report time have been considered: 20 ms, 100 ms, 200 ms, 300 ms, and 400 ms. They have been chosen, because 20 ms and 100 ms are corresponding to the typical report rate of PMUs monitoring the Italian transmission system and the European transmission system, i.e. 50 fps and 100 fps respectively [16], [17]. Authors have, however, taken into account higher report times, in order to assess the regulation efficiency also when the amount of transmitted data is reduced.

The obtained results are shown in Figure 4, where the relevant capability of the proposed regulation can be appreciated. It can be also noticed that the PMU's report rate significantly affects the voltage regulation: the lower the report rate, the higher the oscillations of the pilot bus voltage. The insight on the regulated pilot bus voltage in Figure 5 allows to further appreciate the improved performance associated with higher report rates.

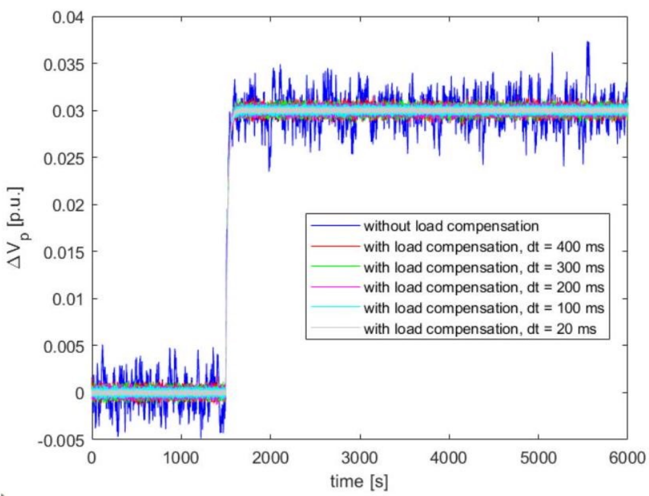

Figure 4. Time evolution of pilot bus voltage according to different PMU's report rate.

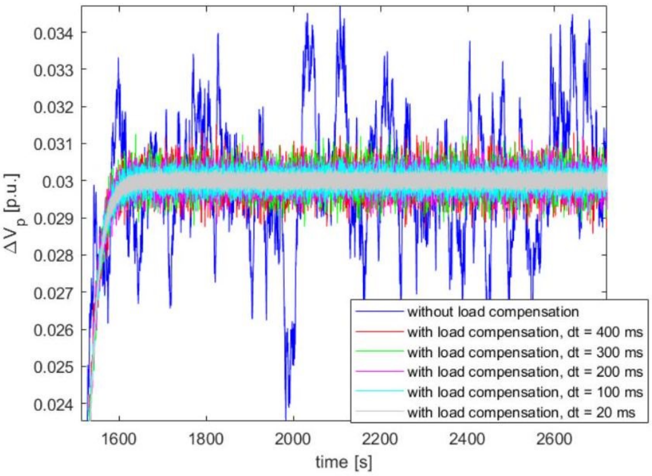

Figure 5. Zoomed pilot bus voltage according to different PMU's report rate.

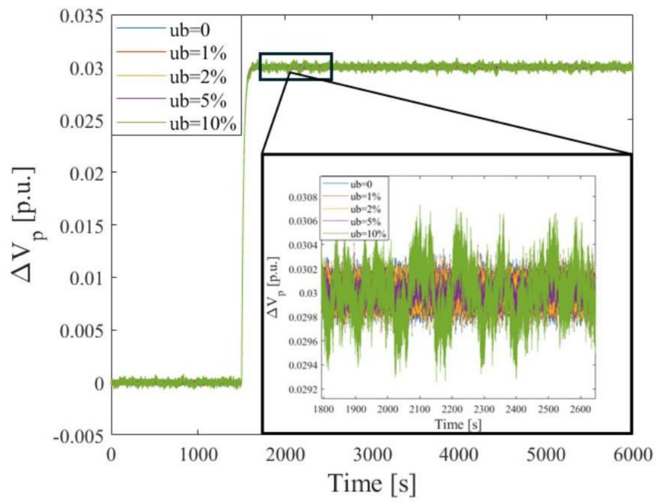

Figure 6. Pilot bus voltage according to different PMU's uncertainty.

In order to quantify the efficiency of the fast load change compensation, the mean value, the peak-to-peak value and the RMS value of the pilot bus voltage have been evaluated in the time interval from 2000 s to 6000 s. The results are reported in Table 2.

The mean value in the table represents the reference value that is reached by the pilot bus voltage for compensation. The report rate of the PMU does not influence this value, as it has been assumed that the load varies randomly. As expected, the report rate modifies the oscillations affecting the bus voltage. In particular, the peak-to-peak value arises from 0.0009 p.u. up to 0.0033 p.u. as the report time increases from 20 ms to 400 ms.

As regards the uncertainty associated with the power measurements, i.e. the type B uncertainty u_b it has been modelled as a gain error, that affects the measures, leading to a deviation from the reference value, proportional to the power readings. It is worth noticing that the regulation system would compensate for eventual PMU's offset errors affecting the power measures; so, this type of uncertainty has not been taken into account. The following values have been simulated for the gain error: 1 %, 2 %, 5 %, 10 %; the report time has been set according to the best scenario, i.e. 20 ms.

The obtained time evolution of the pilot bus voltage is shown in Figure 6. From the figure, the effect of the uncertainty of power measurements can be appreciated. The pilot bus voltage is estimated according to the deviation between the measured and the model-predicted powers. So, even if the deviation is caused by the measurement uncertainty, it is interpreted by the model as a load change. The SVR, therefore, modifies the reference bus voltage, trying to compensate for this deviation. The result is the presence of rapid variations in the pilot bus voltage, the amplitude of which is directly dependent on the maximum uncertainty of the PMU.

To better appreciate the effect of uncertainty, Table 3 shows the parameters of the pilot bus voltage, for the considered uncertainty values.

The table gives useful information about the effect of the adopted measurement instruments. If the maximum uncertainty is lower than 2 %, the oscillations affecting the pilot bus voltage exhibit negligible peak-to-peak amplitude. The oscillation amplitude rapidly increases as the uncertainty exceeds 5 %.

The PMUs compliant with the Standard are characterized by uncertainty below 1 % [18]. However, in order to reduce costs, not all loads are monitored by a PMU. The authors have considered a scenario where, in order to improve the observability of the system, measurement systems exhibiting worse performance could also be installed at some nodes in the network. The conducted study provides insight into the performance of the adopted regulation system, even with low-cost instrumentation, which is characterized by higher uncertainties.

4. CONCLUSIONS

Voltage regulation is essential for ensuring the reliable and efficient operation of power systems, especially in the context of increasing complexity in modern grids that integrate renewable energy sources and distributed generation. This study has demonstrated that the integration of FACTS devices with advanced control strategies, such as optimal linear quadratic control logic, can significantly enhance the SVR. However, the effectiveness of these solutions heavily depends on the accuracy of system models and involves high costs, making them less accessible for less economically developed power systems. Numerical simulations have highlighted how the combination of SVR with a FACTS device, supported by Phasor Measurement

Table 2. Characteristics of pilot bus voltage, according to the PMU report time.

Report time in ms	Mean in p.u.	Peak to peak in p.u.	RMS in p.u.
no compensation	0.0300	0.0139	0.0017
400	0.0300	0.0033	$4.4 \cdot 10^{-4}$
300	0.0300	0.0029	$3.8 \cdot 10^{-4}$
200	0.0300	0.0025	$3.1 \cdot 10^{-4}$
100	0.0300	0.0017	$2.2 \cdot 10^{-4}$
20	0.0300	0.0009	$9.8 \cdot 10^{-5}$

Table 3. Characteristics of pilot bus voltage, according to the PMU's uncertainty.

Uncertainty in %	Mean in p.u.	Peak to peak in p.u.	RMS in p.u.
10	0.0300	0.0018	$0.22 \cdot 10^{-3}$
5	0.0300	0.0012	$0.14 \cdot 10^{-3}$
2	0.0300	0.00092	$0.11 \cdot 10^{-3}$
1	0.0300	0.00091	$0.10 \cdot 10^{-3}$
0	0.0300	0.00090	$0.098 \cdot 10^{-3}$

Units (PMUs), can effectively compensate for rapid load variations. Specifically, it has been shown that higher PMU reporting rates improve regulation capacity, reducing residual voltage oscillations at the pilot bus; increasing the sample period from 20 ms to 400 ms makes both peak-to-peak and RMS values of the residual voltage oscillation increase of one order of magnitude. Nonetheless, it is necessary to balance the PMU reporting frequency with the communication lines' capacity to avoid overloads. Moreover, the impact of the uncertainty affecting the devices mandated to measure the input quantities from the monitored loads. As it can be expected, high performance PMUs, characterized by uncertainty lower than 1 %, do not affect significantly method's performance; however, due to their high costs, PMUs cannot be widely deployed throughout the networks and loads. So, performance worsening associated with cost-effective devices characterized by relative percentage uncertainty within the range from 2 % and 10 % have been investigated; the worst devices doubled both peak-to-peak and RMS values.

REFERENCES

[1] P. Chaudhary, M. Rizwan, Voltage regulation mitigation techniques in distribution system with high PV penetration: A review, Renewable and Sustainable Energy Reviews, vol. 82, 2018, pp. 3279-3287.
DOI: 10.1016/j.rser.2017.10.017

[2] S. Nallusamy, D. Velayutham, U. Govindarajan, Design and implementation of a linear quadratic regulator controlled active power conditioner for effective source utilisation and voltage regulation in lowpower wind energy conversion systems, IET Power Electronics, vol. 8, 2015, no. 11, pp. 2145-2155.
DOI: 10.1049/iet-pel.2014.0633

[3] S. Chatterjee, V. Mukherjee, Comparative performance analysis of classical controllers for automatic voltage regulator, 7th Int. Conf. on Power Systems (ICPS), Pune, India, 21-23 December 2017, pp. 296-301.
DOI: 10.1109/ICPES.2017.8387309.

[4] M. J. Afzal, S. Ahmad, M. A. Arshad, S. A. A. Kazmi, Voltage improvement of loop configured distribution networks with dgs & facts devices, 1st Int. Conf. on Power, Energy and Smart Grid (ICPESG), Mirpur, Azad Kashmir, Pakistan, 9-10 April 2018, pp. 1-5.
DOI: 10.1109/ICPESG.2018.8384503

[5] N. A. Belyaev, N. V. Korovkin, V. S. Chudny, O. V. Frolov, Reduction of active power losses in electric power systems with optimal placement of facts devices, 2015 IEEE NW Russia Young Researchers in Electrical and Electronic Engineering Conf. (EIConRusNW), St. Petersburg, Russia, 2-4 February 2015, pp. 150-154.
DOI: 10.1109/EIConRusNW.2015.7102251

[6] N. Kadivarian, M. T. Bina, M. Akbari, Model predictive control of statcom for grid voltage regulation, Int. Conf. on Renewable Energies and Power Quality (ICREPQ'17), Malaga, Spain, 4-6 April 2017, pp. 328333.
DOI: 10.24084/repqj15.309

[7] C. X. Dou, D. W. Hao, B. Jin, W.-Q. Wang, N. An, Multi-agent system-based decentralized coordinated control for large power systems, Int. Journal of Electrical Power & Energy Systems, vol. 58, 2014, pp. 130-139.
DOI: 10.1016/j.ijepes.2014.01.012

[8] E. Chiodo, P. Di Palma, M. Fantauzzi, D. Lauria, F. Mottola, D. Villacci, Voltage regulation improved by stochastic disturbance compensation, 3rd Int. Conf. on Energy Transition in the Mediterranean Area (SyNERGY MED 2024), Limassol, Cyprus, 21-23 October 2024.

[9] D. Lauria, F. Mottola, G. Giannuzzi, C. Pisani, An advanced secondary voltage control strategy for future power systems, International Journal of Electrical Power & Energy Systems, vol. 156, 2024, p. 109734.
DOI: 10.1016/j.ijepes.2023.109734

[10] R. Singh, D. Ghosh, R. Adhikari, Fast Bayesian inference of the multivariate Ornstein-Uhlenbeck process, Phys Rev. E, vol. 98, July 2018, p. 012136.
DOI: 10.1103/PhysRevE.98.012136

[11] P. M. Anderson, A. A. Fouad, Power System Control & Stability. IEEE Press, New York, 2003.

[12] A. Goldstein, D. Maragal, Synchrophasor measurement system industry standards and guidance: A comprehensive overview, IEEE Transactions on Power Delivery, 2024.
DOI: 10.1109/TPWRD.2024.3377208

[13] P. Castello, C. Muscas, P. A. Pegoraro, S. Sulis, A monitoring system based on phasor measurement units with variable reporting rates, Acta IMEKO, vol. 7, 2018, no. 4, pp. 62-69.
DOI: 10.21014/acta_imeko.v7i4.585

[14] G. Frigo, F. Costa, F. G. Toro, "Phasor measurement unit based reliability index for renewable-based power systems," Acta IMEKO, vol. 12, 2023, no. 3, pp. 1-7.
DOI: 10.21014/actaimeko.v12i3.1446

[15] G. Patrizi, M. Carratù, L. Ciani, P. Sommella, M. Catelani, A. Pietrosanto, Analysis of inertial measurement units performances under dynamic conditions, IEEE Transactions on Instrumentation and Measurement, vol. 72, 2023, pp. 1-13.
DOI: 10.1109/TIM.2023.3284957

[16] F. Bonavolontà, L. P. Di Noia, A. Liccardo, S. Tessitore, D. Lauria, A PSO-MMA method for the parameters estimation of interarea oscillations in electrical grids, IEEE Transactions on Instrumentation and Measurement, vol. 69, 2020, no. 11, pp. 8853-8865.
DOI: 10.1109/TIM.2020.2998909

[17] A. Liccardo, S. Tessitore, F. Bonavolontà, S. Cristiano, L. P. Di Noia, G. M. Giannuzzi, C. Pisani, Detection and analysis of inter-area oscillations through a dynamic-order DMD approach, IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1-14.
DOI: 10.1109/TIM.2022.3186371

[18] IEEE/IEC international standard - measuring relays and protection equipment - part 118-1: Synchrophasor for power systems - measurements, IEC/IEEE 60255-118-1:2018, 2018, pp. 1-78.
DOI: 10.1109/IEEESTD.2018.8577045