Investigations on Secondary Voltage Control for Long-Term Reactive Power Management

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Abstract—**Voltage and reactive power management is a crucial task for system operators worldwide, and particularly in Norway. While manual operations within regional control centers were once the norm, a major shift is currently ongoing towards coordinated and automatic control strategies such as the secondary voltage regulation (SVR) scheme. However, further research is required to fully understand its effectiveness. This paper aims to contribute in this regard by conducting dynamic simulations of a small test system using a Python-based power system simulator. The study addresses SVR performance for post-fault response, daily load following and voltage setpoint reference change scenarios. Results show that the approach improves overall system voltage profiles, ensures fair reactive power sharing among involved generators and reduces active power losses at the transmission level.**

Index Terms—**Coordinated voltage control, dynamic simulation, power losses, reactive power management, secondary voltage regulation.**

NOMENCLATURE

α_j	Participation factor of generator j
AVR_j	Automatic voltage regulator of generator j
$K_{I,c}$/$K_{I,j}$	Central/Distributed integral gain
$K_{P,c}$/$K_{P,j}$	Central/Distributed proportional gain
$Q_{G,j}$	Reactive power contribution of generator j
Q_{total}	Sum total of reactive power contributions
V_{pilot}	Pilot bus voltage setpoint
$V_{ref,SVR}$	SVR reference voltage setpoint
$V_{SVR,c}$/$V_{SVR,j}$	Central/Distributed SVR control output

I. INTRODUCTION

A. Motivation and Background

The worldwide trend of electrification is set to reach record levels of year-on-year growth as a rebound from the economic disruption of 2020. According to the International Energy Agency (IEA), global electricity demand increased by 4.5% – over 1000 TWh – last year, whereas renewables-based generation accounted for more than half of the supply increase required to meet the updated demand [1].

In Norway, a similar trend is noticeable: annual electricity production is projected to reach a second consecutive all-time high, with hydropower representing 92% of the total supply [2]. At the same time, the expected intensification of power flows indicates reduced net export margins and lower availability of transfer capacity within the Nordic power grid. Such limitations are further aggravated by active power losses at the transmission level, which represent an increasingly larger portion of the total grid power flow.

In this context, the Norwegian transmission system operator (TSO) has expressed great interest in novel solutions for loss minimization via optimal reactive power management of existing grid assets. Since reactive power flow and voltage behavior are strongly related at the transmission level, this means that particular focus is to be placed on strategies based on voltage control techniques [3].

Even though voltage and reactive power management is traditionally carried out manually in control centers, a major shift to coordinated and hierarchical structures has been observed over the last decades. Coordinated voltage control is usually divided into three hierarchical levels: primary voltage regulation (PVR), secondary voltage regulation (SVR) and tertiary voltage regulation (TVR). Each level is decoupled from others in terms of action zones and time scales to avoid undesired interactions among device controllers [4].

As the intermediate control level, the SVR layer is responsible for maintaining an adequate voltage profile at buses within a predefined control area, which might include several generator units, flexible ac transmission systems (FACTS) and other reactive power resources. SVR schemes are a staple of voltage control literature, with several successful implementations in real-world settings.

B. Relevant Literature

Reference [5] summarizes the major existing SVR configurations. Despite its pervasiveness, recent works showcase the potential for state-of-the-art innovation within SVR capabilities. The authors of [6], [7] opt to combine the SVR layer with voltage stability indices and TVR, respectively, as a means to account for network vulnerabilities in an optimized manner. A monitoring-based SVR is also the focus of [8], where synchrophasor measurements are applied to reactive power tuning of available generators. Further improvements on the conventional secondary scheme are proposed in [9], [10] through redefinition of static and dynamic control objectives as well as day-ahead dispatch considerations. In [11], the versatility of the SVR approach is emphasized by simulations of an idealized 100% renewable power system.

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In [12], short-term dynamic simulations of a single-area test system including a basic SVR structure are presented in a tutorial manner. This idea is expanded upon in [13] for daily load flow studies and in [14] for reactive power alignment based on pilot bus voltage reference. Such demonstration examples not only facilitate the understanding of SVR operation, but also help identify possible improvements applicable to specific areas of the Nordic power grid. As discussed in [5], a small SVR prototype has been implemented within the TSO's regional control center for Southern Norway in the 2000s. Around 20 years later, no innovation nor concrete expansion upon this idea has been put into practice in the country.

C. Contributions and Paper Organization

The objective of this paper is to demonstrate the benefits of the hierarchical SVR approach through dynamic simulations run in DynPSSimPy, an open-source power system simulator in Python [15]. The primary contribution refers to the case studies and related discussions on bus voltage behavior, reactive power management and active power losses. The secondary contribution is the proposed setpoint reference change approach for mitigation of voltage deviations arising from daily load demand variations.

The remainder of the paper is divided as follows: Section II describes the main portions of the secondary voltage regulation scheme under study; Section III covers the adopted methodology, detailing the 6-bus test system; Section IV presents the dynamic simulation results and the proposed reference change approach; Section V concludes the paper.

II. SECONDARY VOLTAGE REGULATION SCHEME

To properly define SVR capabilities, it is important to have in mind the fundamental distinctions among coordinated control layers. Fig. 1 summarizes the spatial-temporal decoupling that characterizes the primary, secondary and tertiary hierarchical voltage regulation levels.

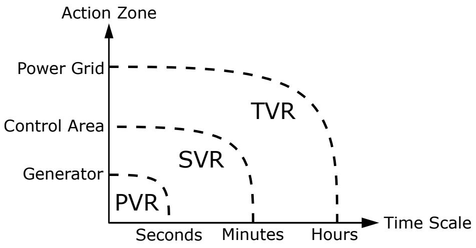

Fig. 1. Spatial-temporal decoupling in a hierarchical voltage control scheme. Source: adapted from [16].

As illustrated, each layer is associated to a different action zone and time scale: PVR action is typically at a generator level, concerning automatic voltage regulators (AVRs), and tends to be the fastest with a range of fractions of a second to some seconds; SVR action involves a predefined control area, including several generator units, and presents slower dynamics with a range of some seconds to some minutes; TVR action influences the entire power grid, adjusting the overall system profile through optimization techniques, and is the slowest with a range of some minutes to several hours.

The hierarchical structure mitigates conflicting control objectives which could otherwise cause long-term issues, such as voltage runaway and wear-and-tear of controllers. Communication between layers is bidirectional, carried out by control signals in such a way that the broadest layer always takes precedence over the narrowest one [16].

In this context, the SVR scheme is responsible for maintaining voltage levels at an acceptable operating range within its action zone, a typically small control area predefined to be electrically distant from other SVR control areas. That way, the impact of local corrective actions on external voltage behavior is minimized.

Since it is unreasonable to perform real-time simultaneous voltage control of hundreds of transmission buses, one or a few of those are selected based on short-circuit capacity studies to be representative of the overall area voltage profile [9]. This is the definition of a pilot bus, which is then the focus of SVR corrective actions towards a desired setpoint. If the pilot bus is properly chosen, these directed adjustments should translate into voltage profile improvements over the entire control area.

The conventional SVR structure can be divided into two main components: the central pilot bus controller and a set of distributed power plant controllers (one for each involved generator). A simple realization of both of these controllers requires proportional-integral (PI) blocks as well as feedback signals from the pilot bus and from the PVR layer of generators. The outputs of such components are control signals fed back to generator AVRs, where the necessary corrective measures are smoothly carried out over time in accordance with the slow SVR dynamics.

Fig. 2 shows the basic SVR scheme with PI-based components. Details on each controller's functionalities and parameters are as follows:

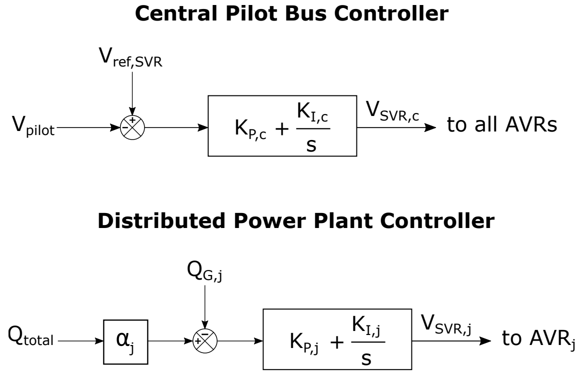

Fig. 2. Simple SVR scheme divided into main PI controllers. Source: adapted from [17]

- Central pilot bus controller: monitors and corrects V_{pilot} according to a predefined $V_{ref,SVR}$. This is done through a $V_{SVR,c}$ signal sent to all AVRs, which is the output of the PI block with $K_{P,c}$ and $K_{I,c}$ gains.

- Distributed power plant controller: provides individual reactive power adjustments for generators, based on a predefined α_j usually proportional to each machine's power rating. This factor scales Q_{total} for comparison with the current $Q_{G,j}$. The result is a $V_{SVR,j}$ signal sent to the respective AVR_j, which is the output of the PI block with $K_{P,j}$ and $K_{I,j}$ gains.

It is worth noting that the SVR also aims to ensure a fair reactive power sharing among involved generators with its distributed controllers. This objective is complementary to pilot bus voltage control, since voltage magnitudes and reactive power flow are strongly related at the transmission level. Moreover, the twofold corrective action has a certain degree of influence over active power losses, as is discussed in Section IV.

The simplified structure of Fig. 2 is nonetheless conceptually similar to real-life SVR schemes adopted in Italian and French control centers. The main difference refers to the assumption of continuous operation, whereas practical SVR implementations are discrete in nature with sampling rates in the range of seconds [17].

III. METHODOLOGY

Fig. 3 illustrates the single-line diagram of the 6-bus test system, comprised of two synchronous machines, seven power lines and two constant power-type load centers, one at bus B5 and another at bus B6. Both machines are fifth-order salient-pole generators and share the same static and dynamic parameters, except for base complex power since the rating of the G2 generator is three times larger than that of the G1 generator. They are also equipped with identically tuned AVRs, which constitute the network PVR layer, and first-order governors. Data for the machines and associated controllers is provided in [12].

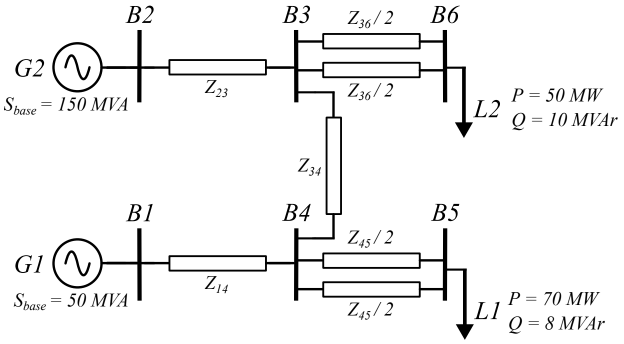

Fig. 3. Single-line diagram of the 6-bus test system.

Network base voltage is 400 kV, a typical nominal value at the Nordic power grid transmission level. This means that the X/R ratio of lines is quite high, but resistances are not neglected as active power losses are part of the analyses. Thus, realistic cable parameters were included in the line modelling as per [2]. Total baseline load demand is (120 + j18) MVA, divided between the two load centers as follows: (70 + j8) MVA at bus B5 and (50 + j10) MVA at bus B6.

The test system of Fig. 3 represents a single voltage control area under the influence of the SVR structure presented in Fig. 2. Control signals from the central and power plant controllers are added as feedback inputs to the AVRs of both generators, as each of them participate in the scheme in proportion to their respective ratings. Gain values for the PI controllers are constant all throughout the simulations, being provided in [12].

Regardless of the case study, the main objective of the SVR strategy is to maintain pilot bus voltage at a predefined setpoint and to ensure reactive power contribution is shared between generators according to their ratings, i.e. G2 reactive power injection should always be exactly three times that of G1. The load bus B5 is chosen as pilot bus for all cases as it hosts the heaviest load center.

For the post-fault response analysis, a sustained line outage event is programmed to occur in one of the parallel lines connecting buses B4 and B5 at t = 50 s onwards. To emphasize the dynamic behavior surrounding the fault, total simulation time in this case is chosen to be 300 s. Voltage setpoints are 1.01 p.u. and 1.02 p.u. at PV buses B1 and B2, respectively, and B5 is regulated at 0.975 p.u. by the SVR. These are typical setpoint values adopted by TSOs in hierarchy-based grid control.

For the daily load following analysis, instead of a fault event, the loads are set to follow the profiles shown in Fig. 4, which exemplify typical 24-hour power consumption curves with peak demand in the afternoon period, starting from their respective baseline values shown in Fig. 3. In this case, voltage setpoints are 1.03 p.u. and 1.04 p.u. at PV buses B1 and B2, respectively, and B5 is regulated at 1 p.u. by the SVR. The same adjustments apply to the voltage setpoint reference change analysis, except that B5 can also be regulated at 0.99 p.u. at the SVR's discretion. The aim of this change is to illustrate that small but well-timed SVR actions are conducive to enhanced quality of supply.

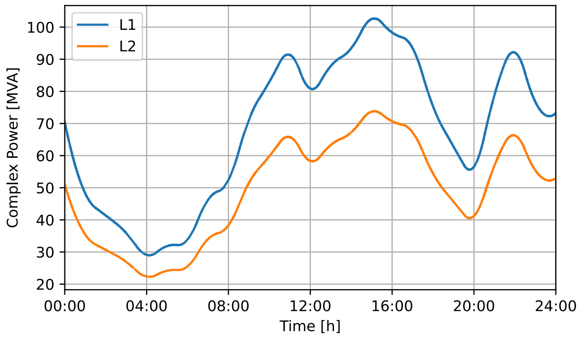

Fig. 4. Daily load profiles for the 6-bus test system.

The software package DynPSSimPy is the chosen tool for dynamic simulations due to its open-source nature and expandability, as well as reasonable real-time performance for small power systems. The associated integration method allows for highly detailed results by discretization of Fig. 4 profiles using an iterative step of variable size around one second. A comprehensive description of the simulator functionalities can be found in [15].

IV. RESULTS

This section aims to illustrate the benefits of a SVR layer implementation in terms of bus voltage profiles, reactive power sharing between the two generators and active power losses under different but realistic system conditions. Results related to voltage magnitudes include black dashed lines representing the lower and upper limits of acceptable operating range: 0.95 p.u. and 1.05 p.u. respectively [5].

A. Post-Fault Response

Fig. 5 shows all bus voltage magnitudes before and after the line outage event without SVR action. The PVR layer ensures that PV buses B1 and B2 quickly recover their original setpoints, whereas the remaining uncontrolled buses suffer a permanent voltage drop. B5 is clearly the most affected bus as it violates the lower voltage limit, thereby leading to an unacceptable operating scenario.

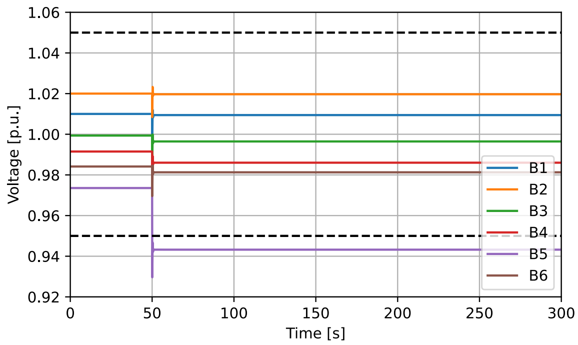

Fig. 5. System voltage profile without the SVR scheme.

The same voltage profiles are shown in Fig. 6, now considering SVR action. The extra control layer smoothly corrects the pilot bus B5 voltage back to its pre-fault value, increasing the magnitudes of all other buses in the process. Since SVR takes precendence over PVR in the hierarchy, B1 and B2 voltages are likewise increased, to the point where the latter gets close to the upper voltage limit. This reinforces the importance of adequate SVR gain tuning as a measure against overcorrection. Overall, SVR action prevents B5 undervoltage and ensures an acceptable post-fault operating scenario.

Fig. 7 refers to the reactive power sharing ratio between generators ($Q_{G,2}/Q_{G,1}$) with and without SVR action. The absence of SVR results in unfair reactive power distribution throughout the simulation, with G2 contributing too much prior to the fault ($Q_{G,2}/Q_{G,1} > 3$) and G1 contributing too much after it ($Q_{G,2}/Q_{G,1} < 3$). This places an unnecessary burden on the machines, which translates into sub-optimal system operation.

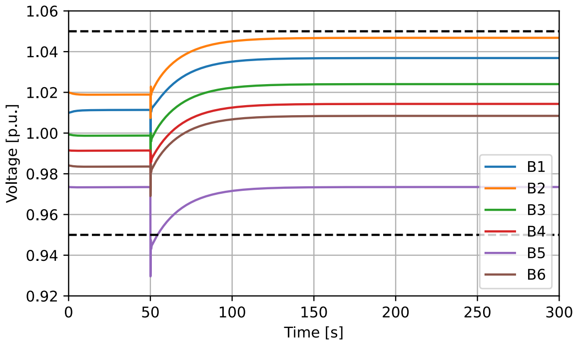

Fig. 6. System voltage profile with the SVR scheme.

The SVR mitigates this issue by lowering the ratio from its uneven start, and then by raising it back once the network is reconfigured. In both cases, it ensures $Q_{G,2}/Q_{G,1} = 3$ after a quick transient period. The correction nicely complements pilot bus regulation towards an improved post-fault performance.

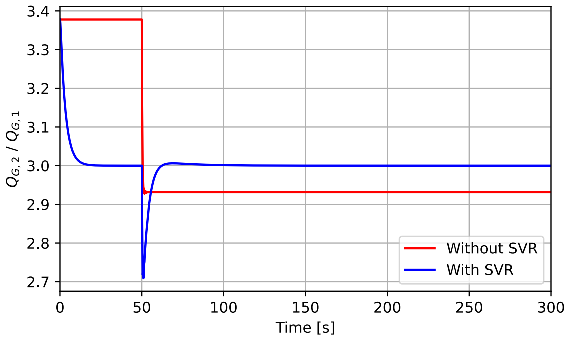

Fig. 7. Reactive power sharing ratio with and without the SVR scheme.

An additional benefit of SVR action is shown in Fig. 8, related to active power losses with and without the scheme. Due to the post-fault voltage and reactive power adjustments, the SVR manages to reduce losses in the new steady-state by 3.3%, i.e. around 68 kW. Although loss minimization is not a main SVR objective, the result attests to the potential for expansions in this regard, possibly through a TVR framework.

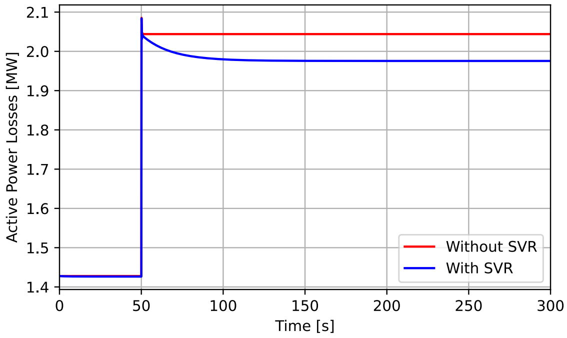

Fig. 8. Active power losses with and without the SVR scheme.

B. Daily Load Following

Fig. 9 shows all bus voltage magnitudes for a 24-hour-long period, during which the load centers follow the demand profiles of Fig. 4. Since no fault events happen, voltage levels remain within the acceptable range throughout the simulation. However, the fact that B5 rarely stays at its desired setpoint of 1 p.u. adversely affects quality of supply in the long run. Ideally, the voltage profile at the heaviest load center should be as flat as possible.

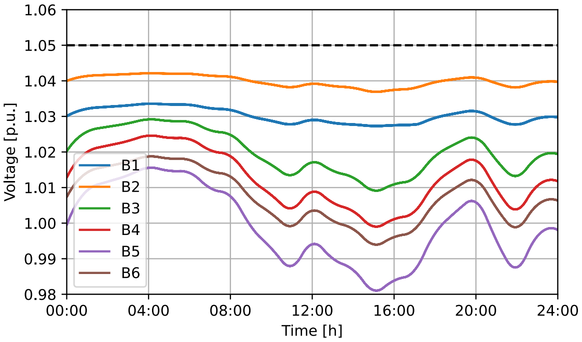

Fig. 9. System voltage profile without the SVR scheme.

The SVR is able to flatten B5 voltage seamlessly, as shown in Fig. 10. Corrective measures are not noticeable in a daily profile, but are still realized smoothly in the range of seconds due to the inherently slow SVR dynamics. It is noticeable that the scheme maintains a tight control over the pilot bus, to the detriment of unregulated bus voltages. Namely, the corrections make B2 voltage increase to unacceptable levels at peak consumption hours. A simple and inexpensive approach to mitigate B2 overvoltage while keeping B5 voltage relatively flat is discussed in the next subsection.

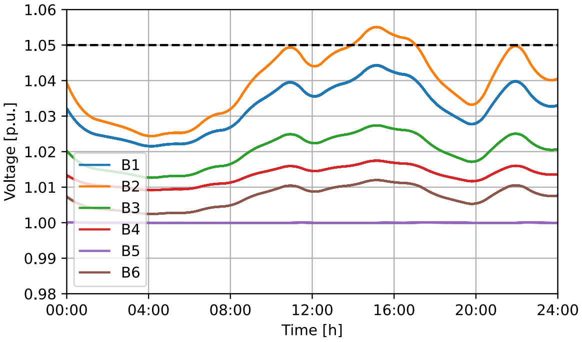

Fig. 10. System voltage profile with the SVR scheme.

Fig. 11 shows the reactive power sharing ratio throughout the day, emphasizing the massive contribution imbalance in the absence of SVR. In this case, G2 is unnecessarily overburdened especially in the first half of the day, whereas G1 is underutilized outside of peak consumption hours. The presence of SVR ensures a fair and consistent partitioning based on machine ratings, with significant improvements to be gained in the long-term reactive power dispatch.

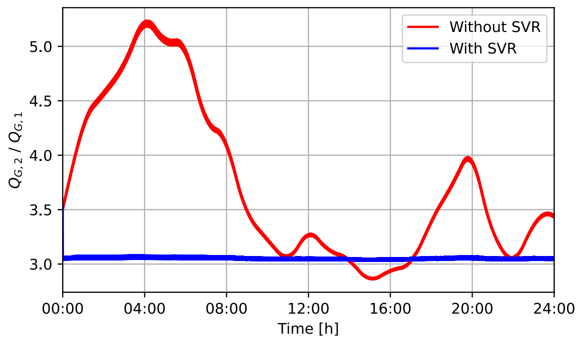

Fig. 11. Reactive power sharing ratio with and without the SVR scheme.

Active power losses with and without SVR are compared in Fig. 12. Both profiles are fairly similar until the periods of higher loading, where the SVR action manages to decrease losses slightly. The zoomed-in subplot refers to the peak of both curves, where the largest difference occurs and losses are reduced by 1.6%, i.e. 37 kW. Significant energy savings can be attained when considering the accumulated reduction over a day and longer time frames.

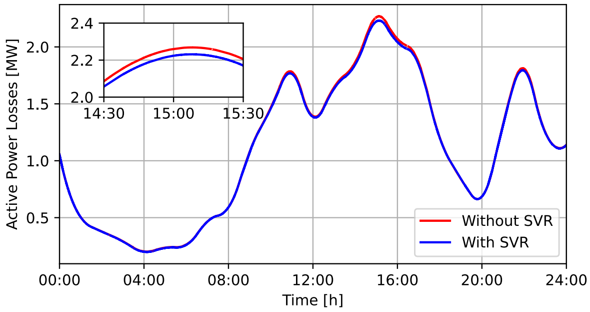

Fig. 12. Active power losses with and without the SVR scheme.

C. Voltage Setpoint Reference Change

A common solution to the overvoltage issue observed in Fig. 10 is automatic switching of local reactive power resources, such as is done with reactor banks in [13]. However, the SVR scheme itself is able to compensate for its own actions by setting up a variable reference for the pilot bus voltage setpoint. That way, setpoint changes can be scheduled for high demand periods, when the SVR is already expected to overcorrect bus voltage levels. The variable B5 setpoint approach is illustrated in Fig. 13.

In this case, B5 voltage is scheduled to drop to 0.99 p.u. from 10:00 to 22:40, which in turn causes other bus voltages to decrease as well, thereby preventing B2 overvoltage. Apart from the quick transition periods, B5 voltage remains flat throughout the entire day, meaning quality of supply is not compromised.

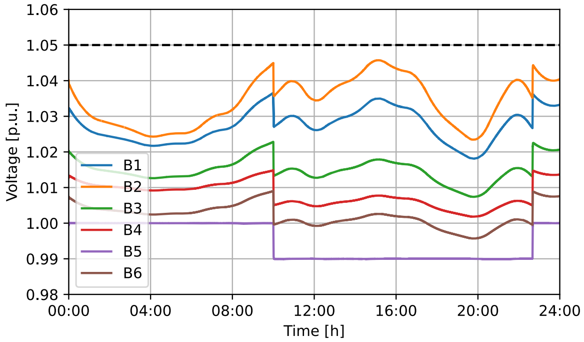

Fig. 13. System voltage profile with the SVR scheme and variable B5 setpoint.

Furthermore, small variations in voltage setpoint are rather non-intrusive, i.e. other system parameters are minimally affected. To show this, Table I summarizes the daily average values of reactive power sharing ratio and active power losses using data from Fig. 11 and Fig. 12, as well as results related to the setpoint change of Fig. 13. The proposed solution actually promotes a slight correction in reactive power partitioning with respect to the fixed-setpoint SVR, at the cost of marginally increasing daily average losses. Nevertheless, the overall result still marks an improvement over the case of no SVR action.

TABLE I
COMPARISON OF DAILY AVERAGE VALUES FOR REACTIVE POWER SHARING RATIO AND ACTIVE POWER LOSSES.

	Daily Average	
	$Q_{G,2}/Q_{G,1}$	*Losses (MWh)*
Without SVR	3.74	26.45
With SVR	3.05	26.26
With SVR + Setpoint change	3.00	26.40

V. CONCLUSION

In this paper, the performance of a basic SVR scheme was assessed through dynamic simulations of a 6-bus test system in a Python-based simulator. Analyses addressed three different network scenarios: post-fault response, daily load following and voltage setpoint reference change.

The post-fault response case attested to the merits of the SVR layer in terms of improved bus voltage profiles, reactive power sharing in proportion to generator ratings and steady-state reduction of active power losses. In a more realistic setting, the daily load following case reinforced the aforementioned benefits by ensuring bus voltage at the heaviest load center was kept as flat as possible. However, SVR action led to generator bus overvoltage at peak consumption hours.

The voltage setpoint reference change case proposed a straightforward solution to this issue, which not only prevented bus overvoltage but also slightly improved reactive power sharing and did not severely impact active power losses. Therefore, this simple approach constitutes a non-intrusive SVR-based response to voltage deviation scenarios commonly encountered in routine control center operations.

Future work building upon this paper's findings aims to tackle the limitations of the pilot bus reference change strategy, with investigations of SVR performance in more complex systems. Possible analyses include the impact of on-load tap changers, over-excitation limiters and other reactive power resources on the hierarchy-based control. The end goal is to devise and validate a SVR scheme suited for the particularities of the Nordic power grid.

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REFERENCES

[1] "World Energy Outlook," IEA, Tech. Rep., 2022.
[2] "National Report," NVE, Tech. Rep., 2021.
[3] T. Trummal, G. Andreesen, and J. Kilter, "Optimal Reactive Power Control in a Multi-Machine Thermal Power Plant," in *2020 21st International Scientific Conference on Electric Power Engineering (EPE)*, Dec. 2020, pp. 1–6.
[4] H. H. Fayek, K. R. Davis, A. A. Ghany, and O. H. Abdalla, "Configuration of WAMS and Pilot Bus Selection for Secondary Voltage Control in the Egyptian Grid," in *2018 North American Power Symposium (NAPS)*, Sep. 2018, pp. 1–6.
[5] "Coordinated Voltage Control in Transmission Networks," CIGRE, Tech. Rep., 2007.
[6] R. Maharjan and S. Kamalasadan, "Secondary voltage control of power grid using voltage stability index and voltage control areas," in *North American Power Symposium*, Sep. 2017, pp. 1–6.
[7] B. Hernandez, C. A. Canizares, J. M. Ramirez, B. Hu, and M. Liu, "Secondary and Tertiary Voltage Regulation Controls Based on Regional Optimal Power Flows," in *Power Systems Computation Conference*, Jun. 2018, pp. 1–7.
[8] M. M. Nascimento, R. T. Bernardo, and D. Dotta, "Data-Driven Secondary Voltage Control Design using PMU Measurements," in *IEEE Power & Energy Society Innovative Smart Grid Technologies Conference*, Feb. 2020, pp. 1–5.
[9] A. E. M. Bouzid, B. Marinescu, and G. Denis, "Structural Analysis and Improved Reactive Power Alignment for Secondary Voltage Control," in *IEEE Milan PowerTech*, Jun. 2019, pp. 1–6.
[10] S. K. Mahmoudi, M. E. H. Golshan, and R. Zamani, "Coordinated voltage control scheme for transmission system considering objectives and constraints of network and control devices," *Electric Power Systems Research*, vol. 192, p. 106908, Mar. 2021.
[11] O. H. Abdalla, H. H. Fayek, and A. M. Abdel Ghany, "Secondary Voltage Control Application in a Smart Grid with 100% Renewables," *Inventions*, vol. 5, no. 3, p. 37, Sep. 2020.
[12] N. Martins, J. Ferraz, S. Gomes, P. Quintao, and J. Passos, "A demonstration example of secondary voltage regulation: dynamic simulation and continuation power flow results," in *2001 Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No.01CH37262)*, vol. 2, Jul. 2001, pp. 791–796 vol.2.
[13] S. K. S. Abdullah, I. Z. Abidin, I. Musirin, and D. M. Nor, "Modeling of Secondary Voltage Regulation for 24-hour load flow and dynamic simulation for coordinated voltage control application," in *2011 IEEE Student Conference on Research and Development*, Dec. 2011, pp. 199–204.
[14] J. K. Goyal, V. Thomas, and B. Marinescu, "A decentralised control strategy for secondary voltage regulation," 2022. [Online]. Available: https://arxiv.org/abs/2205.13833
[15] H. Haugdal, K. Uhlen, and H. Jóhannsson, "An Open Source Power System Simulator in Python for Efficient Prototyping of WAMPAC Applications," in *2021 IEEE Madrid PowerTech*, Jun. 2021, pp. 1–6.
[16] G. Pierrou, "Long-term voltage stability of power systems under uncertainty: Analytical methods and data-driven control," Doctoral thesis, McGill University, 2021.
[17] J. P. V. Villa, "Power systems secondary voltage control: An approach using distributed model predictive control with zone control," Doctoral thesis, Universidad Nacional de Colombia, 2019.