A Real-Time Receding-Horizon Transmission Voltages Control using Sensitivity Matrix and Bias

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Abstract—**In this paper, a simplified multi-step receding-horizon controller is introduced to control the violations in transmission voltages and stop developing long-term voltage instabilities. The system model is derived from the context of quadratic dynamic matrix control and is represented as a set of linear constraints derived from sensitivity analysis and bias terms acting as modelling error corrector. Resulting multi-step optimization is highly structured convex quadratic programming problem for which reliable standard codes are available. The goal of proposed controller is to achieve high performances with simplified system model relying on reliable optimization solver. The Nordic32 test system is used for evaluating the performance of proposed controller and its comparison with existing closely related approaches focusing on minimization of expensive controls (load shedding).**

Index Terms—**Sensitivity, bias, long-term voltage instability, real-time control, receding-horizon.**

I. INTRODUCTION

INCREASING complexity of modern power systems have introduced numerous technical challenges. Among various issues, voltage control of nonviable voltages and unstable situations have gained prominence over the last decades[1].

During emergency conditions, power systems may experience wide disparities between available and required reactive power to maintain adequate system voltages. This potentially leads to unacceptable voltages and eventually to voltage instability problems [2] and its severity has led to several blackouts experienced across the world [3], [4], [5]. Occurrence of such blackouts have further increased the need for corrective control actions to maintain system's stability [1], [6].

A viable approach is to design a response-based real-time control scheme acting in closed-loop. Model Predictive Control (MPC) is one such real-time control method [7], with long history of successful applications in different engineering fields [8], that has found recent interest in power system control applications [9], [10], [11]. It involves obtaining a sequence of future control actions based on present measurements and system model over a time horizon. The controller implements only the first step control actions and repeats the same procedure in the next time step with new measurements. MPC and tree search optimization approach for coordinated voltage control is presented in [9]. A centralized MPC control scheme using Lagrangian decomposition method is adopted for emergency voltage control in [10]. In [11] capacitance control strategy that involves MPC based trajectory sensitivity approach to prevent voltage collapse situation is presented. A multi-step receding-horizon controller, resembling idea of MPC but using static system model, is applied to correct non-viable or long-term unstable voltages in [12]. Load restoration was used as prediction mechanism in this work.

Following the observation of [13] (as in works [14], [15], [16]) that highly detailed models within MPC, or MPC-like, control schemes may be unnecessary, this paper proposes a simplified multi-step receding-horizon of [12] and an extension of the ones proposed in [14], [15]. The controller utilizes a simple sensitivity- and bias-based system model. The system model is transformed into linear constraints derived from non-linear network power flow equations based on sensitivity analysis, similar to [14] and in line with [15]. Bias terms serve as an error correctors able to correct and mitigate the errors introduced by linear approximations. The proposed controller embeds prediction into the system model and no assumption about load recovery is needed as in [12] and improves over sensitivity approach of [14], [15] in terms of the system model accuracy. Essentially, proposed approach fits the context of quadratic dynamic matrix control (QDMC) [17].

Initial results using a similar problem formulation were provided in [18]. Present paper extends it in several ways: modifies the formulation for better handling of generators' overexcitation capability together with more accurate sensitivity computation and along the line of QDMC computes and applies control actions at current step (instead at the first predicted step as in [18] thus avoiding unnecessary delays), more accurate implementation, and analizes two important problems, not considered previously, of the robustness to measurements noise and closed-loop stability of the system.

This paper is organized as follows. Related works are discussed in Section II. Section III presents proposed control. Section IV presents test system and simulation conditions. Section V shows and discusses obtained results. Section VI presents additional cases while Section VII discusses the controller robustness. Section XIII analyzes measurement requirements. Section IX offers some discussions and Section X concludes.

II. CLOSELY RELATED WORKS

The use of sensitivity for voltage control in power systems is not new. The sensitivity of a system variable is a measure of the influence of changes in control to that variable [2].

The sensitivities derived from power flow equations, for a given operating point, were proposed in [19] to allocate reactive power support and load curtailment for voltage unstable situations. In [20] a procedure for dispatching reactive power when voltage deviations are not acceptable was proposed. The

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NOTE: This version is intended for fast dissemination of ideas and the work aiming at improved version is underway.

control actions are chosen based on their efficiency measured by sensitivities, voltage profile and reserve margins of the control. Controls are applied as single step in both [19] and [20]. Work presented in [15], inspired of MPC, introduced sensitivities in multi-step receding-horizon control setting. This work presented and discussed useful ideas on possible uses of the MPC-like setting to control voltage unstable situations but without relevant support. The ideas of [15] were exploited in [14], [21]. In [14] a control approach utilizing linearized system model was formulated based on sensitivity analysis. This approach considers a multi-step control by applying a fraction of computed controls and optimization procedure is repeated until the system settles to acceptable state. Te work presented in [21] used model presented in [15] to develop a multiagent control architecture with minimum communications burden while each agent solves a problem proposed in [15].

III. Proposed control

The idea explored in this work is to formulate a simplified controller, along the idea of QDMC (motivated primarily by its successes in other industries [8]).

QDMC is an input-ouput MPC and extension of one of the earliest MPC controls known as dynamic matrix control (DMC) [8], [17]. These two MPCs found a number of industrial applications, and highly impacted developments in MPC [8] but, to the best knowledge of the authors, not gained attention in power system considerations (an exception is the use of DMC in [22]). The prediction model is derived from responses of the system outputs to step-changes in inputs (with amplitude chosen based on engineering judgement),

$$\mathbf{Y}^{j+1} = \mathbf{Y}^j + \mathbf{A}\boldsymbol{\Delta}\mathbf{u}^j + \mathbf{Y}_d^j,\ j = k, \ldots, k+K-1 \tag{1}$$

where $\mathbf{Y}$ is the vector of system's outputs, $\mathbf{A}$ the dynamic matrix containing step-response coefficients (representing discretized value of the system step responses), $\boldsymbol{\Delta}\mathbf{u}$ the vector of adjusted system's inputs (controls), $\mathbf{Y_d}$ the vector of the estimates of unmeasured disturbance in the system's outputs, and K is the number of prediction steps.

Dynamic matrix $\mathbf{A}$ is obtained from the experiments with the system or its model.

Vector $\mathbf{Y}_d$ is usually estimated form present measurements and contribution of past controls to present value of the outputs (at present step k) [17],

$$\mathbf{Y}_d^k = \mathbf{Y}_m^k - \mathbf{Y}^* \tag{2}$$

and kept constant over the whole prediction horizon.

In line with the idea of QDMC, this work suggests the use of sensitivities (derived from power flow equations) and simple bias terms computed from collected measurements at each step (as a proxy of unmeasured disturbances in the system outputs (1)) resulting in a quadratic programming (QP) problem for which efficient solvers exists even for large-scale systems. The use of sensitivities derived from power flow equations, instead step-response coefficients in QDMC, is justified by the fact that voltages in power systems virtually have no inertia. This fact further implies a simplification through the use of analytic sensitivities (4) kept constant over the whole prediction horizon.

In voltage control problems, for transmission system ($P-\Theta, Q-V$ decoupling), it is important to include voltage magnitude and reactive power generation sensitivity model.

The mathematical formulation of proposed controller is as follows,

$$\min_{\substack{\mathbf{u}_1^k,\ldots,\mathbf{u}_1^{k+K-1}\\ \mathbf{u}_2^k,\ldots,\mathbf{u}_2^{k+K-1}}} \sum_{j=k}^{k+K-1} \left[\sum_{i=1}^{n_1} c_i(\Delta u_{1,i}^j)^2 + \sum_{i=1}^{n_2} c_i(\Delta u_{2,i}^j)^2\right] \tag{3a}$$

$$\text{s.t.}\ \mathbf{V}^{j+1} - \mathbf{V}^j - \mathbf{S}_{V,V_g}(\boldsymbol{\Delta}\mathbf{u}_{1,i}^j) - \mathbf{S}_{V,P_l}(\boldsymbol{\Delta}\mathbf{u}_{2,i}^j) - \mathbf{b}_V^j = 0,\ j = k, \ldots, k+K-1 \tag{3b}$$

$$\mathbf{Q}_g^{j+1} - \mathbf{Q}_g^j - \mathbf{S}_{Q_g,V_g}(\boldsymbol{\Delta}\mathbf{u}_{1,i}^j) - \mathbf{S}_{Q_g,P_l}(\boldsymbol{\Delta}\mathbf{u}_{2,i}^j) - \mathbf{b}_{Q_g}^j = 0,\ j = k, \ldots, k+K-1 \tag{3c}$$

$$\mathbf{u}_1^{min} \le \mathbf{u}_1^j + \boldsymbol{\Delta}\mathbf{u}_1^j \le \mathbf{u}_1^{max},\ j = k, \ldots, k+K-1 \tag{3d}$$

$$\mathbf{u}_2^{min} \le \mathbf{u}_2^j + \boldsymbol{\Delta}\mathbf{u}_2^j \le \mathbf{u}_2^{max},\ j = k, \ldots, k+K-1 \tag{3e}$$

$$|\boldsymbol{\Delta}\mathbf{u}_1^j| \le \boldsymbol{\Delta}_1^{max},\ j = k, \ldots, k+K-1 \tag{3f}$$

$$\boldsymbol{\Delta}_2^{min} \le |\boldsymbol{\Delta}\mathbf{u}_2^j| \le \boldsymbol{\Delta}_2^{max},\ j = k, \ldots, k+K-1 \tag{3g}$$

$$\mathbf{V}^{min} \le \mathbf{V}^{k+K} \le \mathbf{V}^{max} \tag{3h}$$

$$\mathbf{Q}_{g,j}^{min} \le \mathbf{Q}_g^j \le \mathbf{Q}_{g,j}^{max},\ j = k+k_1, \ldots, k+K \tag{3i}$$

where c_i represents the cost associated to each control action, $\mathbf{V}$ denotes the bus voltage magnitudes, $\mathbf{Q}_g$ denotes the reactive power of the generators, $\mathbf{u}_1$ is the control vector of generator voltage set points (dimension n_1), and $\mathbf{u}_2$ is the control vector of load shedding (dimension n_2). For clarity reasons the vector of control variables is separated in two corresponding to those used in this work (generator voltage set-points and load shedding).

The objective of the optimization problem (3a) is to minimize the deviation in control variables distributed over the specified time steps $j = k, \ldots., k+K-1$ where K is the control/prediction horizon. The constraint (3b) and (3c) represent the linearized system model. Each of these constraints includes the sensitivity matrices (derived from the power flow equations) denoted by $\mathbf{S}_{V,V_g}$, $\mathbf{S}_{V,P_l}$, $\mathbf{S}_{Q_g,V_g}$, and $\mathbf{S}_{Q_g,P_l}$ together with bias vectors $\mathbf{b}_V$ and $\mathbf{b}_{Q_g}$ vectors. These matrices are derived from power flow equations as [2],

$$\mathbf{S}_{\lambda,\mathbf{u}} = -\phi_{\mathbf{u}}^T(\phi_{\mathbf{x}}^T)^{-1} \bigtriangledown_{\mathbf{x}}\lambda \tag{4}$$

where $\mathbf{S}_{\lambda,\mathbf{u}}$ is the sensitivity matrix that corresponds to the sensitivity of the change in u to λ (variable of interest). The Jacobian of $\phi(\mathbf{x},\mathbf{u})$ (power flow equations) with respect to $\mathbf{u}(\mathbf{x})$ is denoted as $\phi_{\mathbf{u}}(\phi_{\mathbf{x}})$, while $\bigtriangledown_{\mathbf{x}}\lambda$ represents the partial derivative of λ with respect to $\mathbf{x}$.

Bias is a simple and effective method to correct modelling errors and to reduce discrepancies between the actual measured (each initial step of voltage and reactive power correspond to measured values) and predicted values. The bias terms are computed similarly to QDMC [17], at time step k, as follows,

$$\mathbf{b}_V^k = \mathbf{V}^m - \mathbf{V}^k \tag{5}$$

$$\mathbf{b}_{Q_g}^k = \mathbf{Q}_g^m - \mathbf{Q}_g^k \tag{6}$$

where $\mathbf{V}^m, \mathbf{Q}^m$ represent measured values of the voltages and generator reactive powers respectively, while $\mathbf{V}^k, \mathbf{Q}_g^k$ represents the predicted values of voltage and generator reactive power respectively (they replace contributions of past controls to present value in [17]). Bias vector $\mathbf{b}_V$ is of dimension the number of system buses while $\mathbf{b}_{Q_g}$ the number of generators and are considered constant for all prediction steps.

The remaining constraints represent the upper and lower bounds for each considered variable. Constraints (3d),(3e),(3f),(3g),(3h) and (3i) represent the limits on the controls, bus voltages and reactive power production respectively (generation reactive power limits are updated with the corresponding active power production and terminal voltage, in accordance with the generator capability curves (as in [12])). The limits are imposed only to the final step (the end of control horizon) for bus voltages. Imposing the limits on the final step ensures closed-loop system stability in receding-horizon controls (known as terminal set constraint [7]). However, since terminal constraints are imposed, in proposed approach, only on some system state variables the closed-loop system stability is not guaranteed in this way. This issue is discussed in a later section of this paper.

The constraint (3i) is aimed at proper handling of generators' overexcitation limiters (OXLs). Namely, synchronous generator may temporarily operate above its reactive power limits. This temporal overexcitation can be crucial in critical situations for voltage control. This constraint is simplified with respect to [12], [18] for better handling of temporal overexcitation. If a generator operates below its OXL limit then the value of k_1 is set to 1 and if generator is overexcited k_1 is set to the first time step less than anticipated activation of corresponding OXL. This way, unlike in [12], [18], OXL limit is avoided as main factor driving a system to instability.

The constraints (3f) and (3g) are related to Δ that represents the limits on the rate of change of control variables. The sensitivity based system constraints are the voltage constraint (3b) and the generator reactive power constraint (3c).

The optimization (3) is a convex QP problem for which a number of efficient and reliable generic solvers exists [8]. However, not all (even some most efficient ones) QP solvers are optimized for repeated optimization as the one needed in proposed control [23]. Desirable characteristic of the solver, in addition to sparsity exploitation, is exploitation of warm-starting.

The solution of proposed approach works as follows:

1) Collect all the necessary measurements (voltage magnitudes in all buses and reactive powers of all generators).
2) Compute the sensitivity matrices for the system constraints (3b) and (3c) and the bias terms ($\mathbf{b}_V, \mathbf{b}_{Q_g}$) (bias terms are assumed to be zero only for the initial step).
3) Compute, assuming current step is k, a sequence of control actions for $k, ..., k+K-1$ steps by solving the optimization problem (3).
4) Apply present step control actions ($\mathbf{u}^k$) to the system as soon as they are computed.
5) At the next time step go to item 1.

Item 4 implies the use of very fast optimization solver and fast communication infrastructure (to minimize delays).

IV. Test system, simulation tools and conditions

Nordic32 test system [24] is used to test the presented controller's performance. The system is shown in Fig. 1. It has

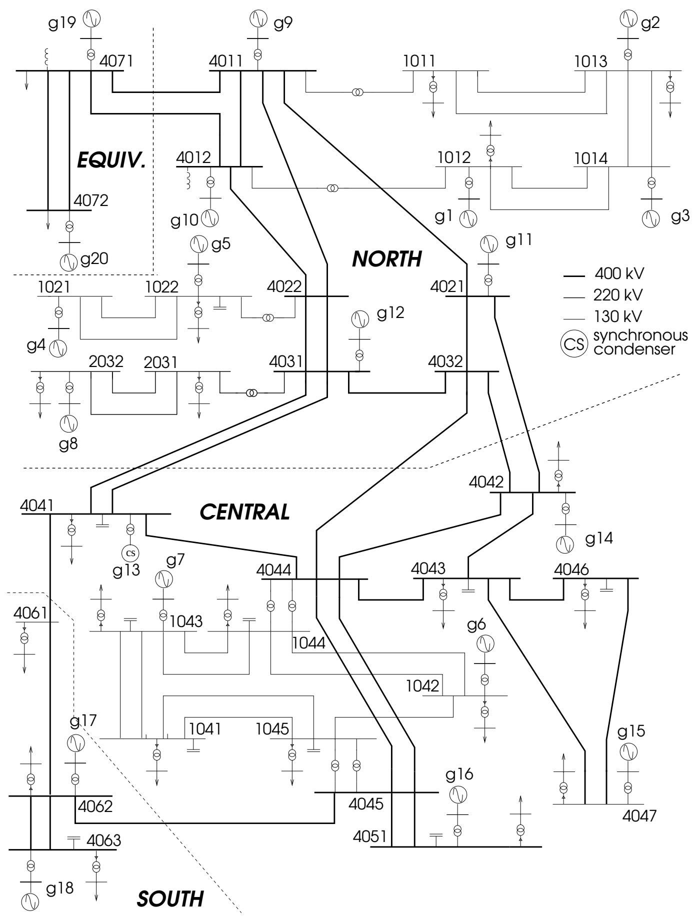

Fig. 1. One-line diagram of Nordic32 test system

20 synchronous machines which are represented by a standard model with three or four rotor windings. For the purpose of testing controller in real-time, a detailed dynamic model of the generators, AVRs, and speed governors are considered. The loads are modelled as constant current for the active power and constant impedance for the reactive power and are fed through transformers equipped with load tap changers.

Matlab/Simulink based tool is used to build and simulate the system model [12], [14]. General Algebraic Modelling System (GAMS) is used to compute the optimal controls for the optimization problem using the interior point primal-dual IPOPT solver. Although a non-linear optimization solver, IPOPT shows excellent performances in solving convex QP problems and offers possibility for the use of warm-starting (unlike many other interior point solvers), with proper tuning of some of its parameters (see [25]). Matlab and GAMS are interfaced with MATGAMS [26].

The proposed controller can modify 20 generator voltages in the range of 0.95 to 1.075 (p.u). There are 7 load buses which are considered for curtailment namely 1022, 1041, 1042, 1043, 1044, 1045 and 2031 and the total active and reactive power available for shedding are 3130 MW and 1025 MVAR, respectively. The available controls and their respective cost are set as in [12] (costs for generator set-points equal 0.001 and for load shedding 1.0). The load shedding is assigned with higher cost when compared to generator voltage set points as it is considered as the last resort control action. A 5% maximum rate of change of controls is imposed on generator set-points. A $10s$ sample period is set to the controller where it collects the measured voltages and bus power injections. The control as well prediction horizon K is taken to be three time steps (based on suggestion of [12]).

All other values considered for the controller settings are similar to [12] to facilitate comparisons. The only parameter changed is minimal amount (block) of load shedding set to be 0.5 MW unlike in [12] where small value and almost continuous load control considered (in the authors view setting minimal amount of load shedding blocks to 0.5 MW is much closer to practice). All the simulations with approach [12] are repeated here for comparison reasons.

The simulations were carried out using a Windows machine with Intel i7 (four cores) 2.40 GHz CPU and 8 GB of RAM. A control cycle consists of measurement collection, solving optimization problem and sending control signals to control devices. This brings some delays in applying control actions. In all simulations presented in this paper a delay of $100ms$ is used (a fast fiber optic digital communication infrastructure is assumed, with small delays, as reported in [27] for Bonneville Power Administration system).

The performances of proposed control are demonstrated though simulation results organized in the following way:

- detailed analysis of voltage unstable situations, together with: comparison of bias and non-bias based controllers, comparison of different sensitivities included in formulated optimization problem, and comparison with closely related existing approaches,
- performances in facing and controlling several different disturbances (line outages, generator outage, slow load increase, stable but low voltages),
- robustness os proposed control with respect to control failures together with comparisons to existing related approaches for these situations, and
- robustness of proposed control with respect to measurement noise.

V. Stabilization of an unstable system

A detailed study of proposed control for unstable system response when subjected to a line outage is presented in this section. The Nordic32 test system experiences a disturbance in the form of an outage of transmission line 4032-4044 at $t = 12s$. The OXL of several generator gets triggered (g14 at $t = 99.25$, g12 at $t = 103.6$, g6 at $t = 108.9$, g15 at $t = 117.1$, g7 at $t = 149.5$, g16 at $t = 152.4$) and finally the voltage collapse takes place at $t = 158s$ (see Fig. 2).

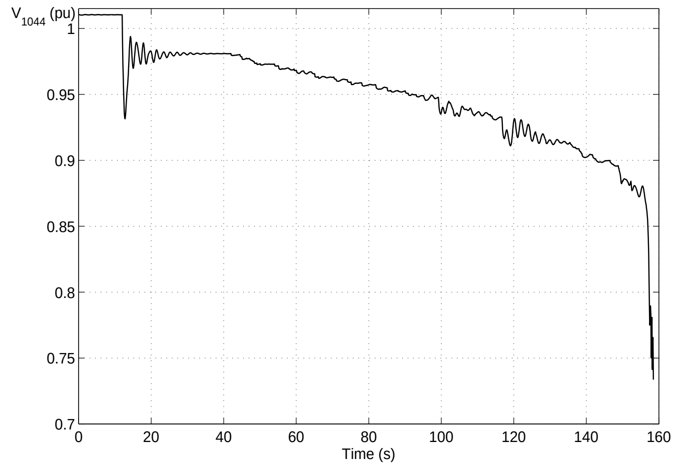

Fig. 2. Voltage at bus 1044 for unstable case

A. Simulation results

The proposed controller was able to stabilize the system with a load shedding of 113 MW. Figure 3 shows the stabilized voltage of bus 1044 (solid line). From this figure, it can be observed that the controller gets activated at $t = 70s$ onwards. Table I shows the amount of curtailed active power values in all buses considered available for the curtailment.

Proposed control is further studied through comparison of system responses when controlled with the controller without adding bias terms. Both controllers were able to stabilize the system as displayed in Fig. 3 (dotted line) with the controller using bias terms providing better performance.

The system settles at $t = 80s$ while in case of non-bias based controller the system settles at $t = 100s$.

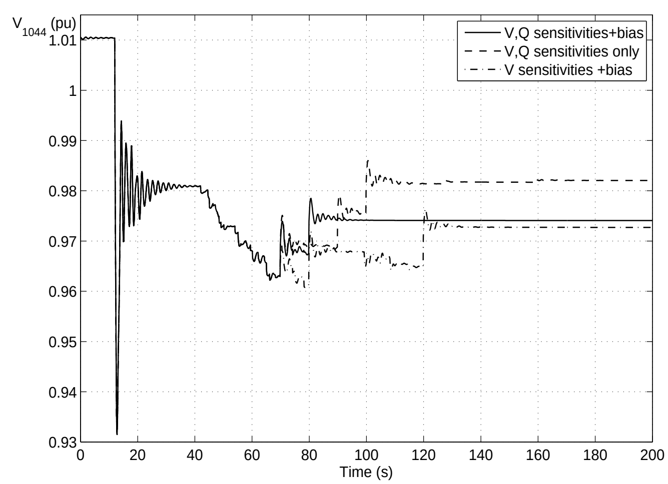

Fig. 3. Voltage at bus 1044 for different control arrangements

From the observations, the bias based controller tends to be better than the non-bias based one on the basis of decrease in settling time and reduced load shedding.

Figure 3 also displays the system response when voltage sensitivities are used only (together with the bias). The controller is able to stabilize the system in this case but with larger load shedding and settling time ($t = 120s$)

TABLE I
ACTIVE POWER SHED IN INDIVIDUAL BUSES

Load buses	P (MW)
1022	14
1041	18
1042	15
1043	15
1044	22
1045	20
2031	9
Total load shed	113

Table II provides a list of controllers and summarizes their respective total load shedding.

TABLE II
CONTROLLERS AND CORRESPONDING LOAD SHEDDING

Controller	P(MW)
with V and bias	173
with V and Q sensitivities	139
Proposed (V,Q sensitivities and bias)	113

The conclusions to be drawn from the results are as follows:

- the system is able to attain stability when accounting for only voltage sensitivity constraint together with bias terms,
- combined V,Q sensitivity constraints performs better providing lesser load shedding, and
- the bias based controller performs much better than the non-bias based controller with decrease in settling time and load curtailment.

B. Comparison with closely related approaches

Performance of proposed control are compared with those, for the same case and simulation conditions, closely related ones, i.e. approaches introduced in references [12] and [14]. Table III summarizes comparisons in terms of load shedding as more expensive control actions.

TABLE III
COMPARISON WITH CLOSELY RELATED APPROACHES

Approach	P(MW)
Reference [12]	118.0
Reference [18]	163.0
Reference [14]	181.0
Proposed	113.0

Load shedding amount shown in Table III for references [12] and [14] correspond to the best setting of considered controllers. This table clearly shows improvements over approach of [14] with linearized model and slight improvement with respect to approach of [12] where full non-linear power flow model is used in multi-step receding-horizon setting.

VI. PERFORMANCES WITH OTHER DISTURBANCES

Other disturbances include all critical ones: line outages other than 4032-4044 connecting Norht and Central parts of the system, outage of the generator g6, smooth load increase in chosen system buses. The outage of line 4032-4044 with decreased initial load in troubled (Central) part of the system resulting in stable but low voltages is also considered for checking controller performances for this situation. The same settings and simulation conditions are considered for all additional cases as with line 4032-4044 outage.

A. Other line outages and outage of the generator g6

The Table IV delivers the amount of load curtailed for the corresponding line outages indicating that for all important outages (the lines between North and Central area of the test system) the controller is able to stabilize the system with reasonable amount of load shedding.

TABLE IV
OUTAGES AND CORRESPONDING LOAD SHEDDING

outage	without controller	with controller (Load shed (MW))
4031-4041	system collapse at t=180.6s	stable, 109
4032-4042	system collapse at t = 526.9s	stable, 62
4041-4044	system collapse at t = 238.6 s	stable, 97
g6	system collapse at t = 92.5 s	stable, 260

A larger load curtailment is, as expected, needed for the system stabilization after generator g6 outage (it produces 360 MW before the outage) and this power is to be delivered by other generators (impacting reactive power limits) including the ones in North part of the system.

B. Smooth load increase

In this case, the loads on buses 1041, 1042, 1043, 1044 and 1045 are increased linearly at the rate of 7.2 MW/min until the system reaches voltage collapse point at $t = 513s$.

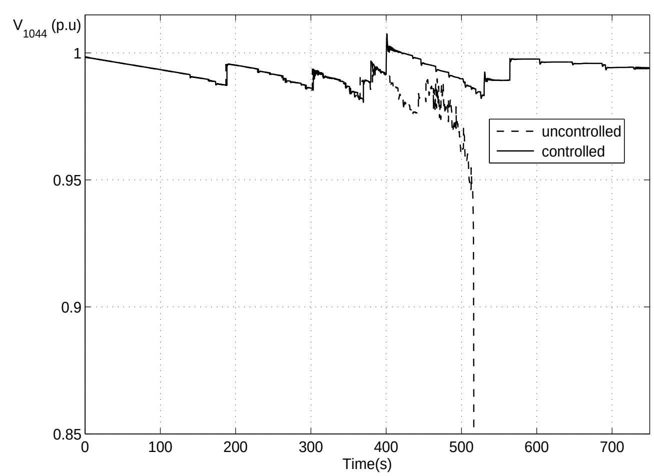

Fig. 4. Voltage at bus 1044 in case of smooth load increase

Upon the activation of the controller, the system is stabilized after $t = 600s$ settling to a new long-term equilibrium point. Figure 4 shows the evolution of voltage at bus 1044 (controlled and uncontrolled). The controller issues the modifications in generator voltage set points and load shedding starting at $t = 400s$. Total amount of load shedding is $118MW$.

C. Stable but depressed voltages

In this case, the controller is tested for a stable system in which voltages at certain buses say for instance the voltage at bus 1041 is 0.94 p.u which is below the desired range of 0.95 to 1.075 p.u. For this case the initial loads in the Central area of the system are decreased, so that the system is able to re-gain long-term stable equilibrium after being subjected to the outage of the line 4032-4044. Figure 5 shows that the controller corrects voltages with load shedding of 82 MW.

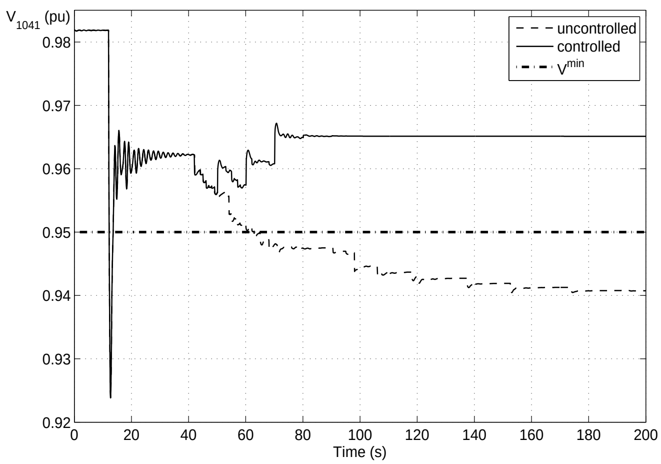

Fig. 5. Correction of low voltage at bus 1041

VII. Robustness of the controller

Robustness of proposed control is partly addressed in a previous section through demonstrating its ability to face and control different system disturbances. In this section it is further demonstrated by exposing it to control failures and tsting performances when the noise is present in measurements.

A. Robustness against control failure

The multi-step controller scheme [7], [8], [12] are known to have inherent fault-tolerance ability to control equipment failures. Outage of the line 4032-4044 is repeated with the control failure of load shedding in bus 1041. (results are shown in Fig. 6). Figure 6 shows the evolution of voltage at bus 1044 with and without the control failure.

As in other multi-step moving-horizon controls, proposed one is able to stabilize the system despite failure of important control (bus 1041 where the failure takes place is in most affected system area) with increased load shedding and the system settling time. Performances of proposed control in this case are much better then with other controllers from the same family as clearly shown through comparisons presented in Table V. Proposed approach is compared with approaches of [12] and [14] for the same control failure.

Better performances shown in Table V are explained by the fact that bias term provides useful feedback in the case of control failure and ensures better re-location of control efforts to other buses. This indicates the bias terms could be useful for design of an fault detection and identification scheme (not only for faults in controls) as a further extension of proposed approach paving the way to a reconfigurable control. This is going to be a part of future research efforts on this problem.

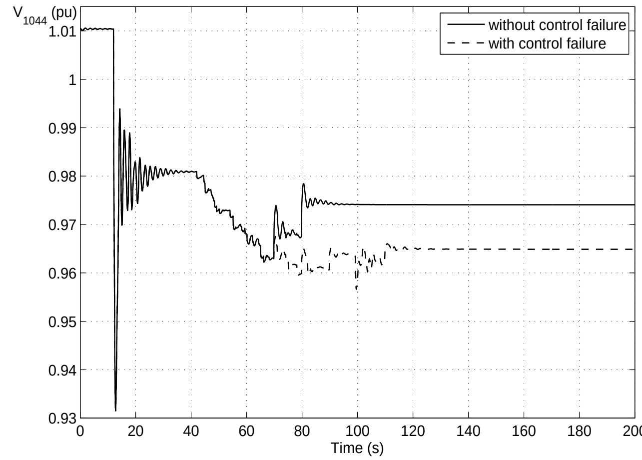

Fig. 6. Voltage at bus 1044 in case of a control failure

TABLE V
COMPARISON WITH CLOSELY RELATED APPROACHES WITH A CONTROL FAILURE

Approach	Total load shedding P(MW)
Reference [12]	126.0
Reference [14]	190.0
Proposed	118.0

B. Robustness against measurement noise

An important observation from [8] is industrial model predictive control applications with a bias term are sensitive to presence of measurement noise. In order to check robustness of proposed approach with respect to measurement noise simulations are run with low random noise and with high random noise (Gaussian distribution $N(0, \sigma)$, with $\sigma = 0.01pu$ for low and $\sigma = 0.04pu$ for high noise).

Results are displayed in Fig. 7. Presence of low noise in measurements does not cause considerable worsening in controller's performances (load shedding is 116 MW, compared to 113 MW without noise). However, high measurement noise worsens controller performances resulting in higher load shedding (122 MW) and longer settling time.

It is strongly recommended to use outputs of state estimator (SE) in proposed approach. Figure 7 also displays results when tracking SE proposed in [28] is used in conjunction with proposed control. Even in presence of high measurement noise, impact on controller's performances when outputs of tracking SE are used is very small (almost same settling time and load shedding 1 MW bigger compared to the case of no measurement noise). An alternative would be to filter measurements (for proposed control a possibility would be to have measurements collected at higher rate and filtered by moving-average filter, known for decreasing the noise, locally before sent to the controller).

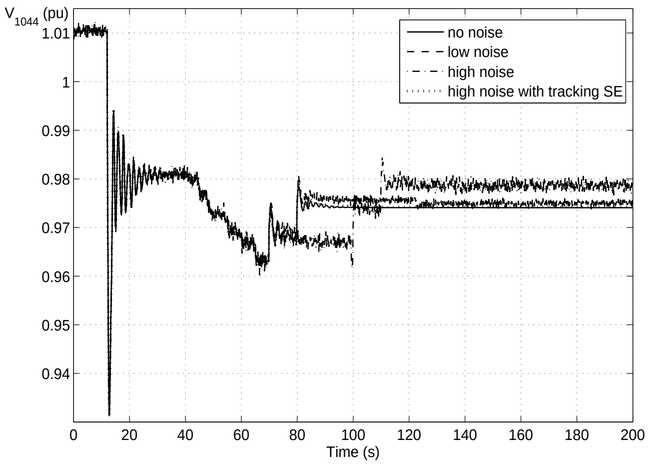

Fig. 7. Impact of measurement noise

VIII. Measurement requirements

The proposed control assumes availability of system bus voltage magnitudes and reactive generation powers at each sampling time (10s used in this work) provided by measurement and communications infrastructure. We suggest that with today's deployment, expected to rise in the future, of phasor measurement units [29] it is reasonable to expect faster system tracking. This faster tracking can be provided either by synchronized phasor measurements only (with linear state estimation) if system observability is ensured by these devices or through a recently proposed efficient combination of limited number of phasor measurements with traditional SCADA measurements [30], [28].

Alternatively, it is possible to use a dedicated measurement configuration covering only some of the system buses and generators. In this case proper locations of measurement devices have to be decided first followed by checking performances of proposed control when limited number of variables is measured. This will be tackled in our future research efforts. However, a general conclusion is the more measurements available the better performances of the controller.

Whatever measurement configuration is in use it has to be supported by adequate communications infrastructure.

IX. Discussions

A. On the computational burdens

The computational burdens are checked for different QP size (in terms of the number of variables and constraints). This is conducted by increasing problem size through the increase of te number of prediction steps (see Table VI).

TABLE VI
Time to solve QP of different size

Nb. of prediction steps	QP size (Nb. variable/Nb. constraints)	Time (ms)
3	297/672	10
10	791/1256	77
20	1510/2176	475

Times given in Table VI correspond to the times needed for the solution of te optimization problem once called by GAMS. Clearly, even for larger problem sizes, times to solve QP optimization problem 3 by IPOPT bring negligible time to a control cycle and thus compatible with real-time requirements.

B. On the closed-loop system stability

Terminal constraints in 3 do not ensure closed-loop system stability since they are imposed only on a subset of system state variables. The choice of this work, with respect to the stability issue, is to be in between industrial applications of MPC [8] where the theoretical frameworks on stability guarantees are usually not implemented and *a posteriori* certification of feasibility considered in [31] (motivated by [32]).

Stability of proposed approach is checked by running simulations for all critical contingencies in the system (outages analyzed in previous sections are known as critical ones for used test system) and no unstable closed-loop system responses are observed. This is a sort of a pragmatic *a posteriori* "certification". Alternatives, to be tested in the future work, would be to use proposed control together with SE of [30], [28] that computes full system state and then to provide a sort of more elaborated feasibility certificate [31] and the use of longer prediction horizons (as suggested in QDMC [17]) with efficient QP solvers (high performances of used QP solver shown in Table VI indicate efficient solving of larger dimension problems).

C. On possible future considerations and extensions

In addition to already mentioned points that will constitute parts of future research, the following considerations/extensions are envisioned:

- extension with other control means (shunt capacitors, FACTS devices, etc.),
- testing proposed method in presence of uncertainties (in both generation and loads) in the framework of chance-constrained programming [33],
- further improvements of the method in terms of exploiting block-diagonal structure of the problem (as in [23]),
- extensions to other voltage-related problems (fault induced delayed voltage recovery and short-term voltage instability) [1], and
- further study of the impact of communication delays, and
- an extension with fault detection and identification scheme leading toward a reconfigurable control.

X. Conclusion

Voltage control is of vital importance for smooth and reliable operations of power systems. In this paper, a multi-step receding-horizon optimization problem approach rooted in the concept of QDMC with linear system model (using analytically computed sensitivities and simple bias term acting as a modelling error corrector) was formulated to correct and control the voltage violations.

The effectiveness of proposed controller was tested on Nordic32 test system for various contingency scenarios. Comparisons were made with the non-bias controllers, limited sensitivities, as well as existing closely related approaches showing advantages of proposed control.

Based on the results, presented in this paper, proposed controller offers the following advantages:

- decreased control efforts and settling time when the system is subjected to disturbances,
- efficient solution of optimization problem (QP), and
- increased fault-tolerance with respect to control failures.

These advantages qualify proposed approach as a viable control scheme for real-time voltage control. Technological solutions, in terms of measurements and communication infrastructure, exist or are expected to be available in near future for real life implementation of proposed approach.

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