Re-thinking Var Planning to Mitigate Reactive Power Reserves Scarcity During the Energy Transition

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Abstract

The progressive replacement of conventional fossil-fueled power plants by renewable energy sources (RES) during the energy transition to renewable-dominated power supply leads to reactive power reserves (RPRs) scarcity, compromising thereby power systems security. This paper envisages the next step after having identified RPRs' scarcity with a methodology proposed previously by the authors. This paper re-thinks reactive power (or var) planning in the new context of mitigating RPRs' scarcity. Specifically, the paper proposes a new methodology and problem formulation of var planning that includes as main novelties: consideration of scenarios modeling RES uncertainty, temporal aspects (e.g. 24 hours operation profiles), accurate reactive power capability model for wind power plant (WPP) collection system, the precise modeling of the conventional generators' reactive power capability curves, and the joint consideration of both dynamic and static reactive power assets. The proposed var planning problem is formulated as a multi-period stochastic security-constrained optimal power flow (SCOPF), which seeks to minimize the investment cost in new reactive power assets while meeting power system constraints under various operating conditions. The value of the proposed methodology is briefly exemplified using a 60-nodes model of the Nordic32 system.

Nomenclature

Indices/Sets

$t \in \mathcal{T}$	Time period
r/c/f	Type of new reactive power device: reactor (r), capacitor (c), FACTS (f)
g	Generator
$k \in \mathcal{K}$	System configuration: normal operation ($k = 0$) or after a contingency ($k \geq 1$)
$s \in \mathcal{S}$	Uncertainty scenario

Parameters

$c_{\text{r/c/f}}$	Reactor, capacitor and FACTS devices' investment cost coefficients
$I_{\text{g}}^{\max}$	Maximum stator current of the generator
$P_{\text{d}}^{t,s,k}, Q_{\text{d}}^{t,s,k}$	Active and reactive power demand in time t, scenario s, and state k
$P_{\text{PV}}^{t,s}$	Solar active power generation at nodes
$P_{\text{WPP}}^{t,s}$	Active power generation of WPPs at nodes
$V_{\text{f}}^{\max}$	Maximum field induced voltage of the generator
V_{MV}	Medium voltage side of the WPP transformer
X_{g}	Synchronous reactance of the generator
$\bullet^{\min}/\bullet^{\max}$	Minimal/maximal limits of the associated variables

Variables (in time t, scenario s, and state k)

$(Q_{\text{g}}^{t,s,k})^{\max}$	Maximum generators' reactive power at nodes
$\theta^{t,s,k}$	Bus voltage angle at nodes
I_{C}	Current magnitude of grid side converter
$P_{\text{g}}^{t,s,k}, Q_{\text{g}}^{t,s,k}$	Active and reactive power generation of generators at nodes
$P_{\text{inj}}^{t,s,k}, Q_{\text{inj}}^{t,s,k}$	Active and reactive power injections at nodes
$Q_{\text{r/c/f}}^{\max}$	Maximum capacity of potential reactive power devices (reactor/capacitor/FACTS) at nodes
$Q_{\text{r/c/f}}^{t,s,k}$	Reactive power dispatch of the potential var sources (reactor/capacitor/FACTS devices) at nodes
$Q_{\text{sh}}^{t,s,k}$	Reactive power dispatch of the existing var sources at nodes
$Q_{\text{WPP}}^{t,s,k}$	Reactive power generation of WPPs at nodes
$r^{t,s,k}$	Ratio of the controllable transformer
$S_{\text{f}\rightarrow\text{t/t}\rightarrow\text{f}}^{t,s,k}$	Apparent power flow in a line (from $\rightarrow$ to/to $\rightarrow$ from)
$U_{\text{r}}/U_{\text{c}}/U_{\text{f}}$	Binary variables modeling the installation (if $U_{\text{r/c/f}} = 1$) of reactor/capacitor/FACTS devices
$V^{t,s,k}$	Bus voltage magnitude at nodes
V_{C}	Voltage magnitude of grid side converter

1 Introduction

Traditionally, the main target of reactive power (or var) planning has focused on determining new required investments in reactive power compensation sources on the pre-estimated locations to avoid voltage issues and thereby secure the operation of transmission grids [1].

Today, there are growing concerns regarding climate change, prices, scarcity increase of fossil-fuel-based sources, and energy supply adequacy are leading to a broad and deep integration of renewable energy sources (RES) into power systems. In response to this shift toward a rapid energy transition away from fossil fuels, utilities have to continue maintaining grid security in the face of new threats. In particular, lacking to enhance reactive power assets when fossil-fueled generators are phased out may cause a lack and/or excess of reactive power in the system, undermining its security [2]. Hence, to mitigate such threats, during the energy transition, system operators should adopt a holistic approach to coordinated var planning while taking full advantage of system var capabilities.

There have been substantial efforts to address the var planning problem, which can be classified into two categories [3]: (i) only normal-state-based var planning and (ii) also contingency-state-based var planning. Furthermore, another key difference in the classification of the proposed models is that power flow constraints in contingency states can be carried out in two modes, *preventive* or *corrective*. To solve these models, which differ in terms of objective and constraints, many solution techniques, with diverse mathematical and computational characteristics, have been proposed [4]-[6]. However, the majority of the literature on var planning addresses only deterministic models without considering the stochastic behaviour of RES and less-detailed modeling of available var sources.

The earliest methods of var planning have largely used linearization [4] due to the key advantages such as reliable performance, accommodation of a large variety of power system operating limits, and ability to identify infeasibilities. However, they present very limited accuracy and cannot generally compute exact solutions, in contrast to the non-linear power system models. Then, techniques such as successive quadratic programming [5] and Newton's method [6], which require the computation of the second-order partial derivatives of the power-flow equations and other constraints, have been explored. Next, some techniques like Benders decomposition and branch and bound were proposed for handling the integer variables. Furthermore, a more recent vein in var planning problems uses intelligence-search-based methods, which are simple to implement but, as heuristics, do not have a mathematical guarantee. Finally, the review paper [7] systematically surveys suggested models and techniques for solving var planning until 2007.

Most of the previously mentioned works have focused on different problem models but in a deterministic way. Furthermore, none of them has evaluated the reactive power reserves during the energy transition to identify the occurrence of RPRs scarcity as a basis to determine key aspects of var planning problem such as the timing and location of new reactive power sources as well as a multi-period stochastic framework. In [8], the authors have tried to identify the location and size of reactive power sources considering a set of operation uncertainty scenarios and critical contingencies. However, there is no systematic way to spot the location of new var sources.

This paper extends our previous work in [9] by proposing a new methodology to re-think var planning in the new context of mitigating RPRs' scarcity. The main contribution of this work is to design a realistic var planning model aimed to identify the location and timing of installing the new var sources during plausible scenarios of energy transition in a multi-period stochastic AC SCOPF framework. The proposed formulation takes into consideration: (i) a set of different operation scenarios modeling RES uncertainty, (ii) accurate modelling of the WPPs reactive power capability model with the collection system, (iii) the precise modeling of the reactive power limits of the conventional generators, and (iv) joint application of dynamic and static var compensators.

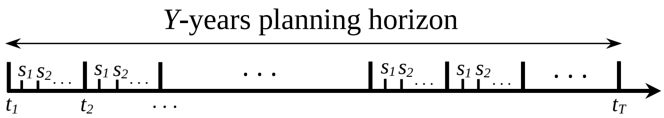

Fig. 1: Y-years planning horizon including T time periods and S scenarios in every time period.

The remaining of the paper is organized as follows. Section 2 presents the proposed tailored AC SCOPF var planning problem. Section 3 provides the numerical results of the proposed methodology. Section 4 concludes.

2 The Proposed Methodology

2.1 Preliminaries

The role of reactive power planning is to deploy appropriate reactive power assets at minimum cost while coordinating them efficiently with existing var sources in order to provide voltage support under both normal system operation and contingency conditions. This need is expressed mathematically in a form of a multi-period multi-scenario preventive/corrective AC SCOPF problem, as detailed hereafter.

The proposed methodology is applied after identifying the occurrence of RPRs scarcity and unsustainable voltage limit violations through the methodology proposed in [9]. The latter methodology can be used in an ingenious way to identify a small subset of effective nodes where var devices may be installed. This is obtained by relaxing voltage limits in the AC SCOPF problem formulation in [9], post-processing the solution and ranking the nodes according to their overall voltage limits violation. Only the nodes highly ranked and exhibiting systematically significant violations over scenarios are selected as potential locations for var devices installation.

Let the ultimate planning horizon be Y years, dividing this time frame into T time periods with S operation scenarios, and K contingencies (see Fig. 1). To model RES uncertainty, we rely on representative hours/days/weeks, based on the practical weather as well as historical data to estimate wind power and solar power production. Specifically, the auto regressive integrated moving average (ARIMA) [10] model is utilized to predict WPP and solar production time-series. To keep the compactness of the formulation, it is worthwhile to mention here that all variables and functions in this paper are presented in vector/matrix form.

2.2 Mathematical Formulation of Var Planning Problem

The var planning problem can be formulated in preventive SCOPF mode as follows. The objective function minimizes the investment cost in new var devices:

$$\min \left[U_{\text{r}}^{T} C_{Q,\text{r}}(Q_{\text{r}}^{\max}) + U_{\text{c}}^{T} C_{Q,\text{c}}(Q_{\text{c}}^{\max}) + U_{\text{f}}^{T} C_{Q,\text{f}}(Q_{\text{f}}^{\max})\right] \quad (1)$$

where the cost of static var devices is assumed proportional with the device size , as (2)–(3). Further, based on vendor data, the cost coefficients of the FACTS devices can be represented by a polynomial function of $Q_{\text{f}}^{\max}$ according to [8, 12], and hence, the total investment cost functions for FACTS devices can be defined as (4).

$$C_{Q,\text{r}}(Q_{\text{r}}^{\max}) = \textbf{diag}(Q_{\text{r}}^{\max})\ c_{0,\text{r}} \quad (2)$$

$$C_{Q,\text{c}}(Q_{\text{c}}^{\max}) = \textbf{diag}(Q_{\text{c}}^{\max})\ c_{0,\text{c}} \quad (3)$$

$$C_{Q,\text{f}}(Q_{\text{f}}^{\max}) = \textbf{diag}(Q_{\text{f}}^{\max})\ c_{0,\text{f}} + \left(\textbf{diag}(Q_{\text{f}}^{\max})\right)^2 c_{1,\text{f}} + \left(\textbf{diag}(Q_{\text{f}}^{\max})\right)^3 c_{2,\text{f}} \quad (4)$$

The problem is subject to the following constraints, which hold $\forall\ (t,\ s,\ k)$, unless stated otherwise.

(a) Nodal power balance constraints:

$$P_{\text{g}}^{t,s,k} + P_{\text{WPP}}^{t,s} + P_{\text{PV}}^{t,s} - P_{\text{d}}^{t,s,k} - P_{\text{inj}}^{t,s,k}(V^{t,s,k}, \theta^{t,s,k}, r^{t,s,k}) = 0 \quad (5)$$

$$Q_{\text{g}}^{t,s,k} + Q_{\text{WPP}}^{t,s,k} + Q_{\text{sh}}^{t,s,k} + Q_{\text{c}}^{t,s,k} - Q_{\text{r}}^{t,s,k} + Q_{\text{f}}^{t,s,k} - Q_{\text{d}}^{t,s,k} - Q_{\text{inj}}^{t,s,k}(V^{t,s,k}, \theta^{t,s,k}, r^{t,s,k}) = 0 \quad (6)$$

(b) Operational constraints:

$$0 \leq Q_{\text{r}}^{t,s,k} \leq \textbf{diag}(Q_{\text{r}}^{\max})U_{\text{r}} \quad (7)$$

$$0 \leq Q_{\text{c}}^{t,s,k} \leq \textbf{diag}(Q_{\text{c}}^{\max})U_{\text{c}} \quad (8)$$

$$-\textbf{diag}(Q_{\text{f}}^{\max})U_{\text{f}} \leq Q_{\text{f}}^{t,s,k} \leq \textbf{diag}(Q_{\text{f}}^{\max})\ U_{\text{f}} \quad (9)$$

$$Q_{\text{sh}}^{\min} \leq Q_{\text{sh}}^{t,s,k} \leq Q_{\text{sh}}^{\max} \quad (10)$$

$$P_{\text{g}}^{\min} \leq P_{\text{g}}^{t,s,k} \leq P_{\text{g}}^{\max} \quad (11)$$

$$Q_{\text{g}}^{\min} \leq Q_{\text{g}}^{t,s,k} \leq (Q_{\text{g}}^{t,s,k})^{\max} \quad (12)$$

$$(Q_{\text{WPP}}^{t,s})^{\min} \leq Q_{\text{WPP}}^{t,s,k} \leq (Q_{\text{WPP}}^{t,s})^{\max} \quad (13)$$

$$S_{\text{f}\to\text{t}}^{t,s,k}, S_{\text{t}\to\text{f}}^{t,s,k} \leq S^{\max} \quad (14)$$

$$r^{\min} \leq r^{t,s,k} \leq r^{\max} \quad (15)$$

$$V^{\min} \leq V^{t,s,k} \leq V^{\max} \quad (16)$$

$$\theta^{t,s,k} = 0, \quad \theta \in \{\text{slack}\} \quad (17)$$

$$U_{\text{r}}, U_{\text{c}}, U_{\text{f}} \in \{0, 1\} \quad (18)$$

$$x^{t,s,k\geq 1} = x^{t,s,k=0}, \quad x \in \{P_{\text{g}\setminus\{\text{slack}\}}, V_{\text{g}}, r, Q_{\text{r/c/f/sh/WPP}}\} \quad (19)$$

In the above formulation, k denotes the system configuration ($k = 0$ refers to the intact configuration and $k \geq 1$ refers to post-contingency k state), and superscript $\bullet^T$ is the transpose of the associated vector. **diag**(.) shows a diagonal square matrix in which off-diagonal entries are zero and the diagonal entries are the same with the associated vector.

The equality constrains (5)–(6) represent the nodal active and reactive power balance considering the impact of new reactive power sources. The limits on the new and existing var sources are defined in (7)–(10). The constraints (11)–(12) ensure that the active and reactive power output of the generators is limited. The constraint (13) imposes limits on the WPPs' reactive power. The constraint (14) limits the apparent power flows of lines. The constraint (15) limits transformers ratio in normal state. Bounds on the voltage of buses are represented by (16). The equation (17) sets the angle phase reference of the slack generator. The constraint (18) stands for the binary variables indicating the potential locations of new var devices; however, to facilitate the solving of this problem, we have taken the methodology described in the Preliminaries section into consideration. Importantly, (19) defines the "preventive mode" stating that generators' active power (except the slack), controlled voltage, ratio of transformers, shunt elements (new and existing) and WPPs' reactive power are state independent.

Also, it is important to mention that the generators are not re-dispatched optimally to reduce the investment cost in var sources but rather they deviate minimally from their optimal dispatch for time periods and scenarios as well as under contingencies. Accordingly, only the slack generator covers the power imbalance after contingencies.

2.3 Realistic Models of Synchronous Generators' Maximum Reactive Power Limits and WPPs Reactive Power

2.3.1 Model of synchronous generators' reactive power limit:

The maximum reactive power limit of the synchronous generators, $(Q_g^{s,t,k})^{\max}$ in (12), can be represented as a function of the maximum rotor voltage, stator current and generator's active power [14, 15]:

$$(Q_{\text{g}}^{t,s,k})^{\max} = \min \left\{ \begin{array}{l} \sqrt{\left(\frac{V_{\text{g}}^{t,s,k} V_{\text{f}}^{\max}}{X\text{g}}\right)^2 - \left(P_{\text{g}}^{t,s,k}\right)^2} - \frac{(V_{\text{g}}^{t,s,k})^2}{X_{\text{g}}}, \\ \sqrt{\left(V_{\text{g}}^{t,s,k} I_{\text{g}}^{\max}\right)^2 - \left(P_{\text{g}}^{t,s,k}\right)^2} \end{array} \right.$$
$$\forall : \{k \in \{0\} \cup \mathcal{K},\ s \in \mathcal{S},\ t \in \mathcal{T}\} \quad (20)$$

Note that constant lower reactive power limit reflects correctly the generator's behavior in under-excitation mode.

2.3.2 Representation of the WPPs Reactive Power Capability:

The model of Type 4 wind turbine (WT) consists of a generator connected to the grid through full scale back-to-back, machine side and grid side converters. It is modelled considering both resistance and reactance in the system [16]. Concerning (13), the upper bound of WTs (in general, WPPs), is not fixed and is modelled as a function of converter loading limits, and the WPP's active power ($P_{\text{WPP}}^{t,s}$) that will be described in detail hereafter.

The equivalent representation of a typical WPP collection system [17] is depicted in Fig. (2), where V_{C} and θ_{C} show

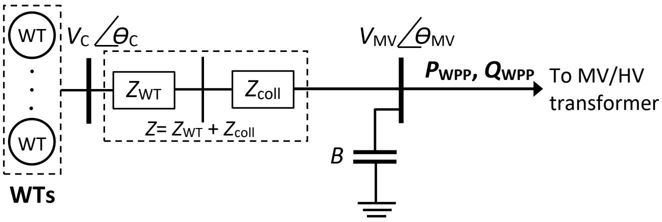

Fig. 2: Equivalent representation of the WPP collection system.

the converter voltage's magnitude and angle, respectively. Voltage and angle of the medium voltage (MV) side of the WPP transformer are represented by V_{MV} and θ_{MV}. $Z = R + jX$ denotes the equivalent combined impedance of WTs (Z_{WT}), and impedance of the WPP collection system (Z_{coll}). Furthermore, B models the equivalent shunt susceptance of WPP collection system.

Th equations for the reactive power capability modeling of WPPs based on the analogy of WT capability with that of synchronous generator are derived from [16], taking into account the aspects discussed in the preceding subsection. Without loss of generality and to fit the active and reactive power outputs of WPPs into the var planning problem, the relation between the active and reactive power of WPPs, given by [16] and using the parameters in Fig. (2) can be formulated as (21)–(24) which apply to $\forall : \{k \in \{0\} \cup \mathcal{K},\ s \in \mathcal{S},\ t \in \mathcal{T}\}$:

$$Q^{t,s,k}_{V,\mathrm{WPP}} = \sqrt{\left(\frac{V_{\mathrm{MV}} V^{t,s,k}_{\mathrm{C}}}{|Z|}\right)^2 - \left(P^{t,s}_{\mathrm{WPP}} + \frac{V^2_{\mathrm{MV}} R}{|Z|^2}\right)^2} - \frac{V^2_{\mathrm{MV}} X}{|Z|^2} \quad (21)$$

The constraint (21) models the WPP reactive power limited by converter voltage ($Q^{t,s,k}_{V,\mathrm{WPP}}$), as a function of active power of the WPP ($P^{t,s}_{\mathrm{WPP}}$), converter voltage, the voltage at MV side of WPP transformer, and the equivalent impedance as well. On the other hand, the WPP reactive power limited by converter current ($Q^{t,s,k}_{I,\mathrm{WPP}}$) relying on the current of grid side converter, ($I^{t,s,k}_{\mathrm{C}}$), as well as active power of WPP can be obtained as (22):

$$Q^{t,s,k}_{I,\mathrm{WPP}} = \pm\sqrt{(V_{\mathrm{MV}} I^{t,s,k}_{\mathrm{C}})^2 - (P^{t,s}_{\mathrm{WPP}})^2} \quad (22)$$

Notice that the positive root in (22) gives the maximum injection capability of WPP, and negative root describes the maximum absorption capability of WPP limited by converter current. Now, to calculate the maximum injection and absorption of reactive power limited by converter voltage in (21), $V^{t,s,k}_{\mathrm{C}}$ is replaced by the maximum $V^{\max}_{\mathrm{C}}$, and minimum $V^{\min}_{\mathrm{C}}$ allowable converter voltage, respectively. For, reactive power limited by current voltage, $I^{t,s,k}_{\mathrm{C}}$ is replaced by $I^{\max}_{\mathrm{C}}$.

In addition, the reactive power injected by cables due to the equivalent WPP collection system susceptance is considerable, thus it is added to the maximum injection and absorption capability obtained at the MV side of the transformer.

Accordingly, knowing the required parameters like the equivalent impedance, aggregated shunt susceptance, voltage at MV side of the WPP transformer, and maximum (minimum) values for voltage and current of converters at a certain operating point, the WPP reactive power capability is the minimum (maximum) of voltage-limited and current-limited reactive power in injection (absorption) mode as follows,

$$(Q^{t,s}_{\mathrm{WPP}})^{\max} = \min\left((Q^{t,s}_{V,\mathrm{WPP}})^{\max}, (Q^{t,s}_{I,\mathrm{WPP}})^{\max}\right) + BV^2_{\mathrm{MV}} \quad (23)$$

$$(Q^{t,s}_{\mathrm{WPP}})^{\min} = \max\left((Q^{t,s}_{V,\mathrm{WPP}})^{\min}, (Q^{t,s}_{I,\mathrm{WPP}})^{\min}\right) + BV^2_{\mathrm{MV}} \quad (24)$$

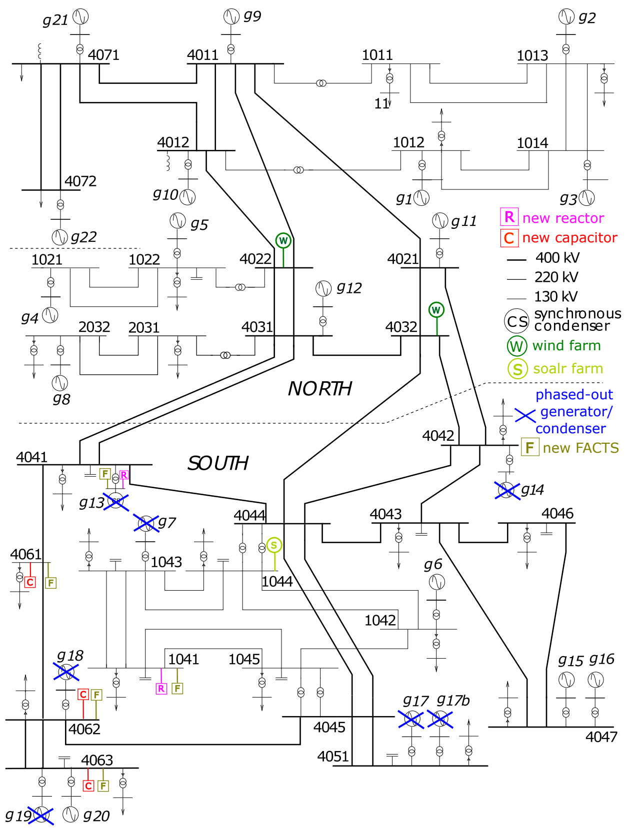

Fig. 3: One-line diagram of the modified Nordic32 system.

3 Numerical Results

To validate the proposed methodology, this section showcases four case studies on the Nordic32 test system [18] for different sets of postulated contingencies. The one-line diagram of this system is shown in Fig. 3. One can be observe that two identical 1000-MW WPP are located at nodes 4022 and 4032 as well as one 500-MW solar PV farm is installed at node 1044 during the assumed energy transition scenario. The necessary parameters for modeling the reactive power capability of the WPPs and Q-limits of the fossil-fuel-based generators are given in Table 1. All simulations are carried out in the open-source Julia/JuMP programming language. IPOPT is used to solve for the var planning problem defined in preventive mode.

The planning analysis starts from the state where RPRs are scarce, obtained after removing generators g17b, g18, g17, g14, g19, g7 and one synchronous condenser at bus g13 [9]. The proposed post-processing technique described in Section 2 uses post-investigation of the buses with voltage limit violations and selects the highly ranked hot spots. This procedure identifies thus the potential best candidate locations at buses 1041 and g13 (for installing reactor/FACTS to absorb reactive power) and at buses 4061, 4062, 4063 and g13 (for deploying capacitors/FACTS to produce reactive power). A linear model for estimating the cost coefficients of the FACTS devices (here

SVC) has been used and required data are adopted from [12] and the cost coefficients of reactors and capacitors are taken from [13].

A 1-year ($Y = 1$) planning horizon considering 24 hours ($T = 24$) operation profiles and 8 scenarios ($S = 8$) forecasted by ARIMA model for generating realistic WPP and solar power production scenarios, have been assumed. However, we consider this a case-dependent horizon, and addressing new var resource planning can be easily considered after a big change/mutation in the grid network for e.g after phasing out of any other fossil-fueled-based generators.

Table 1: Parameters used for modeling the WPPs reactive power capability and Q-limits of the conventional generators.

parameter	value (p.u.)
$I_{\mathrm{C}}^{\max}$	1.25
$V_{\mathrm{C}}^{\max}$	1.1
$V_{\mathrm{C}}^{\min}$	0.8
V_{MV}	1.0
R	0.0114
X	0.0096
B	0.021
$I_{\mathrm{g}}^{\max}$	[21]
$V_{\mathrm{f}}^{\max}$	[21]
X_{g}	[21]

For benchmarking purposes, four different test cases have been performed as presented in Table 2. **Case 1** considers 13 single generation contingencies while 33 $(N-1)$ line contingencies has been assumed in **Case 2**. Furthermore, the contingencies in **Case 3** constitutes the outage of 13 single generators together with 33 $(N-1)$ single line contingency set. To facilitate the comprehension of RES impact, **Case 4** gives the estimated investment total cost and per assets for further penetration of RES i.e., deploying another WPP at bus 4051 with 500 MW capacity. This means that WPPs can provide more reactive power and supports the transmission system operator to maintain security.

One can observe that, expectedly, the larger the number of contingencies, the larger the amount of investment cost. In particular, considering overall 46 contingencies requires 97.86% larger investment cost than 13 $(N-1)$ conventional generators outages with 0.3648 \$M. In all cases, there is a trade-off between the cost and provided reactive power, which is a matter of both security and efficiency. More to the point, despite charging capacitors with more var production, however, the main cost of the investment is for SVC. This is of course attributable to the fact that the FACTS devices are not comparable in cost with the static var compensators.

Another important outcome of the proposed methodology is the interpretation of **Case 4**. Indeed, not only does the dominance of clean energy sources causes lower investment costs substantially but also the falling year-on-year cost of these sources can reduce the costs even more. Obviously, another different sequence of decommissioned synchronous generators/condensers leads to distinct investment costs, and hence selecting the best sequence is of importance.

4 Conclusion

The paper has revisited the fundamental problem of var planning in the new context of mitigating RPRs' scarcity. The proposed methodology goes beyond the existing SCOPF problem formulations by taking into account: (i) RES' uncertainty, (ii) temporal aspects, (iii) precise reactive power capability modeling for WPPs based on the aggregated wind power collection system, (iv) proper modeling of the conventional synchronous generators' capability curves, and (v) the joint application of both dynamic and static reactive power services.

The proposed extended SCOPF framework determines the optimum location and size of the new var sources, allowing the system to withstand generator and line contingencies. This is an extremely complex non-convex mixed integer non-linear programming problem. To circumvent the presence of binary variables and relieve the combinatorial burden, a realistic prioritization of the potential var installation nodes has been adopted by post-processing the output of the methodology in [9].

The results obtained on the 60-bus Nordic32 system show that the proposed methodology is able to provide a realistic var plan during the ongoing energy transition. This informs the system operators on the location, size, and usage of new var sources to maintain security in different operating conditions. More precisely, the proposed planning methodology can serve as a realistic tool for long-term grid planners to identify, at different stages and time resolutions, the location and timing of installing new var sources taking into account: different plausible sequences of conventional generators to phase out, high shares of variable renewable generation, and the joint operation of static and dynamic var sources.

Future work is planned to develop a scalable solution algorithm for the proposed var planning problem formulation.

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Table 2: Nordic32 system results for different cases.

Case	number of contingencies	capacitor location	reactor location	SVC location	objective value (M $)	investment on capacitor (M $)	investment on reactor (M $)	investment on SVC (M $)	total WPPs capacity (MW)
Case 1	13 (generator)	4063	–	–	0.3648	0.3648	–		2000
Case 2	33 (line)	4062 4063	g13	1041	13.5681	2.6939	0.4468	10.4273	2000
Case 3	33+13 (line+generator)	4062 4063	g13	1041	17.0249	4.7767	1.1605	11.0876	2000
Case 4	33 (line)	4062 4063	g13	1041	7.8629	2.3947	0.6326	4.8356	2500

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