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Var Planning Assessment in a meshed AC/DC System: The future Irish Transmission System

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Abstract

The importance of wind power generation has risen in the last years so much as to be considered among the most important and affordable Renewable Energy Sources (RES) with a growing rate faster than other technologies. Nowadays, wind technology is looking at offshore installations, due to the both lack of land resources and environmentalist opposition. This requires new criteria to set out the appropriate architecture for future offshore grids, in terms of topology, technology and control structures. This paper describes a var planning methodology aiming at identifying reactive needs for future mixed meshed AC/DC system.

I. Introduction

The 2020 EU Target for carbon emissions, as well as new ambitious national targets to de-carbonize most of the electric industry by 2030 and beyond, have driven attention to a Transmission Grid capable of coping with the new generation technologies, in particular RES-based.
Onshore Wind and Solar, after a decade of development driven by ad hoc incentive policies, are rapidly evolving towards the Grid parity in many European countries. There are other technologies that may also offer promising future large scale potential which are at the R&D phase namely, offshore wind, wave, and tidal. However, they are all mostly located in remote marine areas and need to be connected to the main grid by means of undersea cables.
In Europe, efforts have been made to provide connection in a framework of a pan-European grid which may facilitate not only the RES deployment but also further integration between countries. In particular, many studies have focused on the development of a grid able to exploit the potential synergies between connecting resources and enhancing interconnection, which will increase grid utilization [1][2].
Because of the peculiarities of RES, it is also of paramount importance to carry out technology selection for their grid connection to the transmission system. In fact, traditional transmission technology, i.e. overhead line (OHL) based, may not be acceptable or even technically infeasible. Onshore, environmental sensitivity has made the conventional OHL solutions in many instances not viable. Furthermore, when dealing with offshore connections, AC and HVDC submarine cables are the only possible choice.
Recent advances have provided transmission planners with new alternatives to offset part of the increased capital cost by improving system performance; in particular, the enhanced control capability of HVDC options or power flow controller devices. These devices may allow for coping with multiple dispatching conditions and RES variability as well as providing ancillary services, i.e. voltage control and reactive power, synthetic inertia, etc., which will be necessary to manage the increasing penetration of RES [3-5].
This paper presents a reactive planning methodology able to deal with the most important security issues in a mixed AC/DC system: in particular, the reactive planning is carried out to minimize an economic function and taking into account the (N-1) security and voltage collapse margin constraints. The results of the proposed procedure are shown with reference to a test system.
The paper is organized as follows: Section II provides a brief review of the Reactive Power Planning (RPP) problem, while Section III describes the proposed mathematical algorithm for the RPP. Section IV presents the results obtained by the application of the model to a test system and Sections V describes some application to Irish Transmission System (ITS) and the related results. Finally, Section VI provides the conclusions.

II. The Reactive Problem

The purpose of the Reactive Power Planning is to provide the system with sufficient var resources so that it can operate in an economic and secure condition while all operational constraints are met. The Objective Function (OF) can include various terms, such as the real losses or the investment costs for the reactive resource allocation. Different formulations and solution algorithms have been introduced [6][7]. A common characteristic of many of these methods is that not all issues related to security (contingencies voltage collapse, capability of generators) are considered at the same time.

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Basically, the RPP has always been considered for traditional AC Transmission Systems based on OHLs and cables. However today, new transmission technologies (i.e. VSC (Voltage Source Converter), CSC (Current Source Converter), submarine cables, etc.) are available and become a structural part of future transmission assets.
With this in mind, it is of paramount importance to provide the system with the suitable reactive resources and grid expansion [8-12] to withstand future generation deployment and to exploit all available technical facilities.

III. Mathematical algorithm for RPP

The RPP analysis described in the paper is divided into two parts:

- Var PLanning Assessment (VPLA), which identifies the location and the type of installation of var resources needed to minimize costs.
- Voltage security assessment in terms of Voltage Collapse Margin Analysis (VCMA), computed on the VPLA scenarios by introducing a user-defined voltage collapse margin constraint. The module may also integrate VPLA results, with siting and sizing of additional reactive resources, if necessary

A. Var PLanning Assessment (VPLA)

The first step starts from the determination of the expansion planning, which is carried out by mean of a DC PF-based procedure [8]. On the scenario identified by this procedure, the integration [13] of var resources is carried out by means of a complete AC analysis.
The goal of the VPLA is the planning of the var allocation, evaluating the most cost effective and technically viable solutions by an optimization problem characterized by an OF to be minimized:

$$\min OF_{VPLA} \left[\frac{k€}{year}\right]$$

With

$$OF_{VPLA} = IC + OC \qquad (1)$$
$$OC = RC + RUC + EIC + WCC + GSC + LSC$$

Where:

- Investment costs (IC): cost of reactive resources;
- Operational Costs are made by several components:
  - Re-dispatching Costs (RC): costs of the generation redispatching compared to the DC PF-based solution above mentioned above;
  - Reactive usage costs (RUC): costs of the reactive power (e.g., if a reactive power market is in place).

In addition, because of possible convergence difficulties of the optimization procedure, some “penalty terms” are added in OC in order to find, in such cases, a numerical solution, although not a technicality feasible solution the constraints to be relaxed by increasing the OF:

- Extra Investment Costs (EIC): costs of the reactive resource further with respect to the maximum resource technically allocable in a total;
- Wind Curtailment Costs (WCC): costs of the wind generation shedding, when necessary;
- Generation Shedding Costs (GSC): costs of the conventional generation shedding, when necessary;
- Load Shedding Costs (LSC): costs of the load shedding, when necessary.

Each of these contributions is assigned a suitable cost, according to the EirGrid experience.
The OF is calculated on a yearly basis and therefore OCs are modeled considering a sufficiently large number of Load/Generation scenario snapshots, which are considered to adequately representative of the yearly system operation.
The OF is subject to equality constraints (e.g. AC and DC power flow equations, AC and DC bus equations, etc.) and inequality constraints (e.g. power transit limit, limits on independent variables, etc.). Tap-changers and phase-shifters are also modeled and considered, which provide a greater operational flexibility.
Moreover, according to EirGrid Transmission Planning Criteria (ETPC) [14][15], the reactive power limit for the generators is no longer identified by the typical PQ capability curve but with the blue area in Fig. 1.

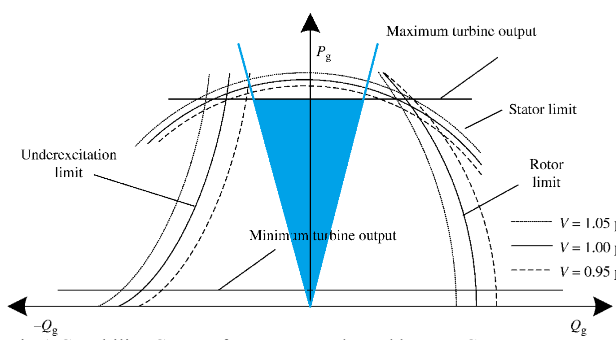

Fig.1 Capability Curve of generators adopted by ETPC.

B. Security assessment

In order to improve the power system security, in addition to the case N (intact grid), the loss of every line or a transformer contingency (N-1) are considered.
Ideally, the single optimization problem that considers the costs, the equations and the constraints for the N case and for all the possible N-1 cases at the same time should be implemented; however, present computational limitations make this problem intractable. Consequently, a sequential problem has been introduced, as shown in Fig. 2. After

the var planning on the intact system, the (N-1) security constraints are accounted for by solving N_{RP} var planning problems, one for each contingency or set of contingencies (called C_k), as described below.
Once the N_{RP} var planning problems have been solved, the final var planning outcome is the result of the envelope (ENV) of all N_{RP} solutions. Finally, the exploitation of these var resources within the considered scenarios is determined by solving an ORPF problem for each scenario and the corresponding yearly cost is determined for comparison.

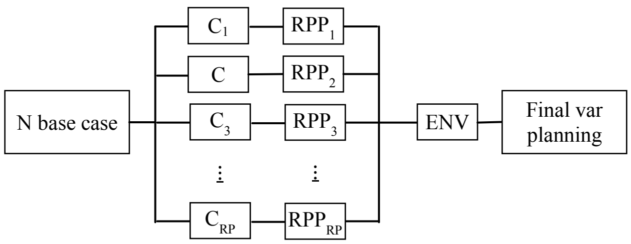

Fig.2 VPLA as a sequential problem

Two different algorithms were adopted to deal efficiently with the (N-1) security constraints, as follows:

a. Single contingency (Fig. 3): is the simplest approach from the computational point of view, it determines the var allocation by carrying out a RPP for each contingency. In this case, each C_k corresponds to a single contingency.

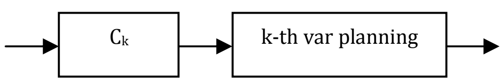

Fig.3 Single contingency method for the (N-1) analysis

b. Grouping method (Fig. 4): this method is a compromise between the method in a) and the ideal general optimization. In fact, the problem is solved taking into account some pre-defined contingency sets, each one holding a limited number of contingencies. If the complete set of contingency is divided into some small contingencies sets, and the (N-1) problem is solved for each of them separately, then the flow chart in Fig. 2 can still be adopted, where C_k is actually a set of contingencies; this results in a var allocation cheaper than for case a. In this case, OCs associated to each contingency is weighted by their own outage rate.

Due to the possible synergies between different contingencies, the "Grouping method" is a trade-off between the full solution (a single large optimization taking into account at the same time the (N-1) constraints, cheap but burdensome) and the "Single contingency" method.

In order to group contingencies, a geographical criterion was adopted, based on EirGrid experience.

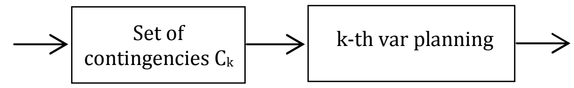

Fig.4 Grouping method for the (N-1) analysis

C. Voltage Collapse Margin Assessment (VCMA)

In the VCMA module, the margin from the voltage collapse guaranteed by VPLA solution is sequentially investigated in order to assess the var planning resulted from the VPLA procedure and, if necessary, to modify it to ensure enough margin against the voltage collapse.
The optimization is carried on by using the "loadability concept", that is the extra load, λ, the system can withstand before reaching the voltage collapse. The increase in the load is assumed to occur at constant load power factor.
Using for an initial solution the reactive resources allocated by VPLA, the objective function is modified as follows:

$$\min OF_{VCMA} = \min(OF_{red} - \lambda_C)\ [k€/year]$$

$$OF_{red} = RC + RUC + EIC + WCC + GSC + LSC \quad (2)$$

where OF_{red} is the same objective function used for the VPLA, not including var resources, i.e. the Investment Cost. Only EIC are considered for any further var allocation. In this case, the maximum amount of additional reactive resources in each bus is assumed to be 500 Mvar.
To let the optimization process increase the load, the "Loadability Cost", λ_C, accounts for a negative contribution in the minimization of (2). Hence, λ_C is:

$$\lambda_C = \sum_{i=1}^{NS} \lambda_{C,i} = \sum_{i=1}^{NS} \left(WS_i \cdot \sum_{j=1}^{N_{bus}} LC \cdot Pd\_extra_{j,i} \right)$$

where:

- i, NS, WS_i represent, respectively, the i-th scenario, the number of scenarios and the time duration (in hours) of the i-th scenario;
- LC [€/MWh] is a suitable value of the security margin cost;
- $Pd\_extra_{j,i}$ [MW] represents the increase of load in bus j in the scenario i;
- N_{bus} is the number of busses in the network model;
- $\lambda_{C,i}$ [k€] is the loadability cost for scenario i and;
- λ_C is the total loadability cost.

The load increment $Pd\_extra_{j,i}$ is computed as follows:

$$Pd\_extra_{j,i} = Pd\_base_{j,i} \cdot \lambda_i$$

where $Pd_{base\,j,i}$ is the original load in bus j in the scenario i, and λ_i is an independent variable in the optimization model. According to the above equation, λ_i is assumed to be different for each scenario and uniform for all the busses.

In VCMA, a minimum value $\lambda_{i,0}$, which is user defined, can be required and a new constraint is introduced:

$$\lambda_i \geq \lambda_{i,0}$$

Compared to VPLA optimization, in this optimization problem the following changes have been assumed to reach the loadability limit for the system:

- lines, converters and transformers capability constraints are relaxed;
- minimum voltage limit of AC busses is relaxed;
- reactive allocation is 'frozen' at VPLA, and;
- minimum loadability $\lambda_{i,0}$ requirement constraints are introduced.

With this procedure, it is possible to:

- identify the weakest bus of the grid (i.e. the one that constrains the loadability process) and the more severe Load/generation snapshot;
- evaluate the loadability guaranteed by the system with a reactive planning;
- stress the VPLA in more severe operating conditions (i.e. taking into account a simultaneous fault regarding a branch and a generating unit) and with a higher load, and;
- install further reactive resources to guarantee the desired margin $\lambda_{i,0}$ from the Voltage collapse.

IV. Test and results

A. The Test System

The procedure has been carried out on the test system depicted in Fig. 5. It is made by 30 busses and is divided into four areas (A, B, C, D) where loads (red squares), converters (dashed circles) and generators (empty circles) are connected through OHLs and/or cables. In area A, a meshed HVDC system is considered, assuming a VSC technology. Area D is interconnected to the neighboring areas, A, C, by means of submarine cables while West and East areas are introduced to model wheeling flows kept fixed for the whole analysis.

Conventional generators considered are shown in Table 1.

As depicted in Table 2, the whole year is represented with five scenarios.

The first two scenarios represent the winter and the summer load peak, characterized by the same amount of total load but differently located on the busses. Scenario 3 identifies the minimum load. Finally, Scenarios 4 and 5 take into account a wheeling flow of 2.000 MW from West to East and from East to West, respectively.

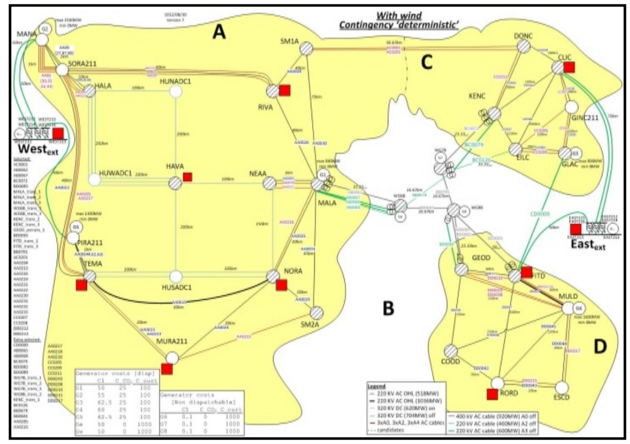

Fig.5 Test grid

Tab.1 Generation installed in each area

Area	Installed Generation [MW]
A	7280
B	0
C	1600
D	3200
West	2020
East	2020
Total	16120

Tab.2 Load and weight for each scenario

Scenario	Weight [h]	Load [MW]
1	1060	10000
2	4700	10000
3	1000	5000
4	1000	9500
5	1000	9500

B. Results of VPLA – intact system

The first step of this problem is the analysis of the intact system (Table 3). The main term of the OF is represented by the Operation Cost. This is due to the DCLF nature of the initial Transmission Expansion Planning, that makes it necessary to re-dispach generators when losses are accounted for; neither generation curtailments nor load shedding are necessary to obtain feasibility.

Tab.3 OF for the N analysis of VPLA

TERMS OF THE O.F.	COSTS [k€]
Operational Cost	208023
Investment Cost	1732
Extra Investment Cost	0
Reactive Use Cost	341
Generation Curtailment Cost	0
Generation Shedding Cost	0
Load Shedding Cost	0
TOTAL COST	**210097**

In Table 4, the reactive allocation (capacitors and reactors) in each area is reported. It is worth noting that in area D several capacitors are located, due to the weakness of this area in terms of available reactive support from the generators.

Tab.4 Reactive allocation per area

AREA	CAP. [Mvar]	IND. [Mvar]
A	1330	-173
B	0	0
C	309	0
D	1529	-123
Total	3168	-296

In Table 5, the behavior of each scenario is considered in the presence of the reactive allocation. Scenario 4 and 5 show different behavior due to the wheeling flows in opposite directions, resulting in different losses.

Tab.5 Real losses for each scenario

SCENARIO	**LOSSES**	
	[%]	[MW]
1	3.9	387
2	3.9	386
3	4.4	220
4	4.8	455
5	2.1	199

C. Results of VPLA – N-1 analysis

Starting from the reactive allocation on the intact system, the impact of the (N-1) analysis on var allocation is investigated by means of the procedures described in Section III.B. Table 6 describes the results obtained by procedures a) and b), in the latter case with 2 and 3 contingencies considered for grouping, respectively.
Increasing the number of contingencies considered at the same time in the same optimization (i.e. group), the total allocation of reactive resources decreases, taking advantage of the sharing of reactive resources to cope with many contingencies at the same time, while limiting the computational resources necessary.

Tab.6 Reactive additional allocation at the end of the N-1 analysis

METHOD	#	ALLOCATION [Mvar]
Single	1	772
Grouping	2	612
	3	512

In Fig. 6, the additional Investment Costs for var resources due to N-1 security constraints are plotted with reference to the cheapest solution associated to Grouping 3 method of table 6. It is worth noting that the Single method is clearly less efficient from the economic point of view.
The last step of the VPLA is the computation of the yearly costs obtained by optimizing the exploitation of installed var resources for each time period.

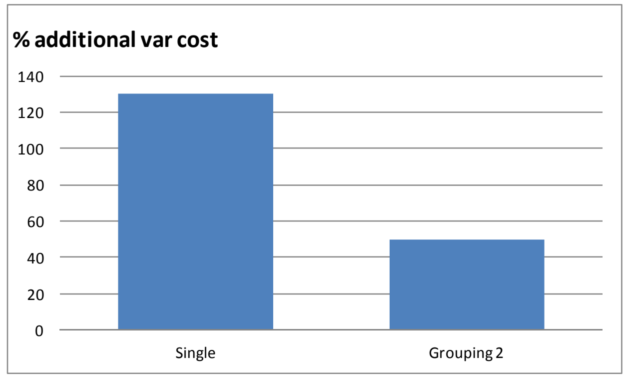

Fig.6 Increase of Investment Costs

Tab.7 Yearly costs for the considered var allocations

	GROUPS OF 1	GROUPS OF 2	GROUPS OF 3
	[k€]	[k€]	[k€]
Investment costs	1970	1890	1840
Operational costs	207882	207906	207921
Reactive use costs	288	312	317
TOTAL COST	**210141**	**210109**	**210078**

In Table 7 the resulting costs are shown according to the scenario assumed.
For this last phase, no further reactive allocation is allowed. Hence, the Investment costs are considered constant and equal to the costs of the envelope provided at the end of the (N-1) analysis. The overall yearly costs slightly benefit from the grouping criteria.
This is mainly due to the reduction in investments in var resources; in fact, the Operational costs increase with the grouping size due to the decrease of reactive resources installed; also, the Reactive use costs increase due to a larger exploitation operationally of the reactive resources already available in the grid (i.e. generators and VSCs).

D. Results of the VCMA Analysis

A first test is carried out to determine the minimum loadability that can be guaranteed by the var planning resulting from the VPLA.
Table 8 groups the loadability results both for the intact system and considering contingencies (including generator contingencies). For the intact system, the results were obtained by solving problem (2). It is worth noting that the value of λ_i, expressed in percentage of the initial load, is very high, although no extra var resources are installed. No extra var resources are necessary also in N-1 conditions, because the loadability obtained by the VPLA is still sufficient (in table 8 DD0042 represents the contingency with the lowest collapse margin).

Tab.8 Loadability values

λ_i [%]					
Contingency	Scenario				
	1	2	3	4	5
None	81.3	81.2	176.4	101.8	121.9
DD0042	49.2	49.2	122.5	74.1	79.5
G4_DD0047	27.6	27.6	96.4	35.8	61.9
G4_AA0031	42.3	42.3	124.9	36.5	94.7

In order to access that the procedure works correctly, more stressed conditions, i.e., N-2 conditions, have been investigated, and in particular, the simultaneous fault of a generator and a branch. According to this analysis, it can be seen that case G4_DD0047 (generator G4 and line DD0047) is the closest to the voltage collapse. In this case, the only generator in area D (G4) and the line that connects the two loads of the same area (DD0047) are set out of service. Hence, in the first two scenarios, the loadability is 27.6%. In scenario 2, in particular, as shown in Table 9, the bus mostly affected by low voltage is RORD211, located in area D, the same as generator G4.
For example, case G4_AA0031 is less critical, as the line contingency considered is in area A, where generators and VSCs are installed and can provide suitable voltage support.

Tab.9 Voltage profile in case G4_DD0047 [p.u.]

Bus	Area	1	2	3	4	5
RORD211	D	0.77	0.77	0.77	0.79	0.76
ESCD211	D	0.84	0.84	0.83	0.85	0.83
COOD211	D	0.92	0.92	0.93	0.86	0.95
SM2A211	A	0.98	0.98	0.99	0.93	1.00
GLAC211	C	1.05	1.05	1.05	1.05	1.05

It is assumed from the results that the minimum loadability occurs for contingency G4_DD0047, and further analyses are focused on this double contingency.
After the first step (voltage security assessment), a constraint on the minimum safety margin from the voltage collapse is introduced to identify further var planning allocation that could be necessary. This is performed by introducing a constraint on the minimum loadability value $\lambda_{i,0}$.
In order to show the properties of the procedure, a minimum loadability of 50% is assumed in the solution of problem (2). The results are summarized in Table 10 which shows that the solution calculated makes it possible to reach, for each scenario, the expected loadability of at least 50%. In particular, the maximum amount of reactive resources allocable to each bus, 500 Mvar, is installed in the weakest bus of the system, RORD211 and 117 Mvar are allocated to bus ESCD211, the closest bus to RORD211. Of course, as a consequence, the OF increases significantly. However, thanks to the additional reactive support, scenarios 3 and 5 increase significantly their loadability.

Tab.10 Results for the margin to voltage collapse constraint

Contingency G4_DD0047		
Scenario	No λ_{i0} min	$\Lambda_{i0}\geq 50\%$
	Loadability [%]	
1	27.61	50.00
2	27.59	50.00
3	96.39	126.51
4	35.75	50.00
5	61.99	91.79
OF [k€]	**530133.2**	**1367494.2**

At the end of the complete security analysis (for N-2 condition taking into account all combinations of a single line and a single generating unit fault), an envelope of the new reactive resources required is performed. The weakness of area D is further demonstrated by Table 11. When a minimum loadability of 50% is required, about 77% of the total var resources of the system are located in this area.

Tab.11 Final additional reactive allocation in each area

Additional var allocation [Mvar]	
Area	$\Lambda_{i0}\geq 50\%$
A	341.4
C	0
D	1124.9
Total	1466.4

Assuming the system in N conditions and with the var planning summarized in the table 11, the problem (2) is solved to compute the maximum voltage collapse margin. The Table 12 shows the loadability margin for each scenario and the voltage in bus RORD211 before the collapse.

Tab.12 Loadability and voltage in N conditions with the new var planning

Scen.	VPLA+VCMA ($\lambda \geq 50\%$)	
	λ [%]	RORD211 V [pu]
1	111.16	0.82
2	111.11	0.96
3	224.85	0.79
4	130.56	0.91
5	165.05	0.79

V. The 2015 Irish Grid

The Irish Transmission System (ITS) is an interesting case study to develop future Transmission development strategy for Power System Planning and Operation and is a good test of the previous optimization tool. The system is limited with two radial interconnectors with Scotland and Wales.
The 2020 Irish Strategy is very aggressive with targets accounted for 40% of energy produced by RES by 2020. Indeed, wind conditions facilitate the goal with an average loading factor at present above 31% which

increases from the eastern side of the country to 37-40% close to the western coast.

Fig.7. 2015 ITS solution

EirGrid, the Independent System Operator has launched three rounds of generation connections in 2007-8-9 which has accumulated 5000 MW of generators in the process of being grid connected onshore for Republic of Ireland. In Northern Ireland a similar process has accumulated c.2000 MW. In 2008, a long-term grid development program was launched to allow this deployment strategy. At present, about 2100 MW have been connected, resulting in a 17% overall energy from RES, [8].
However, as the wind penetration is becoming higher, often and often curtailments is increased because of technical constraints, when wind power production exceeds 50% of the consumption.
In the future to facilitate up to and in excess of 75% further interconnectors together with storage devices and the implementation of more advanced generation control systems may be required. Consequently further development offshore with grid developments towards UK and France using mainly HVDC technologies can be expected.
There is evidence in ITS that more system ancillary services will be required in the future to handle the high wind penetration and variability.
However, the development of controlled Transmission Technologies, i.e. Power Flow controllers, HVDCs, in addition to the duty of connecting wind farms, interconnecting countries and allowing RES exploitation, may have the capability to provide them.
Therefore, the techno-economic analysis becomes of an increasing complexity, with extensive coordination control to make use of Technology flexibility and increase system performances. EirGrid is working towards the development of a Smarter Transmission Grid concept which is aiming at reducing the impact infrastructure investments in the Electricity industry.
The AC OPF optimization tool is applied to the ITS Expansion solution of 2015 as it results from the study carried out in [8], see fig. 7.
A sensitivity analysis is carried out by using three different var investment costs (i.e. 50, 500, 1000 k€/Mvar).
The multiscenario analysis is carried on considering only the N conditions of the VPLA procedure.
General Results are shown in Table 13 for the each var investment cost.

Tab.13 Comparison between the OFs of the test and the planned Irish Grids [k€/y]

	Var investment cost [k€/Mvar]		
	1000	500	50
Operational Cost	668183.1	574464.5	521271.0
Investment Cost	252139.8	194949.9	111239.2
Extra Investment Cost	0	0	0
Reactive use Cost	2806.1	2710.1	2411.9
Generation curtailment Cost	0	0	0
Generation shedding Cost	0	0	0
Load shedding Cost	0	0	0
Total Cost	**923129.0**	**771821.5**	**634922.1**

Table 14 demonstrates the losses that belong to the typical range of transmission systems.

Tab.14 Losses for the ITS

Scenario	Losses [%]		
	Var investment cost [k€/Mvar]		
	1000	500	50
1	3.58	3.56	3.60
2	3.81	3.84	3.95
3	3.98	3.95	4.27
4	3.15	3.25	3.38
5	3.21	3.35	3.59

Finally, in Table 15, a focus on installed reactive power devices.

Tab.15 Reactive allocation in the ITS

Reactive allocation [Mvar]			
	Var investment cost [k€/Mvar]		
	1000	500	50
Capacitive	2760	3920	22060
Inductive	1900	3020	16740
Total	4660	6940	38800

It is noteworthy that only for a very high cost of reactive capital investment that the results are in line with the present var resources installed in the ITS (about 3000 Mvar). This confirms that the planning criteria dictating the installed var at present is based only on technical considerations to overcome extreme scenarios, where vars are essential whatever be the cost; however the techno-economic analysis suggests that a different approach, may improve system performances in term of power system efficiency which offsets the additional vars investment costs, see tab.13.

VI. Conclusions

The paper describes a long term var planning methodology, based on an optimisation of the overall operation cost of reactive power provision and reactive support investments costs.

The tool has been developed to the purpose of providing the planner a techno-economic criterion to investigate future voltage support needs in the presence of an expected large variety of new technologies which in themselves may provide or consume reactive power. The analysis method is performed in two subsequent stages, VPLA and VCMA.

The VPLA stage is performed based on N and the most likely N-1 contingencies. Single, as well as grouping contingencies analysis, can be managed. Results show that contingencies grouping may provide a more efficient reactive support allocation, as well as a least cost solution. The subsequent VCMA stage is aiming at assessing the suitability of VPLA RPP solution under more severe conditions. VCMA can also be used to investigate the scale and location of additional var resources in order to fulfill a pre-defined minimum voltage collapse safety margin requirement.

A test system has been used for the analysis and preliminary findings have been shown for the Ireland transmission system. The analysis suggests that reactive power resources may be installed not only to overcome extreme system conditions, but also that they are economically justifiable to increase power system efficiency.

Results of this ORPF-based methodology implicitly assume the capability of TSOs to handle the control variables altogether. Therefore, this coordination of controls may constitute the real challenge for the future development of a smarter Transmission System.

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