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A METHOD FOR ENHANCING POWER SYSTEM'S STEADY-STATE VOLTAGE STABILITY LEVEL BY CONSIDERING ACTIVE POWER OPTIMAL DISPATCH WITH LINEAR GRID MODELS

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Abstract: In this study I propose an optimisation approach towards enhancing power systems' voltage stability level which links reactive power redispatch of existing generating units with adding new reactive power compensators to the system. For voltage stability assessment, two methods were used: *Continuation Power Flow* and *Modal Analysis*. The main target was to link voltage stability enhancement module with active power dispatch via optimisation problems with linear grid models, such as DC-OPF. Thanks to such an approach, the method can be implemented by operators that solve similar problems in their Market Management Systems (MMS). For testing purposes the method was implemented using MATLAB with MATPOWER. LP/QP optimisation problems were coded in CVX 2.0 and solved with MOSEK 8.0. The approach was tested on 30-bus IEEE 30 and 200-bus Illinois 200 test systems.

Keywords: Voltage Stability, Optimal Power Flow, Optimisation, Market Management Systems.

1. INTRODUCTION

As electric power systems are becoming more and more loaded, they are more prone to blackouts due to losing voltage stability as the loading increases. Many studies have already been conducted in the field of voltage stability. Some approaches towards its assessment were given in [1, 2, 3]. However, it is important to consider all technical limits of generation while assessing the level of stability [4]. In [5] authors addressed enhancement of voltage stability level by optimal redispatch of reactive power generation[1]. In [6] they however tried to maximise the distance between current network solution and the point of voltage instability. These works studied system's behaviour only when active generation is dispatched using nonlinear, nonconvex problems which can cause convergence problems.

In this study I present an optimisation approach for mid-term investment planning, allowing TSO to enhance the level of voltage stability, when active power flow is planned with the help of a simplified DC-OPF network model. The method is based on the algorithm proposed in [7]. For so-aligned active power operating points, it commences voltage stability enhancement actions through management of reactive power generation and investment. Optimality and convergence of the cost-impacting result is guaranteed, as an LP/QP convex problem is being solved.

2. VOLTAGE STABILITY ASSESSMENT METHODS

In this work *Continuation Power Flow* and *Modal Analysis* are used. The first one returns the exact distance between current network solution and voltage instability. The second, gives information on the mechanism of possible loss of system's voltage stability. In this section the methods will be briefly introduced.

2.1. Continuation Power Flow (CPF)

This method was first proposed in [1]. CPF's goal is to recreate the voltage change curve as a function of increasing active or reactive load of the system. In its classic version, CPF uses a predictor-corrector method with tangent predictor corrected with Newton-Raphson method. A slightly different formulation was proposed in [8] and is used in this paper. It assumes the increase of the load from the current network state to a pre-defined target one.

Let $\boldsymbol{P}_b^{in}$ be the vector of overall active power base case injection as and, by analogy, $\boldsymbol{Q}_b^{in}$ reactive power injection. Overall injections in the target case are denoted by $\boldsymbol{P}_t^{in}$, $\boldsymbol{Q}_t^{in}$ and $\boldsymbol{P}(\boldsymbol{x})$, $\boldsymbol{Q}(\boldsymbol{x})$ are power injections at any given state $\boldsymbol{x}$. Let also λ be system's scalar loading parameter providing information by how much it is possible to stress the system until no feasible network solution can be found. Expressing the above mathematically

$$\begin{aligned} &\boldsymbol{P}(\boldsymbol{x}) - \boldsymbol{P}_b^{in} - \lambda\left(\boldsymbol{P}_t^{in} - \boldsymbol{P}_b^{in}\right) = 0 \\ &\boldsymbol{Q}(\boldsymbol{x}) - \boldsymbol{Q}_b^{in} - \lambda\left(\boldsymbol{Q}_t^{in} - \boldsymbol{Q}_b^{in}\right) = 0. \end{aligned} \tag{1}$$

Set of equations (1) is solved numerically in iterations. In the point of instability (bifurcation point), λ reaches its maximum value denoted as λ_{crit} and starts deceasing. Its value can be seen as system's maximum loadability. However, it is unitless and thus uncomparable when the overall target injections are changed, e.g. when new units are added to the system. To overcome this issue, let us denote the Stability Margin (SM) expressed in MW as

$$SM = \lambda_{\text{crit}}\left(\sum_{i\in N} P_t^{L,i} - \sum_{i\in N} P_b^{L,i}\right), \tag{2}$$

1. The wording *reactive power generation* is used as simplification. The positive/negative reactive generation is understood as capacitive/ inductive load.

$$\Delta \boldsymbol{P} = [\boldsymbol{H} - \boldsymbol{M}\boldsymbol{K}^{-1}\boldsymbol{N}]\Delta\boldsymbol{\Theta} = \boldsymbol{J}_{RP}\,\Delta\boldsymbol{\Theta}. \qquad (7)$$

where $P_b^{L,i}$, $P_t^{L,i}$ are the values of active power demand in bus i in base and target cases respectively, and N is the set of buses in the system. This index can also be formulated in terms of reactive and apparent power, if needed.

Unfortunately, pure CPF method, as described here, is unable to estimate correctly the true level of voltage stability. It only shows numerical lack of Power Flow solution, without considering all limits of generation. To incorporate them into the algorithm, once a generator hits its reactive limit, the relevant node changes from being PV to PQ [8].

2.2 Modal Analysis

In [2] another method of assessment was shown. It analyses absolute values of eigenvalues of reduced power system jacobian and their linked left and right eigenvectors. The method was derived from linearized Power Flow equations and from a well-known fact that system's jacobian becomes singular in the point of voltage instability (bifurcation point) [2, 7, 9].

Contrarily to CPF, it does not give deterministic information on current network solution's distance to the bifurcation point. Yet, thanks to this technique it is possible to determine buses that mostly influence the voltage stability level. According to [2], all remedial actions should be located in the most influential buses, to have the highest impact (this includes reactive power compensation).

Let us remind the form of Power Flow jacobian (notation: $\underline{U_j} = U_j \angle \Theta_j$)

$$\boldsymbol{J} = \begin{bmatrix} \boldsymbol{H} & \boldsymbol{M} \\ \boldsymbol{N} & \boldsymbol{K} \end{bmatrix}, \qquad (3)$$

where

$$H_{ij} = \frac{\partial P_i}{\partial \Theta_j},\ M_{ij} = \frac{\partial P_i}{\partial U_j},\ N_{ij} = \frac{\partial Q_i}{\partial \Theta_j},\ K_{ij} = \frac{\partial Q_i}{\partial U_j}. \qquad (4)$$

In its classic formulation, Modal Analysis looks at Q-U sensitivities assuming $\Delta \boldsymbol{P} = 0$. In such case the increment of reactive injection is expressed as

$$\Delta \boldsymbol{Q} = [\boldsymbol{K} - \boldsymbol{N}\boldsymbol{H}^{-1}\boldsymbol{M}]\,\Delta \boldsymbol{U} = \boldsymbol{J}_{RQ}\,\Delta \boldsymbol{U} \qquad (5)$$

Matrix $\boldsymbol{J}_{RQ}$ is called *reactive power reduced jacobian*. From its eigenvalue decomposition we get bus' participation factor defined as

$$QPF_{ki} = \xi_{ki}\eta_{ik}, \qquad (6)$$

where QPF_{ki} - reactive participation factor of bus k in mode i, ξ_{ki} – right column eigenvector linked with i^{th} eigenvalue of $\boldsymbol{J}_{RQ}$, η_{ik} – left row eigenvector linked with i^{th} eigenvalue of $\boldsymbol{J}_{RQ}$. The higher the QPF_{ki}, the more inluential bus k is. As only the most critical mode ($\min_{i\in N}\{|\lambda_i|\}$) is interesting in terms of system's voltage stability, only participation factors related to it will be investigated [2].

In [2, 7, 9] it was shown that the reactive power reduced jacobian also becomes singular, and this justifies the use of Modal Analysis. The same applies to the so-called active power reduced jacobian - $\boldsymbol{J}_{RP}$. It is derived assuming $\Delta\mathbf{Q} = 0$ and is expressed as

By analogy, we can perform eigenvalue decomposition of $\boldsymbol{J}_{RP}$, and compute active power bus participation factors of bus k in mode i, denoted as APF_{ki}. Then, for each mode i participation factors can be grouped based on whether they represent participation of PV or PQ bus ($APF_{PU,i}$, $APF_{PQ,i}$). According to [9], to enhance the level of stability, a generator with low *APF* should inject more reactive power to the system.

3. PROPOSED SOLUTION

In this section the method is presented. It can be summarised in the following steps:

1. Load grid model and statistical data on loading.
2. Solve DC-OPF.
3. Solve standard Power Flow on the result of DC-OPF to include reactive power. Active power generation is kept constant as computed in Step 2 for all buses except the slack bus, whose injection can vary to compensate for power losses.
4. Assess voltage stability margin using CPF.
5. If the margin is not satisfactory, perform Modal Analysis and compute *QPFs* and *APFs.*
6. Iteratively add compensating units and dispatch them by solving the optimisation problem described in Section 3.3. (At start no compensators are added - so only reactive generation is redispatched - see Section 3.2.)
7. Stop when the level of stability becomes satisfactory, or the maximum number of compensators was added.

Starting point assumes the knowledge of the most common severe loading conditions for the studied grid. Such data can be gathered and archived by operators and can be used for analyses.

3.1 Active power dispatch via DC-OPF

After loading input data, the active power generation is dispatched by solving a standard formulation of DC-OPF which, unfortunately, does not allow us to consider the nonlinearities and voltage stability phenomena present in the AC Power Systems. However, it significantly reduces the computational burden by being a standard LP or QP optimisation problem[2] with limited number of decision variables. Its exemplary formulation can be found in [10] and will not be shown in this paper.

3.2 Reactive power redispatch

DC-OPF's result is corrected by Power Flow problem to address possible power losses in the grid – only slack bus' active power dispatch is subject to change. The calculated active power operating points are kept constant throughout further procedure.

Then, the algorithm tries to redispatch reactive power generation of already existing units to enhance the level of voltage stability. Let *A* denote the feasible set of standard OPF problem as shown in [10]. Proposed redispatch is then effectuated by solving (8).

$$\min_{\boldsymbol{P},\boldsymbol{Q},\boldsymbol{\Theta},\boldsymbol{U}} w_1 \sum_{i\in N_G} \mu_i Q_{G,i} + w_2 \sum_{i\in N} U_i \qquad (8a)$$

2 Depending on generation cost formulation.

$$\text{subject to: } P_{G,m}^{PF} \leq P_{G,m} \leq P_{G,m}^{PF}, \; m \in \Omega_{ref} \quad (8b)$$
$$P_{G,i}^{DC} \leq P_{G,i} \leq P_{G,i}^{DC} \quad (8c)$$
$$\boldsymbol{x} \in A, \quad (8d)$$

where N_G - set of PV buses, Ω_{ref} - set of slack buses, w_1 and w_2 - scaling factors (w_2 negative) μ_i - linear coefficient, $\mu_i = \overline{APF_{PU}} - APF_{PU,i}$. Constraints (8b, 8c) force active power dispatch to remain constant during computations. Although the vector $\boldsymbol{P}$ no longer groups decision variables in the problem, it was kept in the formulation to maintain links with standard forms of OPF.

3.3 Inclusion of newly built compensating units

If the result of the above procedure is not satisfactory in terms of voltage stability margin, some new compensating units can be added and dispatched in the grid. The units are inserted in the most influential PQ buses, as computed by using Modal Analysis. At the beginning of the procedure, the list of the most influential buses is created. Then, in each iteration of the algorithm, a single compensator is added. In each iteration all units are dispatched for reactive power by using the problem (9) .

$$\min_{\boldsymbol{P},\boldsymbol{Q},\boldsymbol{\Theta},\boldsymbol{U}} w_1 \sum_{i \in N_G} \mu_i Q_{G,i} + w_2 \sum_{i \in N} U_i + w_3 \sum_{i \in N_C} \alpha_i Q_{C,i} \quad (9a)$$

$$\text{subject to: } Q_{C,i}^{min} \leq Q_{C,i} \leq Q_{C,i}^{max} \quad (9b)$$
$$\boldsymbol{x} \in B, \quad (9c)$$

where N_C - set of added compensators, $Q_{C,i}$ - reactive power generation from compensator i , α_i- QPF of bus i, w_3 - usually negative scaling factor expressing importance of generation from added compensator, $Q_{C,i}^{min/max}$- lower and upper bounds of generation from added compensator, B - feasible set of (8).

4. SIMULATION RESULTS

Tests were performed on 2 test cases: 30-bus IEEE 30 system and synthetic 200-bus Illinois 200 system. In both cases, the demanded possible increase of loading was equal to 30% as compared to the base loading for both active and reactive power, which stood for $\lambda_{crit} = 1$. The level of voltage stability was assessed using CPF with respect to all generation limits, letting to estimate technically feasible margin. To make the test cases harder, added compensators did not respond to increasing loading, i.e. their dispatch remained constant throughout CPF computations. I have also assumed that I can build compensators in maximum of 20% of buses and that their generation can be controlled in continuous mode, with setpoint chosen from the interval [−20,80] MVAr.

4.1. IEEE 30 test system

As described in the previous section, I proposed a two-stage algorithm and so it was tested. As the system could not stand the 30% loading increase after active power dispatch, I tried to redispatch by solving (8). We can see in Fig. 1 that the system was not prepared for 30% increase, as $\lambda_{crit} = 0{,}4$ for this scenario. Best results were obtained when setting $w_1 = -30$ and $w_2 = -100$. Nose curves for bus with lowest voltage profile - before and after redispatching are shown in Fig.1

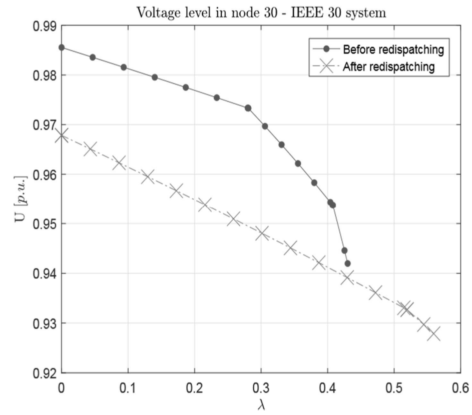

Fig. 1: Nose curves after first stage - IEEE 30 system

It can be seen that a small increase in voltage stability was experienced, however it implied the drop of nodal voltage below its acceptable limits (in this case 0,94 p.u.). Therefore, the algorithm proceeds to the second stage, i.e. building and dispatching compensators.

This time the weights were chosen to $w_1 = -16$, $w_2 = -9, w_3 = -2$. The best results were obtained after adding and dispatching 6 compensators. Resulting nose curves at critical bus are shown in Fig. 2.

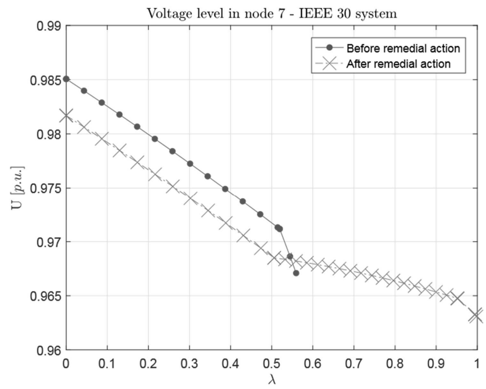

Fig. 2: Nose curves after adding 6 compensators - IEEE 30 system

Resulting λ_{crit} equals 1, which means that the system is prepared for a sudden increase of loading of 30% and will not lose voltage stability. Voltage stability margin was equal to $SM = 101{,}79$ MW as compared to $SM = 57{,}06$ MW at the input of the algorithm - an increase of around 78% was experienced. One can notice the unusual shape of the curves, which is due to the fact that in this case the limit-induced bifurcation was experienced and not the true bifurcation, i.e. the solution to the Power Flow problem could still be found, yet it would not be technically attainable.

4.2 Illinois 200 test system

Tests were performed also at the Illinois 200 system. For this system, lower limit of nodal voltage equals 0,9 p.u. After DC-OPF, the maximum loading parameter was equal to 0,72. Therefore, the system did not meet voltage stability margin requirements. The first stage of the approach was then applied with weights chosen to $w_1 = -1, w_2 = -10$. As can be seen from Fig.3, after reactive redispatch, system's maximum loading parameter increased to 1.11. It is now able to stably accommodate loading increase of more than 30%. Corresponding values of stability margin are: SM = 433,26 MW before and SM = 667,93 MW after redispatch – the stability margin was increased by around 54%. the demanded level of stability was achieved, the approach stops - no compensators are added to the system.

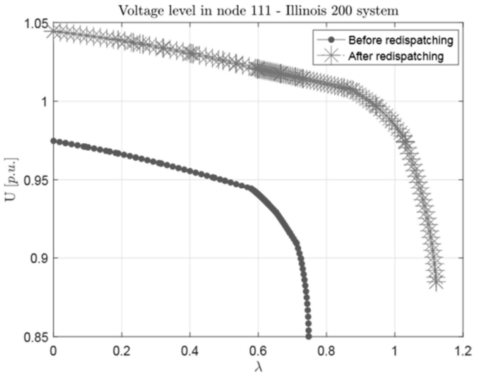

Fig. 3: Nose curves after first stage - Illinois 200 system

5. CONCLUSION

I presented an optimisation approach towards enhancing feasible steady-state voltage stability level of power systems, given that active power is dispatched using optimisation problems with linear grid models. For assessment of the stability margin, all generation limits were taken into account - computed operating points are always technically feasible.

I have shown that it is possible to accomplish the task by either correcting reactive power dispatch, or by adding new reactive power compensating units to the system. Thus, the output of this work can be both seen as on-line remedial action and as an approach for investment planning in the field of the power system's stability.

Thanks to taking into consideration prior dispatch via linear model optimisation problems, this approach could provide a basis for stability-enhancing module for Market Management Systems using such models. By using such an approach, the convergence of the optimisation problem is guaranteed.

Research perspectives include extension of the method to N-1 , N-2 states analyses and synchronising it with MMSs.

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METODA POPRAWY STABILNOŚCI NAPIĘCIOWEJ SEE, ZAKŁADAJĄC OPTYMALNĄ DYSPOZYCJĘ MOCY CZYNNEJ PRZY LINIOWYM MODELU SIECI

Praca przedstawia algorytm zwiększający poziom stabilności napięciowej SEE wykorzystując optymalną dyspozycję mocy przez rozwiązywanie zadań typu DC-OPF. Dla dobranych przez nie punktów pracy mocy czynnej przystępuje do zarządzania dyspozycją mocy biernej tak, aby zwiększyć poziom stabilności napięciowej. Początkowo, celem poprawy poziomu stabilności napięciowej, próbuje redyspozycji generacji mocy biernej już istniejących jednostek wytwórczych. Gdy nie przynosi ona zadowalającego efektu, iteracyjnie budowane są kompensatory mocy biernej. Dyspozycja mocy czynnej przez zadania o liniowym modelu sieciowym pozwala na implementację prezentowanej metody przez operatora, który z nich korzysta do zarządzania pracą SEE oaz planowania inwestycji. W pracy do analizy poziomu stabilności napięciowej wykorzystywany był algorytm *Continuation Power Flow* oraz *Analiza Modalna.* Na potrzeby testów wykorzystano środowisko MATLAB z pakietem MATPOWER i interfejsem modelowania CVX 2.0 oraz solwer LP/QP MOSEK 8.0. Testy przeprowadzono dla 30-węzłowej sieci IEEE 30 i 200-węzłowej syntetycznej Illinois 200.

Słowa kluczowe: Stabilność Napięciowa, Optimal Power Flow, Optymalizacja, Systemy Zarządzania Rynkiem Energii.