Voltage Stability Constrained OPF Using A Bilevel Programming Technique

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Abstract :

This paper presents a voltage stability constrained optimal power flow that is expressed via a bilevel programming framework. The inner objective function is dedicated for maximizing voltage stability margin while the outer objective function is focused on minimization of total production cost of thermal units. The original two stage problem is converted to a single level optimization problem via the KKT optimality conditions. Here to assure that the KKT optimality conditions are both necessary and sufficient the original inner problem is replaced with an equivalent problem with different structure. The applicability of the proposed method is demonstrated by implementing it in IEEE-30 bus test system.

Keywords: Voltage Stability, Optimal Power Flow, Bilevel Optimization, Complementary conditions, Convexity.

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Nomenclature

ψ_g	Set of owned generators
ψ_d	Set of load buses
ψ	Set of network buses
ψ_l	Set of network lines
x	Set of upper level decision variables
y	Set of lower level decision variables
a_i, b_i, c_i	Cost coefficients of thermal units
$\sim$	Superscript for uncertain variables
Pg_i	Active power generation in i^{th} bus
Pg_i^{max}	Upper limit of Pg_i
Pg_i^{min}	Lower limit of Pg_i
PG_i	Active power procured from pool market in i^{th} bus
Pd_i	Active power load in i^{th} bus
Qg_i	Reactive power generation in i^{th} bus
Qg_i^{max}	Upper limit of Qg_i
Qg_i^{min}	Lower limit of Qg_i
Qg_i^c	Reactive power generation in i^{th} bus at critical point
Qg_i^{c-max}	Upper limit of Qg_i^c
Qg_i^{c-min}	Lower limit of Qg_i^c
Qd_i	Reactive power demand in i^{th} bus
$V_i\angle\delta_i$	Voltage phasor in i^{th} bus
V_i^{max}	Upper limit of V_i
V_i^{min}	Lower limit of V_i
$V_i^c\angle\delta_i^c$	Voltage phasor in i^{th} bus in critical point
V_i^{c-max}	Upper limit of V_i^c
V_i^{c-min}	Lower limit of V_i^c
BS_i	Shunt susceptance in i^{th} bus
G_{ij}, B_{ij}	Conductance, susceptance of line connecting bus i and j
α	Lagrange multipliers for equality constraints
β	Lagrange multipliers for inequality constraints
$\lvert S_{ij}\rvert^{max}$	Maximum apparent power flow limit of line connecting bus i and j
S_{ij}	Apparent power flow of line connecting bus i and j
S_{ij}^{max}	Upper limit of S_{ij}
S_{ij}^c	Apparent power flow of line connecting bus i and j at critical point
S_{ij}^{c-max}	Upper limit of S_{ij}^c
λ	Voltage stability margin
H^{up}	Set of upper level inequalities
G^{up}	Set of upper level equalities
H^{new}	Set of inequality constraints in single level optimization framework
G^{new}	Set of equality constraints in single level optimization framework
h^{low}	Set of lower level inequalities
g^{low}	Set of lower level equalities
kg_i	Fraction of active power losses compensated by i^{th} generating unit at critical point

1. Introduction

The primary aim of power system operators is to supply demand load with a desired level of stability and security under various fault conditions. Voltage stability as one of most important types of stability phenomena refers to the ability of power system to maintain a desired level of voltage magnitude at all buses under normal and under credible contingencies [1]. Voltage stability problem could be optimized as a separate problem (i.e. as a Volt-VAr problem or as an ancillary service market) or could be satisfied as a constraint in an optimal power flow problem named Voltage Stability Constrained Optimal Power Flow(VSC-OPF). Voltage stability has been considered in optimal VAr planning [2], [3], optimal dispatch in deregulated power systems [4], sensitivity-based security-constrained OPF market clearing model [5], assessing reactive power reserves [6], [7], optimal under-voltage load shedding [8]–[11]. However, due to the interconnected and complex nature of power system it is required to optimize the voltage stability margin inside the main optimal power flow. The successful applications of bilevel programming techniques are reported in the literature such as optimal contract pricing of DG units in distribution networks [12], capacity expansion in the integrated supply network in electricity market [13], generation [14] and transmission [15] expansion planning and vulnerability analysis under multiple contingencies [16].

Appearance of new resources have added type of uncertainties in voltage stability analysis.
Probabilistic voltage stability assessment has been done in [17], [18]. The uncertain voltage stability problem could be analyzed using different techniques such as Information Gap Decision Theory. The IGDT technique has been implemented in power system studies [19], [20] such as self-scheduling of a wind producer [21], unit commitment in high wind power penetration [22]. It is noted that the uncertainty modeling is not the focus of this paper and can be found in other references [23]. Recently voltage stability has been considered in microgrids and distribution systems [24]-[27].

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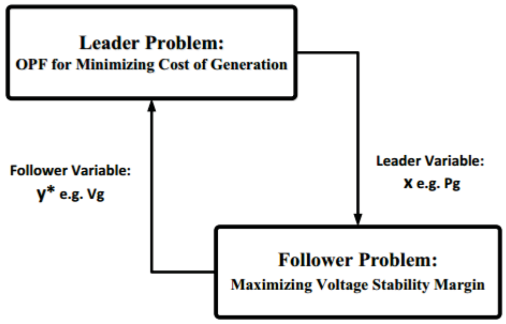

Fig. 1. Framework of the proposed Bilevel optimization

1.1. Contributions

In previously proposed methods the voltage stability criteria has been considered as an inequality constraint inside the optimal power flow (i.e. single level VSC-OPF) formulation or as a separate problem(e.g. volt-var problem, under voltage load shedding, and etc). No effort has been done for voltage stability maximization via a bilevel framework. The contributions of this paper are two-fold:

- Voltage stability maximization problem is defined as the follower of a leader OPF problem. The objective function of the leader problem is to minimize the production cost of thermal generating units while the follower problem is dedicated to maximize the voltage stability margin. In other word the leader objective function has an economic nature while the inner objective function has a technical nature. The decision variables of the follower problem are the passive shunt switching and the voltage magnitudes of voltage-controlled nodes(i.e. PV nodes). The follower problem is replaced with a set of new constraints via Karush-Kuhn-Tucker optimality conditions.
- The original two stage problem is converted to a single level optimization problem via the KKT optimality conditions. Here to assure that the KKT optimality conditions are both necessary and sufficient the original inner problem is replaced with a new equivalent problem.

1.2. Paper organization

The rest of this paper is organized as follows. In section 2, the fundamentals of bilevel optimization problem is presented. The details of the bilevel VSC-OPF are described in Section 3. The results of applying the proposed method over IEEE-30 bus are presented in Section 4. Finally, the conclusions are provided in section 5.

2. Framework of the Proposed Optimization

The bilevel optimization technique is defined as solving an optimization problem (in the upper level) which contains another optimization problem in the constraints (in the lower level). The general formulation of a bilevel optimization problem can be expressed as follows.

$$\min_{x} \quad F^{up}(x, y^*) \tag{1}$$

s.t

$$H^{up}(x, y^*) \leq 0 \tag{2}$$

$$G^{up}(x, y^*) = 0 \tag{3}$$

$$y^* = arg\left\{\min_{y} \quad f^{low}(x, y)\right\} \tag{4}$$

s.t

$$h^{low}(x, y) \leq 0 \tag{5}$$

$$g^{low}(x, y) = 0 \tag{6}$$

Where $x \in X \subseteq R^n$ and $y \in Y \subseteq R^m$ are called upper-level and lower-level decision variables respectively. The $F^{up}(x, y): R^{n+m} \to R$ is upper level objective function, $H^{up}(x, y): R^{n+m} \to R^p$, and $G^{up}(x, y) R^{n+m} \to R^q$ are upper level constraints. Parameters p, q are dimensions of inequality and equality constraints of the upper level optimization. The $f^{low}(x, y): R^{n+m} \to R$ is the lower level or inner objective function. $h^{low}(x, y): R^{n+m} \to R^l$ and $g^{low}(x, y): R^{n+m} \to R^w$ are upper level constraints. l and w are dimensions of inequality and equality constraints of the upper level optimization problem. The upper and lower level optimizations are also called leader and follower in the context of bilevel optimization.

3. Concept of Bilevel VSC-OPF

The bilevel voltage stability constrained optimal power flow (VSC-OPF) contains two objective functions namely: operating cost minimization (in the upper level) and voltage stability maximization (in the lower level). In this section, each objective function along with its associated constraints are defined as follows:

3.1. Leader Problem

The decision variables in this level are the active power outputs of thermal units, (Pg_i). The operating cost of thermal generating units depends on the total fuel consumption. It is usually expressed as a quadratic function of produced power of each unit as follows:

$$\underset{Pg_i}{Min} F^{up} = \sum_{i \in \psi_g} (a_i Pg_i^2 + b_i Pg_i + c_i) \tag{7}$$

The power flow equations should be satisfied in each bus of the network as follows:

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$$\tilde{G}_{1i}^{up}: Pg_i - Pd_i - V_i\left(\sum_{j\in\psi} V_j\left(G_{ij}Cos(\delta_{ij}) + B_{ij}Sin(\delta_{ij})\right)\right) = 0 \quad (8)$$

$$\tilde{G}_{2i}^{up}: Qg_i - Qd_i + BS_iV_i^2 - V_i\left(\sum_{j\in\psi} V_j\left(G_{ij}Sin(\delta_{ij}) - B_{ij}Cos(\delta_{ij})\right)\right) = 0 \quad (9)$$

The voltage magnitudes at all PV buses is determined as the results of the inner optimization problem shown by $V_i^{c^*}$:

$$\tilde{G}_{3i}^{up}: V_i - V_i^{c^*} = 0 \qquad i \in \Psi_g \quad (10)$$

The power flow passing through each line of the network should be kept less than the maximum allowed value as stated below:

$$\tilde{H}_{1ij}^{up}: |S_{ij}| \le |S_{ij}|^{max} \quad (11)$$

The active and reactive power of each generator should be kept between safe operating limits as follows:

$$\tilde{H}_{2i}^{up}: \begin{Bmatrix} Pg_i^{min} - Pg_i \le 0 \\ Pg_i - Pg_i^{max} \le 0 \end{Bmatrix} \quad (12)$$

$$\tilde{H}_{3i}^{up}: \begin{Bmatrix} Qg_i^{min} - Qg_i \le 0 \\ Qg_i - Qg_i^{max} \le 0 \end{Bmatrix} \quad (13)$$

The voltage magnitudes at all load buses should be kept between safe operating limits as follows:

$$\tilde{H}_{4i}^{up}: \begin{Bmatrix} V_i^{min} - V_i \le 0 \\ V_i - V_i^{max} \le 0 \end{Bmatrix} \quad (14)$$

3.2. VSM maximization problem (Follower)

The aim of inner or follower objective function is to maximize Voltage Stability Margin. The voltage stability margin is defined as the loading margin. For a particular operating point, the amount of additional load in a specific pattern of load increase that would cause a voltage collapse is called the loading margin. Here the voltage collapse point is determined considering reactive power limits of voltage controlled nodes. This type of bifurcation is named Limit Induced Static Bifurcation (LISB). At the limit induced static bifurcation point the two solutions of steady state equations merge and disappear. This point coincide with the maximum loadability point in power flow models. The decision variable in this level includes the values of voltage magnitudes at voltage controlled nodes, $V_i^c(\Psi_g)$. The objective function of the follower problem is to maximize this margin over probable scenarios as follows:

$$\{V_i^c(\Psi_g)^*\} = arg\left\{\max_{V_i^c(\Psi_g)^*} f^{low} = \lambda\right\} \quad (15)$$

where $V_i^c(\Psi_g)^*$is the optimal value of voltage magnitudes at PV nodes. For reactive shunt switching (i.e. *BS*) the same equations as given in (10),(14), and (15) could be written. The input parameters of the follower problem include Pg_i, PG_i, and Pd_i. In other words these variable are optimized by the leader problem and are then passed to the follower problem. The steady state equality constraints at the maximum loadability point are written as follows:

$$\tilde{g}_{1i}^{low}: (1+\lambda+kg_i)(Pg_i+PG_i) - (1+\lambda)Pd_i - V_i^c\left(\sum_{j\in\psi} V_j^c\left(G_{ij}Cos(\delta_i^c - \delta_j^c) + B_{ij}Sin(\delta_i^c - \delta_j^c)\right)\right) = 0 \quad (16)$$

$$\tilde{g}_{2i}^{low}: Qg_i^c - (1+\lambda)Qd_i + BS_i(V_i^c)^2 - V_i^c\left(\sum_{j\in\psi} V_j^c\left(G_{ij}Sin(\delta_i^c - \delta_j^c) - B_{ij}Cos(\delta_i^c - \delta_j^c)\right)\right) = 0 \quad (17)$$

where the λ is the loading margin between the base case operating point and the LISB point . The kg_i parameter forces the i^{th} generator to participate in active power loss compensation in a distributed slack mode.

Other operational limits are expressed as follows:

$$\tilde{h}_{1i}^{low}: Qg_i^{c-min} - Qg_i^c \le 0 \quad (18)$$

$$\tilde{h}_{2i}^{low}: Qg_i^c - Qg_i^{c-max} \le 0 \quad (19)$$

$$\tilde{h}_{3i}^{low}: V_i^{c-min} - V_i^c \le 0 \quad (20)$$

$$\tilde{h}_{4i}^{low}: V_i^c - V_i^{c-max} \le 0 \quad (21)$$

$$\tilde{h}_{5i}^{low}: |S_{ij}^c| - |S_{ij}|^{max} \le 0 \quad (22)$$

3.3. Solution Method

The follower optimization problem should be converted into a set of constraints using the optimality conditions of Karush-Kuhn-Tucker (KKT). These constraints give the optimal values of lower optimization variables and are then passed to the upper level. The Lagrangian function of the lower optimization problem (L^{low}) is defined as follows: where *x* contains the upper-level decision variables namely, Pg_i. The lower-level decision variables, *y*, contains include the voltage magnitudes at PV nodes, $V_i^c(\Psi_g)^*$.

3.4. Single Level VSC-OPF

The KKT optimality conditions are necessary and sufficient for defining the optimum of the inner level problem only under convexity conditions. In other words the KKT optimality conditions are necessary and sufficient if for fixed x, the control variable of outer problem, 1) the inner functions f, g, and h are continuous and second order differentiable and 2) the inner functions f and h are convex and g is linear in y.

$$\tilde{\mathcal{L}}^{low}(x,y,\alpha,\beta) \quad (23)$$
$$= f^{low}(x,y) - \sum_{j\in\psi,\notin slack} \alpha_{1j} g_{1j}^{low}(x,y)$$
$$- \sum_{j\in\psi_d} \alpha_{2j,s} g_{2j}^{low}(x,y) - \sum_{j\in\psi_g} \alpha_{3j} g_{3j}^{low}(x,y)$$
$$+ \sum_{j\in\psi_g} \beta_{1j} h_{1j}^{low}(x,y) + \sum_{j\in\psi_g} \beta_{2j} h_{2j}^{low}(x,y)$$
$$+ \sum_{j\in\psi_g} \beta_{3j} h_{3j}^{low}(x,y) + \sum_{j\in\psi_g} \beta_{4j} h_{4j}^{low}(x,y)$$
$$+ \sum_{ij\in\psi_l} \beta_{4j} h_{5ij}^{low}(x,y)$$

The optimality conditions are categorized into three groups:

- Stationary conditions:

$$\nabla_y \tilde{\mathcal{L}}^{low}(x,y^*,\alpha,\beta) = 0 \quad (24)$$

- Primal feasibility conditions:

$$\tilde{g}_{1i}^{low}(x,y^*) = 0, \quad \forall i \in \psi, i \notin slack \quad (25)$$
$$\tilde{g}_{2i}^{low}(x,y^*) = 0, \quad \forall i \in \psi_d \quad (26)$$
$$\tilde{g}_{3i}^{low}(x,y^*) = 0, \quad \forall i \in \psi_g \quad (27)$$
$$\left(\tilde{h}_{1i}^{low}, \tilde{h}_{2i}^{low}\right) \le (0,0) \quad \forall i \in \psi_g \quad (28)$$
$$\left(\tilde{h}_{3i}^{low}, \tilde{h}_{4i}^{low}\right) \le (0,0) \quad \forall i \in \psi \quad (29)$$
$$\tilde{h}_{5ij}^{low} \le 0 \quad \forall ij \in \psi_l \quad (30)$$

- Complementary slackness conditions:

$$(\beta_{1i}, \beta_{2i}) \le (0,0) \quad \forall i \in \psi_g \quad (31)$$
$$(\beta_{3i}, \beta_{4i}) \le (0,0) \quad \forall i \in \psi \quad (32)$$
$$\beta_{5ij} \le 0 \quad \forall ij \in \psi_l \quad (33)$$
$$\beta_{1i}\tilde{h}_{1i}^{low}(x,y^*) = 0 \quad \forall i \in \psi_g \quad (34)$$
$$\beta_{2i}\tilde{h}_{2i}^{low}(x,y^*) = 0 \quad \forall i \in \psi_g \quad (35)$$
$$\beta_{3i}\tilde{h}_{3i}^{low}(x,y^*) = 0 \quad \forall i \in \psi \quad (36)$$
$$\beta_{4i}\tilde{h}_{4i}^{low}(x,y^*) = 0 \quad \forall i \in \psi \quad (37)$$
$$\beta_{5ij}\tilde{h}_{5ij}^{low}(x,y^*) = 0 \quad \forall ij \in \psi_l \quad (38)$$

$$\min_{Pg_i, V_i} F^{up}$$

Subject to

$$\tilde{G}^{new} = 0 : \quad (39)$$
$$\tilde{G}^{new} = \begin{cases} \{\tilde{G}_{ki}^{up}\}, k = 1,\dots,3 & (9-11) \\ \nabla_y \tilde{\mathcal{L}}^{low} & (25) \\ \{\tilde{g}_{ki}^{up}\}, k = 1,2 & (26)-(28) \\ \{\beta_{1i}\tilde{h}_{ki}^{low}\}, k = 1,\dots,5 & (35-39) \end{cases}$$
$$\widetilde{H}^{new} \le 0 : \quad (40)$$
$$\widetilde{H}^{new} = \begin{cases} \{\widetilde{H}_{ki}^{up}\}, k = 1,\dots,4 & (12)-(15) \\ \{\tilde{h}_{ki}^{low}\}, k = 1,\dots,5 & (29)-(31) \\ \{\beta_{ki}\}, k = 1,\dots,5 & (32)-(34) \end{cases}$$

In case of lack of condition 1 or 2 the KKT optimality conditions are only necessary and the obtained result is a local solution. In other words in case of a general non-linear and non-convex bilevel problem, the KKT approach provide an upper bound for the global optimum solution of the single-level optimization problem. Here to assure that the KKT optimality conditions are both necessary and sufficient each inner equality constraint is replaced by two inequality constraints as follows:

$$\tilde{G}^{new}(x,y) = 0 \quad (41)$$
$$\begin{cases} \tilde{G}^{new}(x,y) & \le 0 \\ -\tilde{G}^{new}(x,y) & \le 0 \end{cases} \quad (42)$$

The final single level VSC-OPF formulation could be summarized as follows.

St:

$$\tilde{G}^{new} \le 0 \quad (43)$$
$$-\tilde{G}^{new} \le 0 \quad (44)$$
$$\widetilde{H}^{new} \le 0 \quad (45)$$

4. Simulation Results

The proposed bilevel structure for VSC-OPF problem is applied IEEE 30-bus test case. The single line diagram of IEEE30 bus network has been illustrated in Fig. 2. The conventional OPF and bilevel VSC-OPF are simulated using voltage control and reactive shunt switching as control variables.

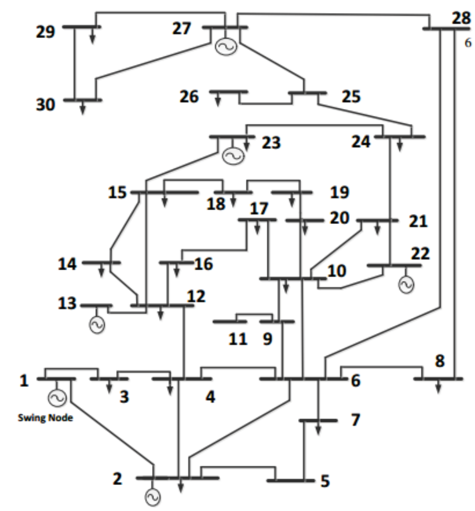

Fig. 2. Single line diagram of IEEE-30 bus test system

4.1. Conventional OPF

The results of conventional OPF without considering voltage stability constraint are given in Table 1 for three different strategies. In the first strategy as given in first column of Table 1 the active power of generators have been considered as the control variable. The second column of this table contains the results of conventional OPF with considering active power and terminal voltage of generators as control variable. At the third column the shunt switching has been added to the control vector. It can be seen that the total production cost has a little change.

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Table. 1. OPF results without voltage stability constraints

Gen No	OPF with no control Pg	Qg	Vg	OPF with voltage control Pg	Qg	Vg	OPF with voltage control and shunt switching Pg	Qg	Vg
1	43.0	-5.00	1	43.1	-1.00	1.050	43.0	-7.80	1.050
2	57.2	36.1	1	57.2	22.8	1.047	57.1	8.00	1.048
13	21.0	11.8	1	20.8	26.2	1.083	20.7	-15.0	1.028
22	23.0	38.5	1	22.9	28.9	1.046	22.8	0.00	1.046
23	16.5	9.70	1	16.3	7.00	1.054	16.2	1.80	1.052
27	31.2	9.60	1	31.4	14.7	1.064	31.3	2.20	1.057
Total Cost ($)	574.33			572.714			571.383		

The voltage profile of the network has been illustrated in Fig. 3. A flat voltage profile is resulted by using additional voltage control.

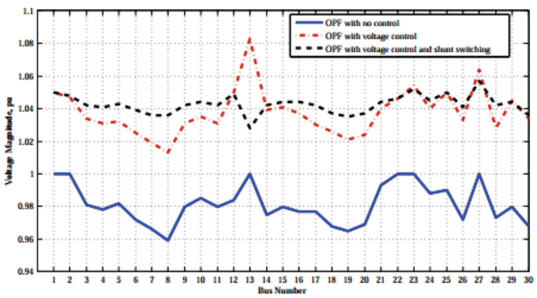

Fig. 3. Voltage profile with and without voltage control and shunt switching

4.2. Bilevel VSC-OPF

In this case, the results of proposed bilevel formulation is presented. The inner voltage stability problem is converted to a series of constraints using KKT optimality conditions. According to Table 2 the total production cost is $667.751 with a voltage stability margin of λ_{SM} = 2.221. Values of shunt switching for conventional OPF and bilevel VSC-OPF have been given in Table III. The voltage profile of the network has been illustrated in Fig. 4.

Table. 2. Results of bilevel VSC-OPF problem

Gen No	Pg (MW)	Qg (MVar)	Qg (MVar)	Vg (pu)
1	0.00	7.20	27.6	1.050
2	50.5	-20.0	84.0	1.044
13	40.0	18.6	62.6	1.073
22	50.0	2.70	87.5	1.053
23	17.3	-10.0	16.8	1.031
27	33.2	-15.0	21.1	1.034
Total Cost ($)	667.751			

Table. 3. Results of bilevel VSC-OPF problem

Bus No	Shunt switching (Bsh), MVar: Conventional OPF	Bilevel-VSCOPF
3	0.00	0.70
4	0.00	3.60
5	0.00	6.60
6	0.00	16.4
7	7.90	0.00
8	22.9	25.0
9	0.00	0.00
10	5.70	19.2
11	0.00	0.00
12	24.6	0.00
14	1.50	0.00
15	2.60	0.00
16	1.70	0.00
17	5.40	0.00
18	0.90	7.30
19	3.20	1.90
20	0.80	0.00
21	10.3	6.30
24	6.10	0.00
25	0.00	0.00
26	2.10	7.20
28	0.00	0.00
29	1.00	0.00
30	2.10	9.20

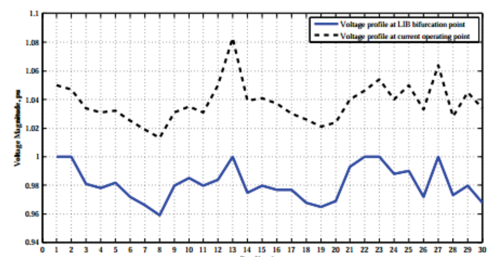

Fig. 4. Voltage profile with voltage control and shunt switching in bi-level VSC-OPF problem

5. CONCLUSION

A bilevel VSC-OPF model was proposed to minimize total production cost and maximize voltage stability margin at the same time. The inner voltage stability problem is converted to a set of constraints using the KKT optimality conditions. The new formulation optimizes the voltage magnitude of PV nodes and reactive shunt switching to provide the maximum voltage stability margin. The results of the proposed scheme was applied over the IEEE 30-bus test system. The obtained results verify the performance of bilevel VSC-OPF model.

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