

Maximization of Wind Energy Utilization and Flicker Propagation Mitigation Using SC and STATCOM

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Abstract—This paper proposes a novel approach to maximize utilization of wind energy by using a combination of flexible AC transmission system (FACTS) devices, shunt capacitor (SC) and static synchronous compensator (STATCOM). The stochastic nature of wind power is considered through a set of scenarios. After running the real market, the proposed model must be applied by the independent system operator (ISO) to determine the parameters such as the value of the real reserve of each generator. The control procedure of the proposed model is easier and more accelerated due to using SC. Moreover, the proposed method improves the voltage flicker mitigation and power quality parameters due to using STATCOM. The proposed method is applied to IEEE RTS. It is shown that the proposed model affects the total flexibility of the energy system compared to the system without SC and STATCOM in order to enhance effective wind energy utilization.

Index Terms—FACTS devices, PCC point, voltage flicker, wind energy utilization.

NOMENCLATURE

1. Indices

s	Index of scenarios, 1 to N_s .
r	Index of wind power units, 1 to N_r .
l	Index of loads, 1 to N_l .
i	Index of conventional units, 1 to N_i .
n / m	Index of buses.

2. Sets

ξ	Set of loads.
ϱ	Set wind units.
π_n	Set of buses adjacent to n th bus.
ζ	Set of conventional units.

3. Parameters

L_l^Q	Reactive load by l th load.
P_i^{fix}	Power production by i th conventional unit.
$\underline{Q}_i / \bar{Q}_i$	Min/Max reactive power production of i th unit.
$\underline{R}_i^D / \bar{R}_i^U$	Min/Max active reserve by i th unit.
T_s	Probability of s th scenario.

L_l^P	Active load by l th load.
$Z_{nm_{loss}}$	Importance factor of loss in objective function.
\bar{S}_{nm}	Capacity of line from bus n to bus m .
Q_i^D / Q_i^U	Min/Max reactive reserve by i th unit.
$Z_{r_{wind}}$	Importance factor of wind spillage in objective function.
$Z_{l_{shedd}}$	Importance factor of load shedding in objective function.
W_{rs}	Output power of r th wind farm in s th scenario.
W_r^{fix}	Output power of r th wind farm as a result of market.
$\underline{V}_n / \bar{V}_n$	Lower and upper bound of voltage magnitude.
X_{trans}	Reactance of transformer of wind power unit.
X_{net}	Reactance of equivalent thevenin circuit of utility grid that is seen by STATCOM.
B_{cap}	Susceptance of shunt capacitor C_{stat} at location of STATCOM.
R_{stat}	Resistance of STATCOM structure.
L_{stat}	Inductance of STATCOM structure.
C_{stat}	Capacitance of STATCOM structure.
ω_e	Operational frequency at the location of STATCOM.
v_{dc} / i_{dc}	DC voltage/current of STATCOM.
v_1 / v_2	Voltage levels of transformer.
4. Decision Variables	
V_n^0	Voltage magnitude at n th bus in first level.
θ_n^0	Voltage angle at n th bus in first level.
Q_i^0	Reactive power of i th unit as a result of market in first level.
$W_{rs_{wind}}$	Wind power spillage of r th wind power in s th scenario.
$L_{l_{shedd}}$	Unserved l th active load in s th scenario.
r_{is}	Deployed active reserve of i th unit in s th scenario.
q_{is}	Deployed reactive reserve of i th unit in s th scenario.
v_{ns}	Voltage magnitude at n th bus in s th scenario.
θ_{ns}	Voltage angle at n th bus in s th scenario.

5. Functions

$P_{nms_{loss}}(v, \alpha)$	Active power loss for line from bus n to bus m in s th scenario.
$P_{nm}^{FL}(v, \theta)$	Active power for line from bus n to bus m in first level.
$P_{nms}(v, \theta)$	Active power for line from bus n to bus m in s th scenario.
$Q_{nm}^{FL}(v, \theta)$	Reactive power for line from bus n to bus m in first level.
$Q_{nms}(v, \theta)$	Reactive power for line from bus n to bus m in s th scenario.
$S_{nm}^0(v, \theta)$	Apparent power for line from bus n to bus m in first level.
$S_{nms}(v, \theta)$	Apparent power for line from bus n to bus m in s th scenario.
Q_{stat}	Injection reactive power by STATCOM.
v^{Td} / v^{Tq}	DQ0 components of v_{Ta}, v_{Tb} and v_{Tc} .
i^d / i^q	DQ0 components of i_a, i_b and i_c .
v^d / v^q	DQ0 components of v_a, v_b and v_c .
$v_a / v_b / v_c$	Voltage behind the impedance of STATCOM.
$v_{Ta} / v_{Tb} / v_{Tc}$	Voltage in terminals of STATCOM.
$i_a / i_b / i_c$	Current in terminals of STATCOM.
$v_1^d / v_2^d / v_1^q / v_2^q$	DQ0 components of v_1 / v_2 .

I. INTRODUCTION

Penetration of wind energy sources has grown over the recent years. Nowadays, wind energy has a great portion of electrical power generation. This increase has made new technical subjects in the power system. Some limitations, like wind power variability, affect integration of wind power production and confine it. Flexible AC transmission system (FACTS) devices due to the quick operation can decrease these technical constraints and improve integration issues of wind power into power system. Therefore, integration of wind farms needs to be managed effectively.

Reference [1] demonstrates a wind management in French power system considering demand respond and market pricing. Some effects in integration of wind power generation are declared in [2]–[5]. Reference [6] introduces a method that control the power system and consumes surplus wind production by electrical storages. Now in smart grid, electrical storages are grown. Therefore, they are available in power system and system doesn't need extra investment. One of the most important subjects in a power system is reliability that can be affected by integrated wind farm [7]. As in [8], the potential of hydro-power plants to work as storage is applicable, when the power system contains wind power plant. As it is noted, FACTS devices can help with integration of wind power system. Optimal location and sizing of these tools can control the effectiveness of wind power plant. In this vein, [9], [10] analyze these devices in different aspects and use different objective functions to improve the operation of network. In methods that use FACTS devices, every method

uses some of them. Shunt fixed capacitor (SFC) and thyristor controlled series capacitor (TCSC) are investigated in [11]. Shunt variable capacitor (SVC) and STATCOM can control the transmission capacity in power system with wind and photovoltaic power system [12]. Therefore, it results in better utilization of photovoltaic and wind power. In [13] the impacts of SVC and STATCOM are analyzed on operation of power system with wind farms. Reference [14] controls power quality of wind farms by STATCOM. As in [15], the resonant is controlled with capability of STATCOM. In the same vein, [16] uses STATCOM to improve stability in power systems. As in [17], both STATCOM and storages are capable to control voltage in power systems containing wind farms. Reference [18] proposes a methodology to determine the setting of FACTS in power system with renewable power plant. Using STATCOM can prevent the flicker of wind generator. Details of preventing the flicker of wind generator are proved in [19]. The proposed model has used the SC to make the control easier in contrast to controlling by TCSC [11]. Moreover, the model is suitable to prevent flicker from wind energy source to power system by STATCOM. In other words, STATCOM is used to modify voltage profile like SFC and it can lead to maximization of wind energy utilization. The results based on this model in next parts have shown the impact of these types of FACTS devices on technical constraints of network that leads to utilization of wind energy resources effectively.

II. IMPROVING OF WIND ENERGY UTILIZATION AND THE FLICKER PHENOMENA

A. Flowchart of the proposed model

The procedure of the proposed model is shown in Fig. 1. This model is run after the outputs of day-ahead market and spot market are determined. As we see, outputs of market are used in first level of optimization. The model uses a bi-level optimization. In first level, outputs are independent from stochastic features, while in the second level, stochastic features are taken apart in the optimization. Therefore, the outputs are different for each state of stochastic conditions. The outputs of the first level, as it is shown in Fig. 1, are as inputs of the second level. The proposed model is run by system operator. Therefore, an OPF model is used that is proposed in [11].

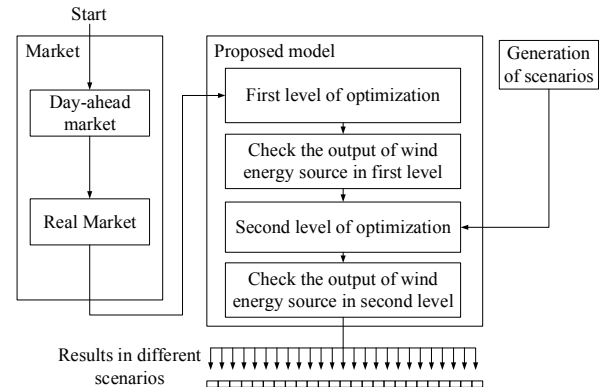


Fig. 1. Framework of the proposed model

III. FORMULATION

A. STATCOM

Output reactive power of STATCOM is modeled by equation (1) that is followed by other equations to declare it in details [19]. We can see the output power of STATCOM is related to the voltage in PCC point of wind power plant and to the current in terminals of STATCOM. These values are determined by other equations from (2) to (6).

$$Q_{stat} = \frac{3}{2} v^{Td} i^q \quad (1)$$

$$v^{Td} = \frac{X_{trans} X_{net}}{X_{trans} + X_{net} - X_{trans} X_{net} B_{cap}} i^q + \frac{X_{trans} v_2^d + X_{net} v_1^d}{X_{trans} + X_{net} - X_{trans} X_{net} B_{cap}} \quad (2)$$

$$v^d = R_{stat} i^d + L_{stat} \frac{di^d}{dt} - \omega_e L_{stat} i^q + v^{Td} \quad (3)$$

$$v_{dc} i_{dc} = v_a i_a + v_b i_b + v_c i_c \quad (4)$$

$$C_{stat} v_{dc} \frac{dv_{dc}}{dt} = \frac{3}{2} (v^{Td} i^d + v^{Tq} i^q) \quad (5)$$

$$\frac{dv_{dc}}{dt} = \frac{3v^{Td} i^d}{2C_{stat} v_{dc}} \quad (6)$$

The location and structure of STATCOM is shown in Fig. 2. As we see, the STATCOM is located in linking point of wind power plant and transmission network. In other words, the STATCOM is located after the transformer of wind power plant and utility network is imagined as a thevenin equivalent. This makes it possible to control the voltage in PCC point and then prevents flicker propagation [19].

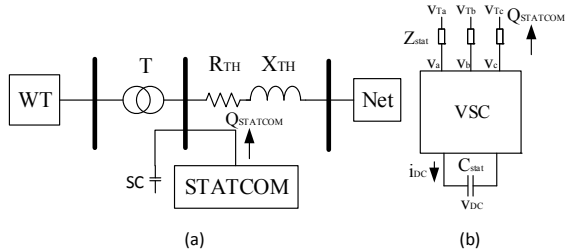


Fig. 2. STATCOM (a) location, (b) model [19]

B. Objective function

Objective function of this model is constructed by three components. The objective function is introduced in equations (7) and (8) [11]. The first component refers to wind power spillage in each wind power plant. The second component refers to load curtailment in each load and the last component refers to losses in grid. The optimization tries to minimize all of the components. In every component, there is a coefficient Z which determines the importance of each component. If a component is more important in contrast to other components, the coefficient in this component must be greater than other coefficients.

$$\text{Objective} = \min \{ F(\cdot) \} \quad (7)$$

$$F(\cdot) = \sum_s T_s \{ \sum_{r \in \rho} Z_{r_{wind}} W_{rs_{wind}} + \sum_{l \in \xi} Z_{l_{shedd}} L_{ls_{shedd}} + \sum_{n(m \in \pi_n)} Z_{nm_{loss}} P_{nms_{loss}}(v, \alpha) \} \quad (8)$$

C. Constraints

Constraints that are considered by this model are illustrated through equations (9)-(26) [11].

$$\sum_{i \in \zeta_n} P_i^{fix} + \sum_{r \in \rho_n} W_r^{fix} - \sum_{l \in \xi_n} L_l^p = \sum_{m \in \pi_n} P_{nm}^{FL}(v, \theta) \quad \forall n \quad (9)$$

$$\sum_{i \in \zeta_n} Q_i^{FL} - \sum_{l \in \xi_n} L_l^q = \sum_{m \in \pi_n} Q_{nm}^{FL}(v, \theta) \quad \forall n \quad (10)$$

$$\underline{Q}_i \leq Q_i^0 \leq \bar{Q}_i \quad \forall i \in \mathcal{G} \quad (11)$$

$$\underline{V}_n \leq V_n^0 \leq \bar{V}_n \quad \forall i \in \mathcal{G} \quad (12)$$

$$-\pi \leq \theta_n^0 \leq \pi \quad \forall n \quad (13)$$

$$\theta_{n=1}^0 = 0 \quad (14)$$

$$S_{nm}^0(v, \theta) \leq \bar{S}_{nm} \quad \forall n, \forall m \in \Omega_n \quad (15)$$

Since the problem is a bi-level optimization, equations (9)-(15) are related to the first level. Equations (9) and (10) represent the active and reactive power balance at each bus, respectively. equation (11) represents a limitation for the value of reactive power production of generating units. equations (12) and (13), enforce the bound voltage magnitude and angle. Equation (14) sets the $n=1$ as the slack bus. equations (15) enforce the upper bound of capacity for each line.

$$\sum_{i \in \zeta_n} r_{is} + \sum_{r \in \rho_n} (W_{rs} - W_r^{fix} - W_{rs_{wind}}) + \sum_{l \in \xi_n} L_{ls_{shedd}} = \sum_{m \in \pi_n} P_{nms}(v, \theta) - \sum_{m \in \pi_n} P_{nm}^{FL}(v, \theta) \quad \forall n, \forall s \quad (16)$$

$$\sum_{i \in \zeta_n} q_{is} = \sum_{m \in \pi_n} Q_{nms}(v, \theta) - \sum_{m \in \pi_n} Q_{nm}^{FL}(v, \theta) \quad \forall n, \forall s \quad (17)$$

$$0 \leq L_{ls_{shedd}} \leq L_d^p \quad \forall l \in \xi, \forall s \quad (18)$$

$$0 \leq W_{rs_{wind}} \leq W_{rs} \quad \forall r \in \rho \quad (19)$$

$$-R_i^D \leq r_{is} \leq R_i^U \quad \forall i \in \zeta, \forall s \quad (20)$$

$$-Q_i^D \leq q_{is} \leq Q_i^U \quad \forall i \in \zeta, \forall s \quad (21)$$

$$\underline{Q}_i \leq q_{is} + Q_i^0 \leq \bar{Q}_i \quad \forall i \in \zeta, \forall s \quad (22)$$

$$\underline{V}_n \leq v_{ns} \leq \bar{V}_n \quad \forall n, \forall s \quad (23)$$

$$-\pi \leq \theta_{ns} \leq \pi \quad \forall n, \forall s \quad (24)$$

$$\theta_{(n=1)s} = 0 \quad \forall s \quad (25)$$

$$S_{nms}(v, \theta) \leq \bar{S}_{nm} \quad \forall n, \forall m \in \pi_n, \forall s \quad (26)$$

Equations (16)-(26) are constraints related to the second level of optimization that they are considered for each state of stochastic features. Equations (16) and (17) represent the active and reactive power balance at each bus and for each scenario, respectively. Equations (18) and (19) enforce the lower and upper bound wind power spillage and unserved load for each scenario. Equations (20)-(22) represent bound of active and reactive reserves for each scenario. These values of limitation are determined by running the energy market. Equations (23) and (24) enforce bound of voltage magnitude and angle for each scenario. Equation (25) sets the $n=1$ as the slack bus for each scenario. equations (26) enforce the upper

bound of capacity for each line and for each scenario. Equations of power of lines are declared in [11].

IV. CASE STUDY

To demonstrate application of the proposed model, a case study which is consist of a standard network, IEEE one area reliability test system (IEEE) is used. The case study is shown in Fig. 3 [20]. The scenarios of the uncertainty of wind power generators are shown in Fig. 4. There are 25 scenarios that model the production of two wind power generators. There are several SFC or SVC at some buses. Their locations are dependent on each case of analysis that are declared as follows:

Two wind power generators are considered at buses 3 and 14. At bus 14, a STSTCOM is connected after the transformer of wind power unit. It means wind power generator with transformer of the unit that are shown in Fig. 2, are as a block for STATCOM that control the voltage of this block. The parameters of the STATCOM and the transformer of the wind power unit are given in TABLE I.

TABLE I. Transformer and STATCOM parameters [19]

Device	Parameters
Network	SCL=5MVA, $X_{th}/R_{th} = 10$
Transformer T	2MVA, 4801V/13.8kV, 5%
STATCOM	600kVA, $R_{stat} = 0.0073p.u.$, $X_{stat} = 0.22p.u.$, $C_{stat} = 3.2mF$, $V_{dc} = 1056 V$

The parameters of conventional generators are shown in TABLE II. These parameters are resulted in running of day-ahead market and spot market and determine the output power of conventional generators. Further, these parameters determine the lower and upper bound of active and reactive reserve that are produced by these generators. There are 28 conventional generators. The locations of them are shown in Fig. 3.

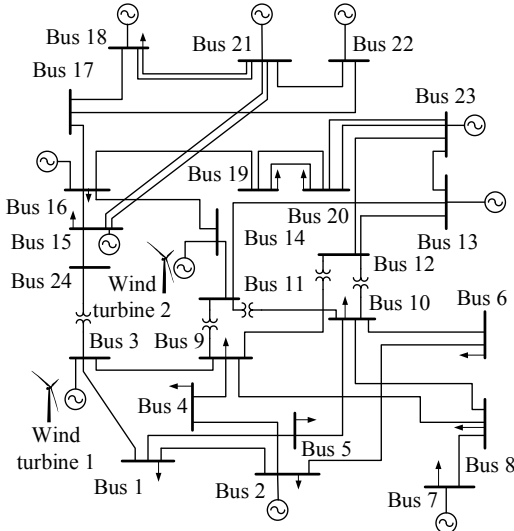


Fig. 3. IEEE one area reliability test system

The parameters of conventional generators are shown in TABLE II. These parameters are resulted in running of day-ahead market and spot market and determine the output power

of conventional generators. Further, these parameters determine the lower and upper bound of active and reactive reserve that are produced by these generators. There are 28 conventional generators. The locations of conventional generators are shown in Fig. 3.

Moreover, there are some active and reactive loads in standard network. The values of active and reactive loads that are shown by L_i^P and L_i^Q , are determined in [11]. Moreover, the locations of loads are determined in [11].

TABLE II. Parameters of generators [11]

Generator (i)	Location (Bus)	P_i^{fix} (p.u.)	R_i^P (p.u.)	R_i^U (p.u.)	Q_i^- (p.u.)	Q_i^+ (p.u.)	Q_i^P (p.u.)	Q_i^U (p.u.)
1,2	2	0.1	0.03	0.03	0	0.1	0.05	0.05
3,4	2	0.76	0.02	0.02	-0.25	0.3	0.15	0.15
5,7	7	1	0.4	0.4	0	0.6	0.3	0.3
8-10	13	1.97	1	1	0	0.8	0.4	0.4
11-15	15	0.18	0.1	0.1	0	0.06	0.03	0.03
16	16	1	0.5	0.5	-0.5	0.8	0.4	0.4
17	18	0	0	0	-0.5	0.8	0.4	0.4
18	21	3.8	0	0	-0.5	2	1	1
19-24	22	3.8	0	0	-0.5	2	1	1
25	23	0.5	0.5	0.5	-0.1	0.16	0.16	0.16
26,27	23	0.5	0.5	0.5	-0.5	0.8	0.4	0.4
28	23	1.8	0.7	0.7	-0.25	1.5	0.75	0.75

In analysis of the proposed model, five different conditions are considered:

1. There are no STATCOM and SCs.
2. There are only SFCs in buses 4 and 13.
3. There are only SFCs in buses 4, 5, 10 and 13.
4. There are only SVCs in buses 4, 5 and 13.
5. There are both STATCOM and SFCs at some buses. SFCs are located at buses 4, 5 and 13.

These conditions are determined as case A, case B, case C, case D and case E, respectively.

To compare load curtailment, wind power spillage and losses in each case, this paper uses the values below.

$$Load\ curtailment = \sum_{sl} T_s \cdot L_{ls_shedd} \quad (27)$$

$$Wind\ spillage = \sum_{sr} T_s \left(\frac{W_{rs_wind}}{W_{rs}} \right) \quad (28)$$

$$Loss = \sum_{snm(m \in \pi_n)} \frac{1}{2} T_s P_{nms_loss}(v, \alpha) \quad (29)$$

In case B, There are two SFCs of j.025 p.u and j2 p.u that are located at buses 4 and 13, respectively. Case C contains four SFCs of j2 p.u, j2 p.u, j2 p.u and j0.25 p.u that are located at buses 4, 5, 10 and 13, respectively. Case D contains three SVCs at buses 4, 5 and 13. A lower and upper bounds are enforced on these SVCs of -j0.2 p.u and j0.32 p.u, respectively. Case E has a set of SFCs of j2 p.u, j2 p.u and j0.25 p.u at buses

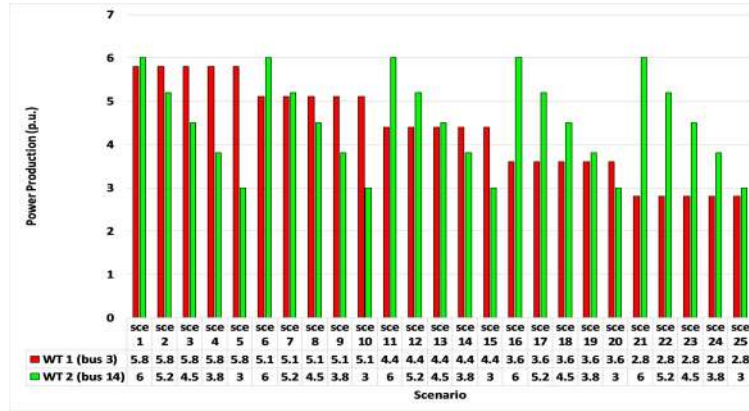


Fig. 4. Scenarios of wind power generators

4, 5 and 13, respectively. Moreover, a STATCOM is connected to bus 14. The lower and upper bound on output reactive power of STATCOM, according to [19], are -5 p.u and 5 p.u.

Numerical results are shown in TABLE III. According to TABLE IV, in case B, when we use SFC, wind spillage is less than spillage in case A, when we have no SC in network. In addition, load curtailment and loss are decreased. In case C, when we use three SFCs, wind spillage and load curtailment are better in comparison with case A and case B. In case D, with SVCs that are adjusted with each scenario, the objective value is better than all of the conditions we analyzed ago. In addition, almost load curtailment, wind spillage and loss are better. Of course, loss is more in contrast to Case A and Case B. In last state, we use SFC with STATCOM. At this state, objective value has the least value. Therefore, load curtailment and wind spillage have less value in comparison with all the prior states. The values of wind spillage and loss are almost the same values of the Case D. According to the results, using STATCOM can improve load curtailment, wind power spillage and loss in the network. As we see, in some states like third state in contrast to second state, losses are increased. Therefore, more SFC in the network cannot decrease loss in every network. In addition, using SVC instead of SFC may increase losses in the network. Therefore, in this aspect, there are not guarantee to use these elements in order to reduce the losses. Since the speed of wind power is variable, there is flicker in output power and voltage in PCC point of wind power units. We modeled the uncertainty of output power through a set of scenarios. Further, flicker propagation can be mitigated by STATCOM. Since the proposed model uses the STATCOM, in addition to maximization of wind power utilization, modifies the voltage curve in PCC point and voltage profile has a modified state. This modification is shown in Fig. 5. Dark blue continuous curve is related to case E. As we see, it changes less than other cases through the scenarios. So flicker propagation is mitigated by STATCOM in case E. In addition, cost investment is reduced by proposed model.

As the problem is a bi-level optimization, there are two groups of outputs. First group of outputs is independent from

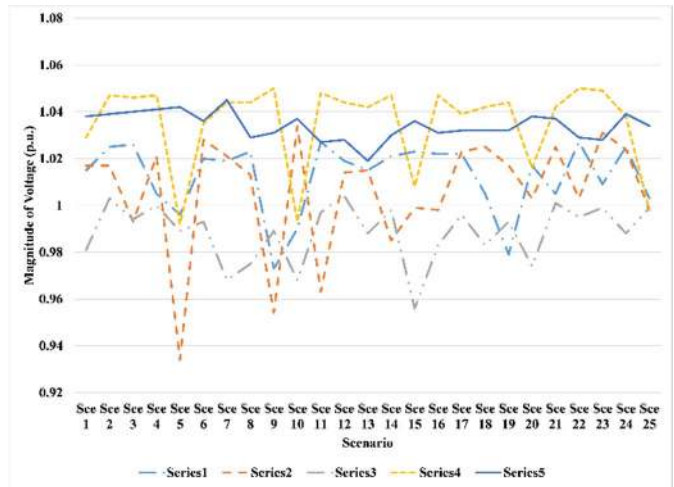


Fig. 5. Voltage at bus 14 in each case

scenarios, while the second group depends on scenarios. Dependent outputs vary by each scenario. One of dependent outputs is output reactive power of STATCOM in each scenario that is shown in Fig. 6.

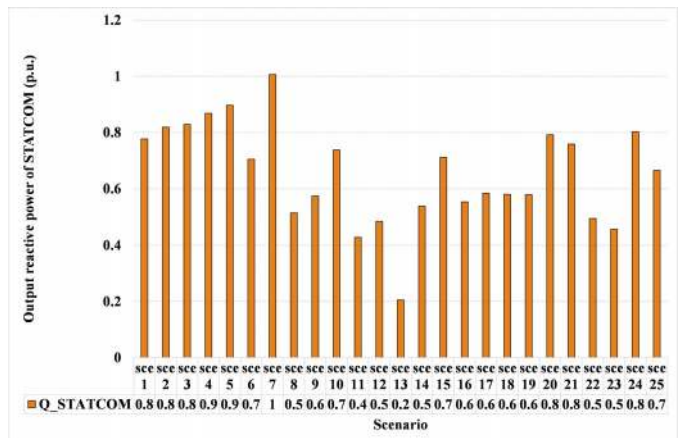


Fig. 6. Reactive power production of STATCOM in each scenario

In addition, the output reactive power prior to uncertainty realization is constant through the scenarios, whereas the output reactive reserve after uncertainty realization vary by each scenario. These two variables with sum of them related to conventional generator 19 are shown in Fig. 7. As we see, the

output reactive power prior to uncertainty realization that is shown by blue curve, is constant in each scenario.

TABLE III. Numerical results of each case of comparison

	The value of objective function (p.u.)	Load curtailment (p.u.)	Wind spillage (-)	Loss (p.u.)
Case A	2921.259	2.441	0.978	0.841
Case B	2343.852	1.887	0.937	0.968
Case C	1844.585	1.447	0.528	1.129
Case D	1381.469	1.021	0.725	1.049
Case E	1146.225	0.782	0.772	1.067

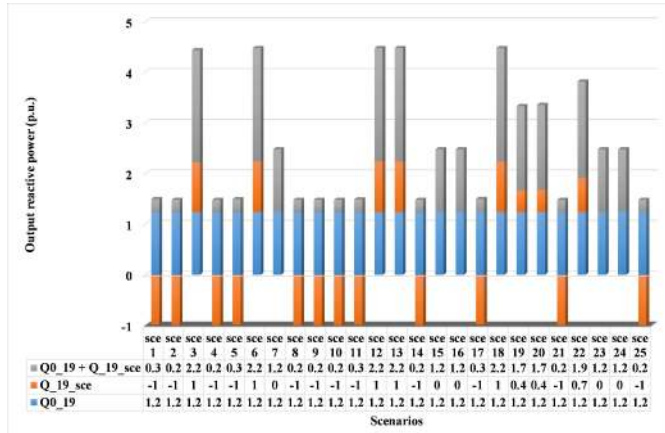


Fig. 7. Output reactive power of generating unit 19 in first and second level of optimization

V. CONCLUSION

A comprehensive stochastic smart district optimization model for wind energy sources in power systems to maximize utilization of wind energy and prevent flicker from wind sources to power system was presented in this paper. The uncertainty of wind energy sources was considered through a set of scenarios.

Due to the utilization of SC, the adjustment time of the proposed model was shorter. Moreover, by using STATCOM, flicker propagation was prevented as well as maximization of wind energy utilization. In addition, unserved load and power loss were considered in objective function. Obtained results showed the proposed model was capable in reduction of wind spillage. In addition, results showed improvement in serving loads and confining of losses.

Future work will consider incorporating assessment of electrical markets containing day-ahead market and spot market. In addition, electrical storage applications make some effects on operation of power systems when there are wind farms.

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