Cost-Benefit Analyses of Active Distribution Network Management, Part I: Annual Benefit Analysis

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***Abstract*—With more and more renewable energy generation (REG) connections, busbar voltage violation and line overloading problems may occur for some parts of a distribution network. However, building new circuits to accommodate REG may have high monetary and environmental costs. This paper considers distribution automation as a supplementary scheme to traditional primary asset investments and analyzes the operational benefits from introducing an autonomous regional active network management system (AuRA-NMS) to a practical distribution system with rich renewable sources. The benefits are quantified in terms of optimal power flow control and investment deferral, and the resulting quantification will inform distribution network operators of the trade-offs between investment in the automation system and in the primary assets, thus helping them to make cost-effective investment decisions. Time-series-based simulation for over an entire year is implemented to calculate the benefits of active power loss and curtailment reductions for AuRA-NMS over the current practice. Part I of this paper illustrates the current schemes for voltage control and constraint management, advanced voltage control and constraint management enabled by the distribution automation, and the annual benefit by introducing the AuRA-NMS to the system with different considerable new DG integrations. Part II analyzes the investment deferral benefit by deploying AuRA-NMS.**

***Index Terms*—Active network management, constraint management, distribution network, renewable energy generation, voltage control.**

I. Introduction

INCENTIVES for investment in renewable energies have already led to enormous expansion in renewable energy generation (REG). The expansion is expected to accelerate as the pressure to decarbonize electricity generation is increasing from many developed and developing governments. In the United Kingdom for example, suppliers are required to supply a certain percentage of their energy from renewable energy; failure to comply with the renewable volume will lead to costly penalties [1]. Additionally, feed-in tariffs have been introduced in April 2010 to provide smaller renewable developers guaranteed and highly attractive rate of returns. This anticipated expansion will place high pressure on existing distribution networks and would require significant network investment if the current passive operation practice continues.

An autonomous regional active network management system (AuRA-NMS) is a system that offers active and flexible control in maintaining voltage, constraint management, and supply restoration to distribution levels that are traditional passive with very little visibility and controllability [2], [3]. The system allows the online state of the whole network to be obtained and enables a more efficient and timely control and management to realize the notion of an active distribution network [3]. However, there is a need to identify clearly the benefits that an active network management system can offer over a passive network system. The comprehensive costs and benefits analyses of such a system are critical for informing network operators, manufacturers, regulators, and end consumers of the benefit of moving to an active network management system.

References [4]–[8] present active distribution network control methods to increase the level of DG penetrations. In [4], an optimal power flow (OPF) model for active control of distribution network with DG is proposed to solve the voltage rise problem, and demonstrates that penetration of DG can be significantly increased. Voltage control and fault current management methods are discussed further in [5] to estimate the benefits of active network controls in the entire U.K. distribution network for different penetration scenarios of DG at medium voltage level (11 kV). A trial of an active network management scheme on part of the North-Scotland electricity network is described in [6] and [7], where the power flow control actions are based on the measurement of power exportation and operation margin of each zone. A break-even economic analysis was carried out to identify the maximum capacity of DG connections without network reinforcement. The benefits of active management are exploited in the expansion of distribution systems by applying heuristic optimization techniques in [8]. The investment and operation costs of passive and different active distribution network management methods are compared using daily load curve, but the cost of active network implementation is not considered.

In the current paper, the benefits of deploying AuRA-NMS are quantified from the optimal voltage control and constraint management during online operations. Cost-benefit analyses are carried out considering future renewable energy generation (REG) integrations.

Manuscript received May 08, 2011; revised October 20, 2011; accepted June 18, 2012. Date of publication August 07, 2012; date of current version August 20, 2012. This work is supported by EPSRC, U.K. Paper no. TSG-00174-2011.

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Digital Object Identifier 10.1109/TSG.2012.2205412

Several studies on the active voltage control of distribution network with DG [9]–[13] have been conducted. Reference [9] provides an active voltage control method that coordinates the on-load tap changer (OLTC) action in the primary substation with the reactive production of DGs plants connected with the medium voltage system. A control algorithm proposed in [10] alters the automatic voltage control (AVC) relay target voltage at the primary substation based on the maximum and minimum nodal voltage magnitude estimates. Several coordinated voltage control schemes are compared in [11] considering cost, efficiency, network characteristics, and communications availability. A simple distributed reactive control approach, which changes the reactive power output of DG to maintain the voltage at the connection point rather than keeping constant power factor, for voltage rise mitigation in distribution networks is proposed in [12]. In [13], generation curtailment is considered as the control means to maintain voltage constraints, and a methodology is proposed based on voltage-sensitivity factors. These works concentrate mainly on voltage rise issue induced by DG connection into distribution networks; the optimal voltage control scheme in the current paper also tries to minimize active power losses.

Increasing wind power penetration in windy areas may also cause congestion or security problems due to limited network transfer capability. In [14], after discussions on the overload problem and basic wind generation curtailment strategy, an optimization algorithm to determine the wind farm set points to relieve overload in a real time operational environment was developed. The wind generation curtailment philosophy is used in this paper to quantify the benefit of AuRA-NMS constraint management function as compared with the last-in-first-off (LIFO) approach used in practice.

Part I of the paper will present a comprehensive approach to quantify the operational benefit of deploying AuRA-NMS over the current passive practice. The operational benefits include the benefits brought by dual functionalities of AuRA-NMS, i.e., optimal voltage control and constraint management to both minimize network losses and generation curtailment over the course of one year, respecting seasonal variations in demand and generation patterns and the number of tap controls that could be afforded by on-line tap changer. Part II of the paper will extent the benefit quantifications from annual operational benefits to investment deferral at the planning horizon.

Part I of this paper is organized as follows. In Sections II and Sections III, models on voltage control and constraint management are presented for both current practice and AuRA-NMS. Section IV describes the time-series-based simulation method to calculate the annual benefits. In Section V, test results on a practical 33 kV network are presented and discussed. Finally, conclusions are drawn in Section VI.

II. Optimal Voltage Control Benefit Analysis of AuRA-NMS

To quantify the benefits of AuRA-NMS optimal voltage control, the current voltage control method is presented first, followed by the proposed voltage control method for the AuRA-NMS. Although advanced control methods have been proposed in [9]–[11], the proposed method is easy to implement and takes constraint of the tap position change into account.

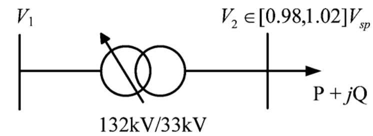

Fig. 1. Illustration of current OLTC control scheme.

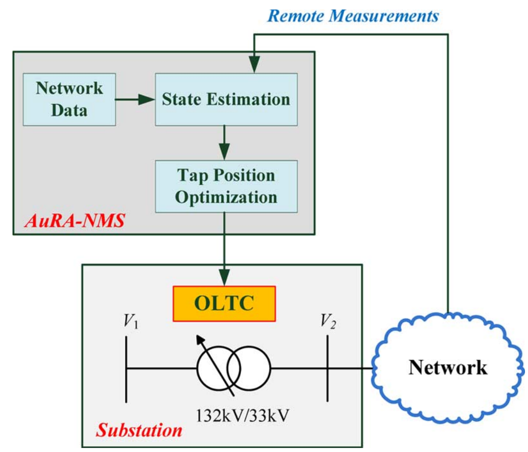

Fig. 2. Schematic diagram of the AuRA-NMS OLTC control.

A. Current Voltage Control

The voltages of a distribution network are controlled mainly by the OLTC(s) installed at the primary substation. The secondary voltage of the transformer is usually maintained by OLTC control within the specified target/nominal voltage range to keep the network voltage magnitude within the allowed voltage range ($+/-6\%$ of the nominal voltage for the 33 kV network in the United Kingdom).

The current control scheme is passive because it only uses local measurements at the primary substations (although voltage violation may be eliminated manually by the operator). For a distribution network with large wind power penetrations, the direction of power flow from the main transformer may change. Hence, the target voltage for OLTC control is difficult to set to guarantee qualified voltage profile and loss reductions.

B. Optimal Voltage Control Enabled by AuRA-NMS

1) Control Scheme Illustration: For a distribution system deployed with AuRA-NMS, there are sufficient real-time measurements to perform state estimation. Using the results of state estimation, control of the OLTC can be optimized, and the control scheme is illustrated in Fig. 2.

2) Modeling of the Optimal Voltage Control Function: The proposed optimal OLTC control has two objectives:

1) maintain all the voltages of 33 kV busbars within the allowable range, and
2) minimize the energy losses in the 33 kV network.

The first objective takes precedence over the second objective. The mathematic formulation of this problem is as follows:

Objective:

$$\min \quad p_{loss}(\boldsymbol{V}, \boldsymbol{\theta}, \boldsymbol{T}_K) \tag{1}$$

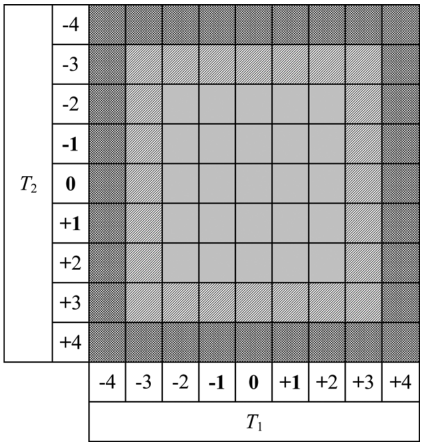

Fig. 3. Schematic illustration of optimal tap position search.

Subject to:

$$\boldsymbol{f}_P(\boldsymbol{V},\boldsymbol{\theta},\boldsymbol{T}_k) = \boldsymbol{P}_d - \boldsymbol{P}_g \tag{2}$$

$$\boldsymbol{f}_Q(\boldsymbol{V},\boldsymbol{\theta},\boldsymbol{T}_k) = \boldsymbol{Q}_d - \boldsymbol{Q}_g \tag{3}$$

$$\boldsymbol{V}^{\min} \leq \boldsymbol{V} \leq \boldsymbol{V}^{\max} \tag{4}$$

$$\boldsymbol{T}_k^{\min} \leq \boldsymbol{T}_k \leq \boldsymbol{T}_k^{\max} \tag{5}$$

$$\left|\boldsymbol{T}_k - \boldsymbol{T}_k^0\right| \leq \Delta K^{\max} \tag{6}$$

where $\boldsymbol{V}$ and $\boldsymbol{\theta}$ are vectors of voltage magnitude and phase angle, respectively; $\boldsymbol{T}_k$ represents the tap ratio vector of transformers; $\boldsymbol{T}_k^0$ is the corresponding initial tap ratio vector; $\boldsymbol{P}_d$ and $\boldsymbol{Q}_d$ are vectors of load active and reactive power; $\boldsymbol{P}_g$ and $\boldsymbol{Q}_g$ are vectors of generating active and reactive power, respectively; $p_{loss}(\cdot)$ represents the function of active power loss; $\boldsymbol{f}_P(\cdot)$ and $\boldsymbol{f}_Q(\cdot)$ are the functions of active and reactive powers flow into busbars; and superscript min and max denote lower and upper limits, respectively.

To limit the tap commutation number for the wear reduction, the maximum steps $\Delta K^{\max}$ that the tap position can be changed to reduce active power loss for each control move are limited. However, if any nodal voltage violates its limit, a wider range of tap movement will be searched to eliminate the voltage violation.

Formulation (1)–(6) is a mixed-integer nonlinear programming problem. The optimal position of a tap can be found by trial-and-error method considering its simplicity and robustness.

Fig. 3 illustrates the proposed tap position search procedure with two OLTCs operating independently. Suppose the current tap positions of the two transformers, T_1 and T_2, are both at zero and $\Delta K^{\max}$ is 2. The grey area corresponding to the tap position range $[-2, +2]$ for both transformers is searched first including the following steps:

1) Change the tap position(s).
2) Calculate the new power flow.
3) Calculate active power loss; count voltage violations and save them with the corresponding tap positions.
4) Go to Step 1 if not all the tap positions have been tested. Otherwise, find the tap positions where all nodal voltages are within the limits. Choose the tap position or the tap position combination with minimum active power loss.

In case voltage violation exists in the entire grey area, the allowable tap position range will be expanded in one step, that is, expanded to $[-3, +3]$, and the area shaded with up diagonal style will be searched. If voltage violation still exists in the entire area, then the outer area shaded with trellis style is searched. The entire procedure stops if a pair of tap positions (T_1 and T_2) with no voltage violation is found or the total number of searched tap position combinations exceeds the preset maximum number.

It should be noted that the optimal control of reactive compensation devices (such as shunt capacitors) and DG reactive power output is not considered in (1)–(6). They can be incorporated if they are available and the control algorithm should be modified with respect to the additional voltage control capabilities.

III. Constraint Management Capabilities of AuRA-NMS

A. Simulating Current Constraint Management Practice

The current constraint management philosophy follows the crude LIFO rule, in which the last-in DG will be the first generation to be tripped or curtailed whenever an overloading condition is detected. The rationale behind is that the new DG connection should not unduly affect the access rights of existing DGs [15].

Under either normal or abnormal conditions, if the network experiences overloading, the last-in generators will generally be tripped off or ramped down if it has ramping capability. The disadvantage with this rule is that the last-in generators may not be the most effective parties to remove the overloading conditions, leading to unnecessarily high energy losses from less effective generation curtailments.

In practice, network operators can exert a certain degree of judgment if the generation is of very little value in reducing overloading conditions. The flowchart to mimic the LIFO constraint management rule is shown in Fig. 4. Here, the sensitivity of the last-in generator to the overloaded line is checked first. If it is less than a threshold which means that disconnecting the last-in DG will not eliminate overloading, the trip-off action will move down to the next last-in generator until the overloading condition is resolved. The $\boldsymbol{S}$ in this figure is a sensitivity matrix of line active power flow with respect to nodal injections, which can be easily derived from dc power flow equations [16].

B. Optimal Constraint Management of AuRA-NMS

When an overloading state is identified, the decision program of AuRA-NMS will find an optimal solution to eliminate the overload. The control means is to ramp down the DG output when necessary, not just to trip DG according to the LIFO rule. For wind farms, their power outputs can only be reduced. The concept of constraint management scheme with AuRA-NMS is illustrated in Fig. 5.

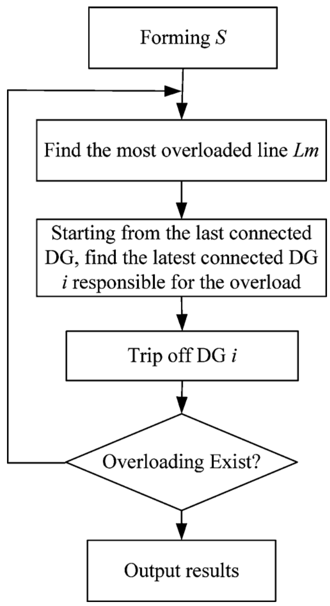

Fig. 4. Flowchart of simulating the current constraint management methods.

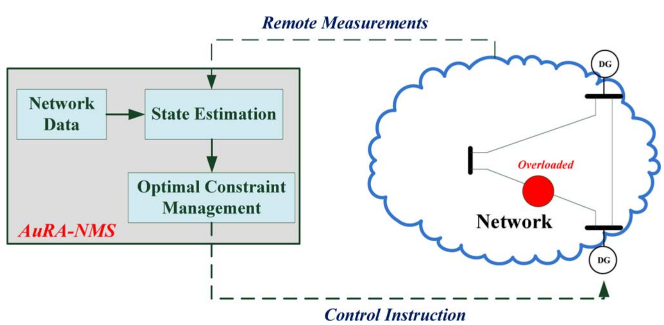

Fig. 5. Schematic illustration of AuRA-NMS constraint management.

C. Formulation of Constraint Management

The optimal decision problem for constraint management under AuRA-NMS is formulated as the following linear programming problem:

Objective:

$$\min \quad \sum_{i\in NG} \alpha_i \Delta P_{gi} + \sum_{i\in ND} \beta_i \Delta P_{di} \tag{7}$$

Subject to:

$$\sum_{i\in NG} (P_{gi} - \Delta P_{gi}) - \sum_{i\in ND} (P_{di} - \Delta P_{di}) = 0 \tag{8}$$

$$\left| \sum_{i=1}^{N} S_{li} \cdot (P_{gi} - \Delta P_{gi} - P_{di} + \Delta P_{di}) \right| \le P_l^{\max}, \quad l \in NB \tag{9}$$

$$P_{gi}^{\min} \le \Delta P_{gi} \le P_{gi}^{\max}, \quad i \in NG \tag{10}$$

$$0 \le \Delta P_{di} \le P_{di}, \quad i \in ND \tag{11}$$

where α_i and β_i are weighting factors for generation curtailment and load shedding respectively; P_{gi} and P_{di} are the power generation and demand at bus i, respectively; P_{gi} and ΔP_{di} stand for the generation and demand power cut at bus i, respectively; $P_{gi}^{\min}$ and $P_{gi}^{\max}$ are the lower and upper limits of the generation output at bus i; S_{li} is an element of sensitivity matrix $\boldsymbol{S}$ of line flow to nodal power injection [16]; $P_l^{\max}$ is the maximum power flow of line l; and NB, NG, and ND represent the set of branch, generation, and demand, respectively.

In the above formulation, β_i is much larger than all the α_i. This means that load curtailment is the last resort for constraint management after generation curtailment is exhausted. The formulation can be solved using either linear programming algorithms or sensitivity analysis. A linear programming program is used to solve the formulation in this paper.

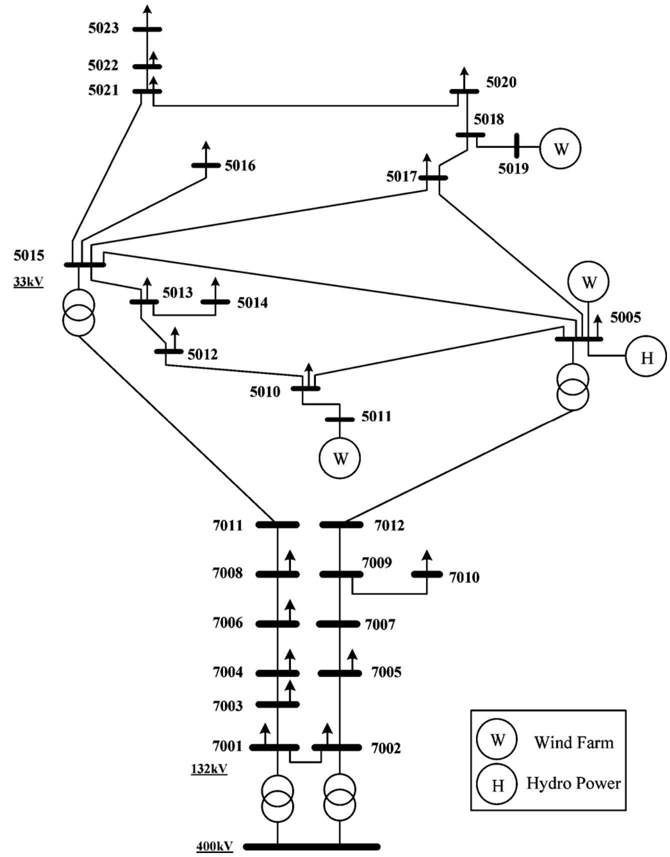

Fig. 6. Single line diagram of the 132/33 kV network.

IV. Time-Series Simulation

Considering the uncertainty and intermittence of REG output, particularly output of wind turbine, the commonly used methods such as load flow analyses under typical operation modes or probabilistic load flow analysis cannot give detailed system operation results over a period of time (for example, one year). Thus, time-series-based simulation method is implemented (similar to the method used in [17] and [18]) to analyze the effects of optimal voltage control and constraint management methods considering the detailed variations of DG output and load power over an entire year. The half-hourly sequential historical data of loads and DG outputs over one year are obtained from the DNO. Then for each half an hour, the steady-state operating states are calculated and analyzed sequentially. The optimal voltage control and constraint management approaches given in Sections II and III are applied.

After solving the optimal problem (7)–(11), curtailment orders are sent to the corresponding wind farms. The wind farms respond to the orders by ramping down the turbines to the specified levels and the overload will be eliminated. After a period of agreed duration, the orders should be nullified, and the wind farms can restore the outputs to their full capabilities. The ramping down of a wind turbine or a wind farm cannot be achieved instantly. However, considering their fast ramping capability [14] as well as the short-term overloading capability of circuits, the procedure of ramping down DG output is not taken into account during the simulation.

During the half hour interval, wind farm output changes with the variation of wind speed. The active power losses and wind power curtailments calculated by the proposed method are not accurate. However, the wind speed may increase and decrease within 30 min. So the overall error of the proposed simulation procedure should be not obvious. The proposed method is applicable if data of wind speed or wind farm output with smaller time interval is available.

V. Case Studies

The test system is a practical 132/33 kV network in the United Kingdom. Its single line topology is shown in Fig. 3. There are two lines connecting with busbar 5023 and 5020, respectively. These two lines are not shown given in Fig. 3 because they are open in normal operating conditions. Also not shown in the figure are several 11 kV lines and transformers through which some of the DGs connect to the 33 kV network.

The half-hourly 33 kV load absorptions and DG outputs are available for the year 2006; there are a total of 17 520 operating states. The maximum total demand and DG output are 51.4 and 71.3 MW, respectively. The DG penetration level of this network is quite high, and the direction of the power flow through 132/33 kV transformers changes (the minimum DG output is 0 MW).

It is identified that new wind generations will be connected into the 33 kV network by expanding or repowering the existing wind farms. With more DG integrations, voltage violation and branch overload problems will occur. Simulations on network losses and generation curtailment over a year are carried out under the current operational practice and with AuRA-NMS while the network is kept unchanged. Network reinforcement problem will be discussed in the second part of this paper.

Moreover, it is found that new wind farms are most likely to connect to busbars 5010 and 5018, with about 20 MW maximum generation capacity in each location [19]. The sequential historical load absorptions and DG outputs will be used, where the loads are kept unchanged and the new DG outputs are in proportion to the outputs of corresponding existing DGs at busbars 5011 and 5019. α_i and β_i are set equal to 1 and 1000, respectively.

A. Constraint Management Benefits of AuRA-NMS

Load flow calculations are carried out for the 17 520 operating states in sequence; both constraint management methods, the passive LIFO method and the active method, are applied to eliminate congestions when circuit overloading situations occur. After simulations for the two methods, the curtailment results are counted and compared. It is assumed that the duration of each curtailment is half an hour.

TABLE I
Total DG Output Curtailments

New DG Capacity (MW)	LIFO rule (MWh)		Proposed optimization method (MWh)		Difference (MWh)	Quantity of overloaded states
	5010	5018	5010	5018		
10	0	0	0	0	0	0
15	0	0	0	0	0	0
20	0	0	0	0	0	0
22	21	0	0.5	0	20	4
24	128	0	6	0	122	22
26	758	0	32	0	726	122
28	2107	0	132	0	1975	318
30	3142	2	306	0.05	2838	446
32	4368	11	536	0.455	3843	588
36	5777	738	1102	40	5373	788
40	6944	2438	1726	184	7472	1022

If an equal DG capacity is added at busbar 5010 and 5018, no overloading operating states are found when the total capacity is smaller than 20 MW. With the increase of DG integration, circuit overloadings occur in some operating states and curtailments are required. The total curtailment identified in the entire year using the two constraint management methods are listed in Table I.

The last column gives the total number of states that overloaded conditions will occur without constraint management. Overloadings dominantly occur on the power flow from line 5010–5012 and 5017–5015 due to the new DG integrations.

For the LIFO curtailment rule, the DG connected to 5010 is tripped when line 5010–5012 is overloaded. Similarly, the DG connected to 5018 is tripped when line 5017–5015 is overloaded. A large amount of renewable wind generation is unnecessarily curtailed with the LIFO rule whenever a circuit is overloaded. However, when the proposed optimal constraint management for AuRA-NMS is employed, the level of curtailment is greatly reduced. The penultimate column gives the differences in the level of curtailment using the two methods. When the two wind farms with total capacity of 22 MW are connected, only four operating states become slightly overloaded. The lost energy is about 21 MWh using the LIFO rule, whereas the curtailment using the proposed constraint management method is smaller than 1 MWh. When the newly connected capacity of wind farms is 40 MW, there are 1022 states with at least one circuit overloaded, and the curtailment difference between the two methods reaches 7472 MWh.

B. Optimal Voltage Control Benefits of AuRA-NMS

The total voltage violation (V_v) and total active power loss $(Loss_E)$ within the entire year are counted to demonstrate the effect of the current and the proposed AuRA-NMS OLTC control schemes using the following equations:

$$Vv = \sum_{t=1}^{m}\sum_{i=1}^{n}\begin{cases} V_{t,i} - V_i^{\max}; & V_{t,i} > V_i^{\max} \\ 0; & V_i^{\min} < V_{t,i} < V_i^{\max} \\ V_i^{\min} - V_{t,i}; & V_{t,i} < V_i^{\min} \end{cases} \tag{12}$$

TABLE II
VOLTAGE VIOLATION AND ACTIVE POWER LOSS

New DG capacity (MW)	Current control scheme			Propose control scheme for AuRA-NMS		
	Vv (p.u.)	Quantity of voltage violation states	Loss (MWh)	Vv (p.u.)	Loss (MWh)	Saved loss (MWh)
10	0.92	191	5835	0	5310	525
15	1.00	214	6025	0	5497	528
20	1.11	234	6292	0	5741	551
22	0.97	205	6410	0	5855	555
24	1.00	247	6537	0	5978	559
26	0.97	244	6666	0	6110	556
28	1.09	262	6813	0	6248	565
30	1.11	275	6990	0	6392	598
32	1.10	294	7140	0	6542	598
36	1.27	324	7485	0	6862	623
40	1.48	394	7878	0	7205	673

$$Loss_E = \sum_{t=1}^{m} loss_t \times D_t \tag{13}$$

where n is the number of nodes in the network; m is the total number of operating states simulated; $V_{t,i}$ is the voltage magnitude of node i and subscript t represents the $t\text{th}$ operating state; $loss_t$ is the 33 kV network active power loss at t; and D_t is the time duration of the $t\text{th}$ operating state, which is half an hour for all the simulated states.

First, voltage magnitude at the secondary busbar of each 132 kV/33 kV transformer is maintained within $[0.98, 1.02]$ p.u. to simulate the present voltage control scheme (see Fig. 2). For the proposed voltage control scheme with AuRA-NMS, is set equal to 4. Table II shows the results of active power losses and voltage violations of the 33 kV network using the current and proposed OLTC control methods. It should be noted that constraint management are executed first and OLTC control is performed after curtailment if overloading is identified for any operating state.

One can see from Table II that the current OLTC control scheme has voltage violations ranging from 191 to 394 states for DG capacities from 10 MW to 40 MW. Voltage violation problem restricts new DG connections. If the proposed voltage control method is implemented with AuRA-NMS, not only can the voltage violations be eliminated, but the active power losses are also reduced distinctly. The loss reductions are from 525 to 673 MWh, which account for 8% to 9% of the total losses resulting from the current OLTC control rule.

Table III presents the statistical results of the tap movements. The proposed method clearly achieved voltage violation elimination and loss reduction at the cost of more tap movements. The last column of this table lists the difference of the total tap movements of the two control schemes.

The cost of a single tapping operation based on maintenance costs is analyzed in [20] and the result is $£0.225$. Hence, the extra OLTC operation cost of AuRA-NMS as compared with the current control scheme is about $£2387$ to $£3031$. Suppose the cost of electricity is $£50/\text{MWh}$, the benefit of loss reduction ranges from $£26\,250$ to $£33\,650$, which is much bigger than the tap operational cost even without considering the benefits of eliminating voltage violations.

TABLE III
TOTAL STEP CHANGE OF TRANSFORMER TAP

New DG capacity (MW)	Current control scheme		Propose control scheme for AuRA-NMS		
	T1	T2	T1	T2	Difference
10	2580	2309	7327	8171	10609
15	2709	2394	7863	8639	11399
20	2913	2601	8837	9087	12410
22	3008	2701	8555	9259	12105
24	3045	2702	8747	9441	12441
26	3313	2917	8946	9594	12310
28	3361	2889	9178	9752	12680
30	3421	2944	9390	9866	12891
32	3541	3136	9565	10066	12954
36	3751	3280	10029	10522	13520
40	4216	3680	10411	10956	13471

TABLE IV
RESULTS AFTER CHANGING THE TARGET VOLTAGE RANGE FOR THE CURRENT CONTROL SCHEME

New DG capacity (MW)	Vv (p.u.)	States	Loss (MWh)	T1	T2	*Move Increment*
10	0.067	36	5804	3668	3037	*1816*
15	0.103	55	5987	3918	3075	*1890*
20	0.169	81	6239	4147	3204	*1837*
22	0.199	101	6359	4225	3320	*1836*
24	0.252	124	6481	4387	3464	*2104*
26	0.298	130	6614	4481	3618	*1869*
28	0.409	159	6762	4511	3688	*1949*
30	0.448	179	6920	4654	3789	*2078*
32	0.484	186	7077	4846	3902	*2071*
36	0.739	262	7424	5154	4193	*2316*
40	0.994	291	7813	5400	4499	*2003*

By analyzing the simulation results, it is found that the main reason of voltage violation for current control scheme is the fact that the voltage magnitudes of some busbars are below the voltage lower limit. If the target voltage level of the secondary busbar voltages of T1 and T2 are changed to $[0.99,\ 1.02]$ p.u., the simulation results are shown in Table IV. The total states of voltage violations and V_v are reduced notably compared with the results shown in Table II. Active power losses are also reduced due to the improvement of voltage magnitude. However, the price is also on the rise in the total tap movements (about 1816 to 2316 increment as listed in the last column of Table IV).

Set the target voltage range at the secondary side of T1 and T2 back to $[0.98, 1.02]$ p.u.. For the proposed OLTC control method, the results are the same as those shown in Table II if $\Delta K^{\max}$ is reduced to 2. The reason is that the tap movement of each OLTC is not bigger than two steps to reduce active power loss. However, the total tap movements and active power loss will increase if $\Delta K^{\max}$ is further reduced to 1. Simulation results are given in Table V. The third and sixth columns of Table V are comparing to the results presented in Table II. Although loss increment is very small, increment of tap movements is remarkable. The reason is that the tap position will change in more operating states with only one step. Based on these results and analyses, it is recommended that $\Delta K^{\max}$ be set to no smaller than 2, and that $\Delta K^{\max}$ should not also be so big considering the calculation burden and control effect.

TABLE V
RESULTS COMPARISON BY REDUCING MAXIMUM OLTC MOVE

New DG capacity (MW)	Loss (MWh)	Loss increment	T1	T2	Tap move increment
10	5329	19	11,440	13,508	9,450
15	5517	20	11702	13570	8,770
20	5762	21	11870	13618	7,564
22	5877	22	11964	13630	7,780
24	6001	23	12060	13622	7,494
26	6133	23	12139	13627	7,226
28	6271	23	12171	13711	6,952
30	6416	24	12289	13733	6,766
32	6568	26	12401	13758	6,528
36	6890	28	12655	13844	5,948
40	7235	30	12853	14060	5,546

TABLE VI
YEARLY BENEFITS OF AURA-NMS (k£)

New DG capacity (MW)	Loss reduction benefit	Loss reduction cost	Curtailment reduction benefit	Total net benefit
10	26.3	2.4	0.0	23.9
15	26.4	2.6	0.0	23.8
20	27.6	2.8	0.0	24.8
22	27.8	2.7	1.0	26.1
24	28.0	2.8	6.1	31.3
26	27.8	2.8	36.3	61.3
28	28.3	2.9	98.8	124.2
30	29.9	2.9	141.9	168.9
32	29.9	2.9	192.2	219.2
36	31.2	3.0	268.7	296.9
40	33.7	3.0	373.6	404.3

TABLE VII
YEARLY BENEFITS WITH UNBALANCED DG CONNECTIONS (k£)

New DG capacity (MW)		Loss reduction benefit	Loss reduction cost	Curtailment reduction benefit	Total net benefit
5010	5018				
10	0	26.2	2.0	0.0	24.2
0	10	26.5	2.7	0.0	23.8
20	0	19.3	2.2	327.6	344.7
0	20	23.0	3.2	151.4	171.2

C. *Yearly Benefits*

Supposing the electricity price is $£50/\mathrm{MWh}$, the comprehensive cost and benefits of the proposed OLTC control and constraint management methods for AuRA-NMS are calculated and listed in Table VI. The loss reduction cost given in this table is calculated by multiplying the increased number of tap movements with the equivalent cost for each step ($£0.225$). The total net benefit increases with the increase in installed DG capacity. In particular, the benefit of the proposed constraint management rises remarkably when the DG capacity is bigger than 26 MW due to deterioration of the circuit overloading. The total net benefit will be more than $£400$ k if the potential 40 MW DGs are connected into the 33 kV network.

The above simulation results are all obtained with equal wind farm capacity connecting to busbar 5010 and 5018. If the capacities for the two wind farms are different, the results will be different. Table VII presents some results. It can be seen that DG connecting to busbar 5010 induces more curtailment; so the total benefit for deployment of AuRA-NMS will be more imminent.

VI. CONCLUSIONS

For distribution systems, active network management is critical in facilitating significant DG penetration. However, performing a detailed cost-benefit analysis before deploying the corresponding hardware and software systems is necessary and important. For the AuRA-NMS under development in the United Kingdom, this paper proposed a comprehensive benefit analysis tool to quantify the magnitude of benefits from introducing AuRA-NMS considering both optimal voltage control and constraint management over the current passive and crude approaches.

In the 33 kV distribution network, the voltage control is usually implemented by adjusting the tap positions of the primary transformer, which cannot guarantee the voltage level of each busbar and becomes a major barrier for DG integration. With the deployment of AuRA-NMS, the online state of the entire network can be obtained. Based on this convenience, an OLTC control method considering the wear and tear on the mechanism is proposed to improve the voltage profile and reduce active power losses.

For the constraint management problem arising from the high penetration of DG, the LIFO rule and automatic tripping mechanism are generally adopted in practice, and the last connected DG will be tripped off once an overloading condition is detected. This current constraint management practice can lead to unnecessarily high generation curtailments. For a distribution system equipped with AuRA-NMS, the optimal constraint management approach can be implemented using global information. The optimal constraint management formulation and procedure are illustrated in the present paper.

For comparison, the current voltage control and constraint management methods are also simulated. Considering the uncertainties and correlations of DG injections and load absorptions, the time-series-based simulation method is implemented to analyze the effects of current control schemes and the proposed control methods for AuRA-NMS. A practical 33 kV network is used as the test system, and the half-hourly historical data over an entire year are collected. All the control methods are tested on the system over the year-round data under different levels of new DG connections. The results of voltage violations, active power losses, and DG curtailments are compared and the yearly benefits of deploying AuRA-NMS from loss and curtailment reductions are obtained. When the new connected DG capacity reaches 40 MW, the total yearly benefit is as high as $£400$ k assuming $£50/\mathrm{MWh}$ electricity price. The results provide an important reference to the investment in AuRA-NMS for DNOs, particularly for a network with a high penetration of renewable energies.

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