Operational windows for decentralized control of renewable DG: Techno-economic trade-offs

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Operational Windows for Decentralized Control of Renewable DG: Techno-Economic Trade-offs

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Abstract—The connection of renewable distributed generation (DG) is expected to increase significantly in the UK. A large volume will continue to connect to rural areas where voltage and thermal constraints are the main issues. It is in this context that Distribution Network Operators (DNOs) need to provide cost-effective connection arrangements, avoiding expensive reinforcements, and looking at innovative ways of actively managing the network. Herein, a decentralized, local control of (renewable) DG is proposed to manage voltage and thermal constraints by regulating the DG reactive power capacity and applying generation curtailment. Given that DG developers will require the highest possible returns of energy exports and DNOs might tolerate short-term, low-impact voltage and thermal breaches, the settings of the actual control mechanism (e.g., thresholds, target values and holding time) require special attention. This work focuses on the fine tuning of the control settings of the proposed scheme in order to assess the technical and economic trade-offs. A concept based on operational windows (related to time and severity) to capture the constrained situations is introduced. Results using a radial test feeder will be presented, highlighting the performance of different tuned settings.

Index Terms—Voltage and thermal constraints, distributed generation, active network management, reactive power management, generation curtailment.

I. INTRODUCTION

LARGE volumes of renewable distributed generation (DG) capacity, particularly wind farms, are expected to connect to UK distribution networks. However, traditional practice in which new generation capacity forces circuit reinforcement will result in costly and potentially unfeasible (due to planning issues) network investments. Consequently, new renewable DG developments, typically in rural areas where networks are weak, are facing a scenario where no further generation capacity can be cost-effectively accommodated. It is in this context that the Distribution Network Operators, under pressure to facilitate renewable targets, are trialing the use of innovative control schemes that make the most of the existing assets to allow further connection of DG. This approach,

called Active Network Management, represents a transition towards Smart Distribution Networks.

Voltage and thermal constraints are the two most significant and commonly found limitations on DG connections. To overcome these, a large number of advanced mitigation schemes aim to overcome voltage rise or line thermal overload. Voltage control schemes outlined in the literature in recent years include: intelligent switching of DG unit power factor and voltage control modes [1, 2], coordination of voltage regulation for substation on-load tap changer (OLTC) utilizing reactive and active power control of controllable DG plants [3]; innovative voltage control of OLTC [4]; voltage control using combinations of mechanisms like generation curtailment and power factor control, energy storage, and network reconfiguration [5]. Thermal constraint mitigation examples include: active management using coordinated generation curtailment [6, 7]. Most of these schemes however only address one particular constraint and omit the fact that both constraints can occur at the same time (although not regularly) which requires special treatment through effective and synchronized control actions. A requirement for costly investment in communication and monitoring infrastructure might make these schemes unfeasible.

This paper proposes a decentralized control scheme to provide cost-effective, local management of both voltage and thermal constraints. Based upon previous work [1, 2, 8, 9], the scheme uses the DG unit's ability to control its reactive and active power output (i.e., applying generation curtailment), while requiring no communication links with other network devices or participants. This control aspect could provide the DNOs and DG developers with an alternative for connecting more renewable DG that is fast-to-deploy, technically effective and economically viable.

II. DECENTRALIZED VOLTAGE AND THERMAL CONSTRAINT MANAGEMENT SCHEMES

Traditional voltage regulation in distribution networks is primarily performed by OLTC at substations. DNOs normally request DG operation at constant power factor with a capability to comply within specific ranges, e.g., in the UK, 0.95 inductive/capacitive. This requirement is particularly valid for current wind turbine technologies. However, DG is commonly operated close to or at unity power factor to maximize energy exports. This arrangement seems to satisfy the DNOs' and DG developers' perspectives but essentially

disregards further generation beyond the capacity already connected. This inefficient use of reactive power capabilities from DG units is also due to the fact that, in most countries, no incentive for DG units to provide such a service is in place.

In a situation where traditional network reinforcements are costly options to connect large volumes of wind capacity, a compelling business case for both DNOs and DG developers appears when such a connection can also be realized by applying generator-based control schemes without the need for communication systems. In this context, decentralized control can be seen as a compromise. The decentralized voltage and thermal constraint management and the corresponding operational window concept are explained in the following subsections.

A. Voltage Constraint Management

The decentralized voltage management ('V Mgt') scheme comprises two control schemes for limiting voltage rise: reactive power control and generation curtailment. The scheme is based around a series of voltage thresholds and holding (delay) times that dictate the severity of actions. When terminal voltage exceeds a voltage threshold, the voltage management instructs a DG unit to provide reactive power support by making the power factor inductive to instantly hold down voltage rise. The amount of reactive power required to keep the voltage within a specified voltage target is calculated through a real-time voltage/reactive power ($\partial V/\partial Q$) sensitivity analysis. In a severe situation where the reactive power control requirement exceeds the DG capability, generation curtailment is enacted with the amount of real power trimmed defined by a voltage/real power ($\partial V/\partial P$) sensitivity analysis and generator ramp rates.

B. Thermal Constraint Management

A generation curtailment scheme is also used in the thermal constraint management ('T Mgt'). The control mechanism is similar to that applied for voltage management with DG output trimmed. The power curtailed to maintain the loading capacity within a given target is estimated using the sensitivity of the binding line capacity to the DG power output ($\partial S/\partial P$) and ramp limitations of the DG unit. As stated earlier, the settings involved in the schemes comprise several thresholds, target values and holding times. In reality, the time delays from mechanical or control actions have to be considered. Details of the control schemes are found in [8, 9].

C. Operational Windows

The operational windows concept uses monitoring of conditions over a continuous fixed sampling period to characterize the behavior of voltage and line power flow variations and determine the appropriate control response. Here it consists of five windows (1 to 5) reflecting the behavior of voltage and power flows due to wind and demand characteristics. Each window is specifically defined by a mechanism that involves two thresholds, a target and a holding time values. The thresholds, consisting of threshold-one and threshold-two, and the target value are set with respect to the statutory limit of voltage or line. As presented in

this study, threshold-one and threshold-two are set below and above the limit, respectively (details are provided in Subsection D). These window settings are tunable and are the key element for capturing the constrained situations and validating the most effective control actions to be implemented. The operation for each window and the corresponding control actions are explained as follows.

Window 1: Normal Operation Voltage or line flow is below the threshold values and therefore no action is required.

Window 2: On-hold When voltage (or line flows) exceeds threshold-one (set slightly below the limit to define the severity), the scheme waits until a holding time is up without performing any action. After the holding time ends, three likelihoods are expected. If the situation returns to normal (window 1), no further action is required. If the measured parameter continues but is below threshold-two, the situation would fall in Window 4 and the holding time restarts. If the measured parameter breaches threshold-two, the situation will be replaced either by Windows 3 or 5 and the holding time restarts.

Window 3: Severe and Sudden Continuing from Window 2, the measured parameter breaches threshold-one and threshold-two. Although the breaching occurrence is less than holding time, control action is immediate to ensure security of the network.

Window 4: Breach and Extended This stage occurs when the measured parameter exceeds the threshold-one for longer than the holding time. This could affect performance of network infrastructure or the situation could be worsened due to other conditions, e.g., a close-by wind farm producing more power.

Window 5: Severe and Extended The last stage is the worst case that may occur. The measured parameter breaches threshold-two for longer than the holding time, prompting an immediate action.

The voltage and thermal constraints are continuously mapped against these windows. For a single constraint, the V Mgt or T Mgt is directly applied. A severe situation when two constraint breaches occur requires a validation of final control action in which the priority is given to the T Mgt [8], i.e., whenever window 3, 4 or 5 for T Mgt is activated, its action will remain until normal operation (without the constraints) of the DG unit can be adopted. Validation of the final control action follows the priority rule as shown in Table I.

TABLE I
OPERATIONAL WINDOWS PRIORITY RULE, (W1 = WINDOW 1)

V Mgt → T Mgt ↓	W1	W2	W3	W4	W5
W1	None	None (V Mgt on hold)		V Mgt	
W2	None (T Mgt on hold)	None (V&T Mgt on hold)			
W3					
W4	T Mgt			V&T Mgt	
W5					

D. Tunable Threshold, Target and Holding-Time Values

Arrangement of the threshold and target values is depicted in Fig. 1. The threshold values are used to define severity of voltage rise or overload and determine whether the control

actions are required. The target value is used as a safe level to estimate the reactive or real power set point required by the corresponding control scheme. Two threshold values are used: threshold-one and threshold-two. Threshold-one is the first level to ensure the scheme activation and is set lower than the maximum limit. If the constraint exceeds threshold-one for a short time (less than the holding time), the corresponding scheme is activated. Threshold-two, set above the maximum statutory/rating level, is the point where the constraint is defined severe with immediate control action implemented. The target value is set below threshold-one (and therefore below the limit) as a conservative, restricted level used in the proposed scheme. The holding time is used to validate the control actions and is set based on frequency of occurrence of the generation variations (e.g., wind peak over time) and time delays or response times of other regulating devices identified in the network.
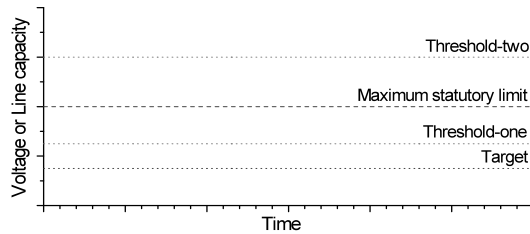

Fig. 1. Arrangement of the threshold and target values.

The threshold, target and holding time values are particularly useful in the context of variable generation, e.g., wind, where fluctuations over a short period are frequent. Therefore, these fixed settings can prevent excessive number of control actions as wind varies. These values are also tunable to allow precise control actions against the occurrence of constraints in different network, load and generation characteristics. It is conceivable that they could be combined with an auto-adaptive learning mechanism that continuously updates the settings.

III. CAPTURING AND MANAGING CONSTRAINTS WITH OPERATIONAL WINDOWS

A simple 3-bus system shown in Fig. 2 is used in the analysis based on a 60-minute time-period simulation to demonstrate how the operational window method would capture the severity of constraint breaches. The feeder accommodates two DG units at the end of the feeder (bus B): a combined heat and power (CHP) unit and a wind farm. The CHP unit has a constant output of 3.4-MW operating at 0.98 capacitive power factor. The wind farm has a 6-MW nominal capacity and operates at unity power factor but has reactive power capabilities of 0.95 inductive/capacitive power factors. The demand is also supplied at bus B with the peak value of 2.2-MW. For this analysis, a constant minimum demand level of 40% of peak is assumed to establish the worst scenarios (minimum demand and maximum generation). The wind generation profile measured from a site in central England (February weekday, 6-7am) is shown in Fig. 3. The simulations were carried out using PSS/E automated Python.
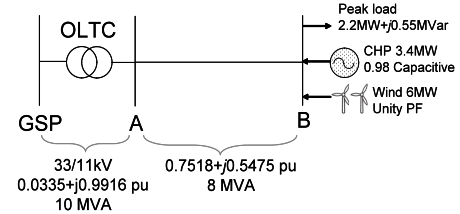

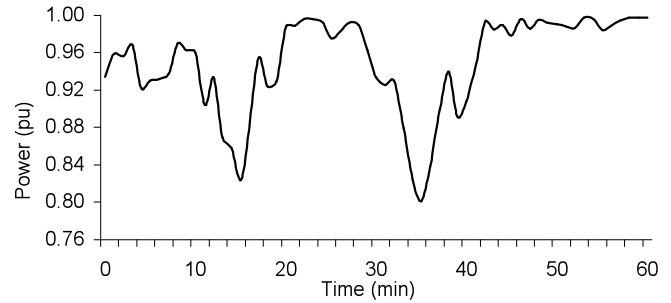Fig. 2. Single line diagram of the 33/11-kV 3-bus test feeder.

Fig. 3. 60-minute wind generation profile (pu of nominal capacity).

Considering the feeder's capacity availability at normal operation (the fit-and-forget capacity), up to 5-MW nominal capacity of wind can be connected without posing severe problems to the system. Consequently, any extra wind capacity is likely to cause problems of excess voltage or line flows. In this analysis, the preset threshold-one, threshold-two, target and time delay for voltage and line flows are shown in Table II. As depicted in Fig. 4, the 6-MW wind farm drives the voltage to rise above threshold-one for most of the time. Based on the preset settings, the operational windows corresponding to the voltage and thermal constraints can be characterized. Given the 5-minute holding time, window 2 (the beginning to 4th minute), 4 (the 5th to 14th minute), 3 (the 17th to 33rd minute) and 5 (around the 42nd to 60th minute) shown in the figure are then identified to assist the voltage management scheme. Window 5 expects immediate voltage control action as the voltage breaches threshold-two over a longer period.

On the other hand, the line flows exceeds threshold-one but is still below threshold-two. Therefore, no action is required until around the 20th minute. Around the 42nd minute (with the wind farm being operated normally), the line flows tends to exceed threshold-one for an extended period therefore expecting immediate control actions.

TABLE II
SETTINGS FOR OPERATIONAL WINDOWS

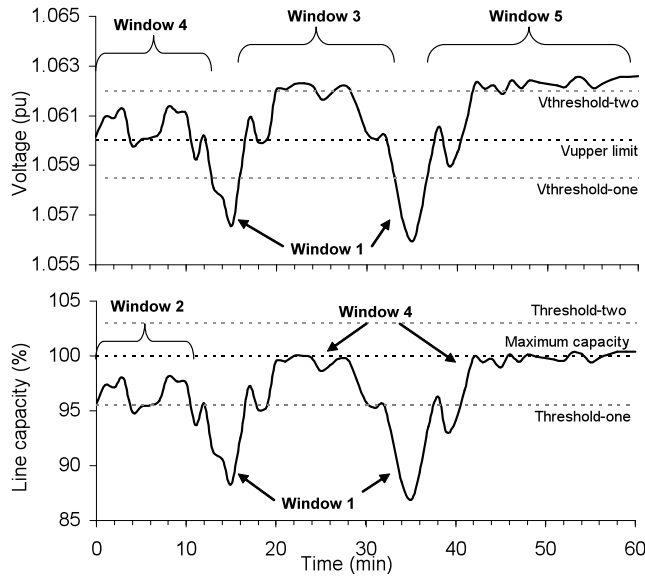| Settings	Voltage	Line flows
Threshold-one	1.0585pu (0.15% below nominal V limit)	4.5% below maximum capacity
Threshold-two	1.062pu (0.2% above nominal V limit)	3% above maximum capacity
Target	1.0575pu (0.25% below nominal V limit)	5% below maximum capacity
Time delay	5 minutes	5 minutes

Fig. 4. Voltage at bus B (top) and line thermal buses A-B (bottom) constraints and the identified operational windows for the wind farm generating 6-MW.

test different window settings that reflect different constraint likelihoods. The scenarios comprise three different settings of the two thresholds in relation to the statutory or asset limits; these are: 'Narrow', 'Normal' and 'Wide' as shown in Table III. Narrow has two thresholds that are closer to the limits, Wide indicates a broader span and Normal is used in Section III. For each scenario, three values of time delay are applied: 2, 5 and 15 minutes. On this basis, For instance, the analysis in Section III is indicated by Normal-5.

TABLE III
SELECTED TUNED SETTINGS (BASED ON THE STATUTORY LIMITS: 1.06PU VOLTAGE AND 100% LINE CAPACITY)

Voltage	Threshold-one	Threshold-two
Narrow	1.059	1.061
Normal	1.0585	1.062
Wide	1.058	1.065
Line flows	Threshold-one	Threshold-two
Narrow	98%	102%
Normal	95.5%	103%
Wide	95.5%	105%

According to the characterized operational windows, the relevant control actions are then validated and promptly applied. The identified windows and the voltage profile at bus B for the cases without control and with the voltage and thermal management are shown in Fig. 5. The shaded area shows when voltage and thermal management control is immediate, i.e., windows 3 to 5 (see Table I). From the beginning to the 4th minute (the first five minutes equal to the holding time), no action is required as the V&T Mgt is on-hold (voltage constraint is defined by window 2). After the holding time is up, i.e. the 5th to 6th minute, the voltage constraint is defined as window 4 as the voltage now exceeds threshold-one for longer than the 5-minute holding time (while the thermal constraint is at windows 1 and 2, as to be observed in Fig. 6). The V Mgt then reacts to request the wind farm for reactive power control in order to maintain the voltage at the target. Similar actions also occur at the 21st and 42nd to 44th minutes.

Fig. 6 shows power flows on the line between buses A-B and the thermal management remains on-hold for most of the time (window 2) except for the 10th, 24th to 25th and 46th to 48th minutes where the constraint is identified as window 4. The thermal management (as the first priority) reacts to curtail the wind power output to relieve the overloaded line. This effect is also seen on the voltage profile as a duplicate trace during the 25-30th and the 46-60th minutes (when the T Mgt was triggered by window 4 and the V Mgt was indirectly disabled). A small increase in the line flows during the 7th and 22nd minutes is due to the reactive power flow by the activation of the voltage management.

IV. PERFORMANCE OF SELECTED TUNED SETTINGS

Performance of the operational windows V&T Mgt scheme relies on the values chosen for the settings described in Subsection II.D. Here, 3 scenarios (comprising a total of 9 cases including the case in the previous section) are used to
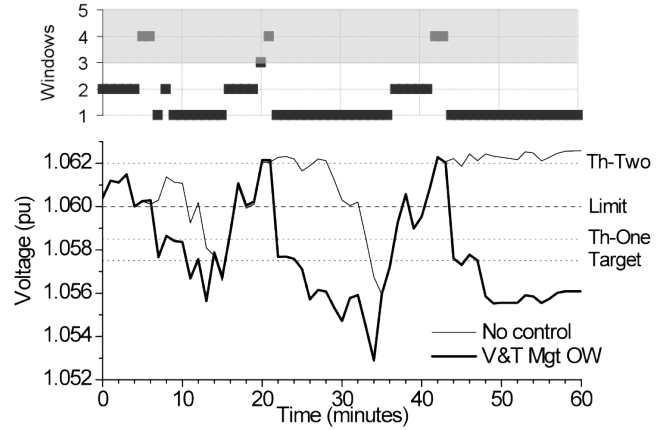

Fig. 5. Identified windows (top) and voltage at bus B (bottom) without control and with the decentralized voltage and thermal management considering operational windows (V&T Mgt OW).
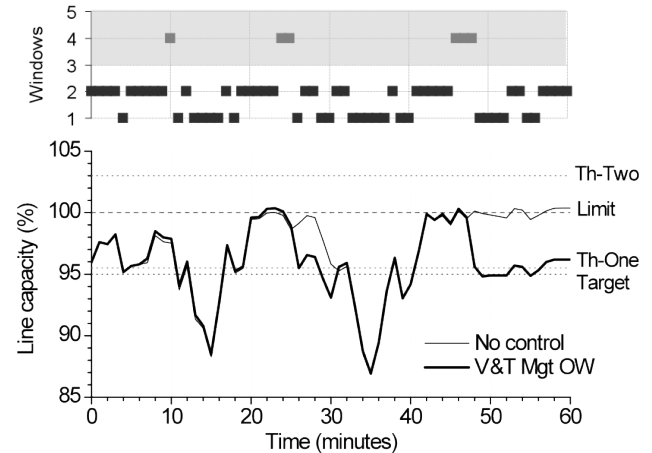

Fig. 6. Identified windows (top) and line thermal buses A-B (bottom) without control and with the decentralized voltage and thermal management operational windows (V&T Mgt OW).
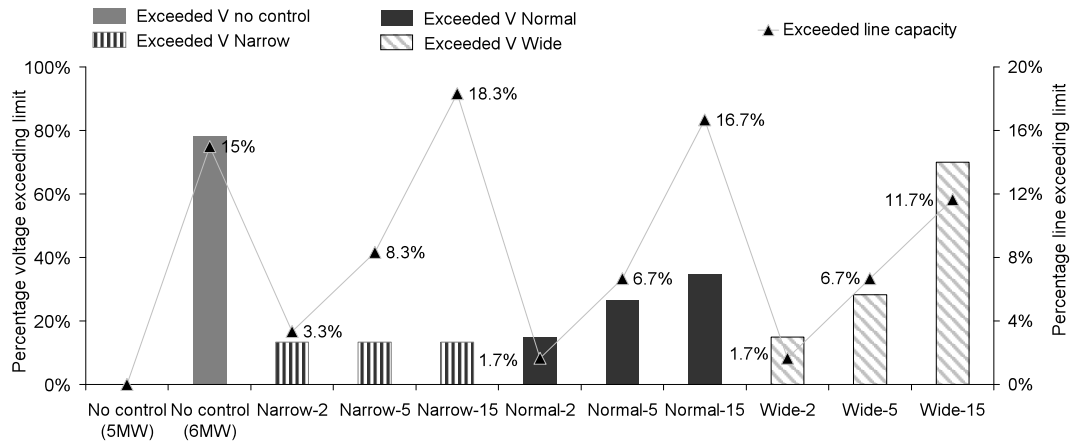
Fig. 7. Performance comparison based on the periods of voltage exceeding the 1.06pu limit (%) and of line flows exceeding capacity (%).
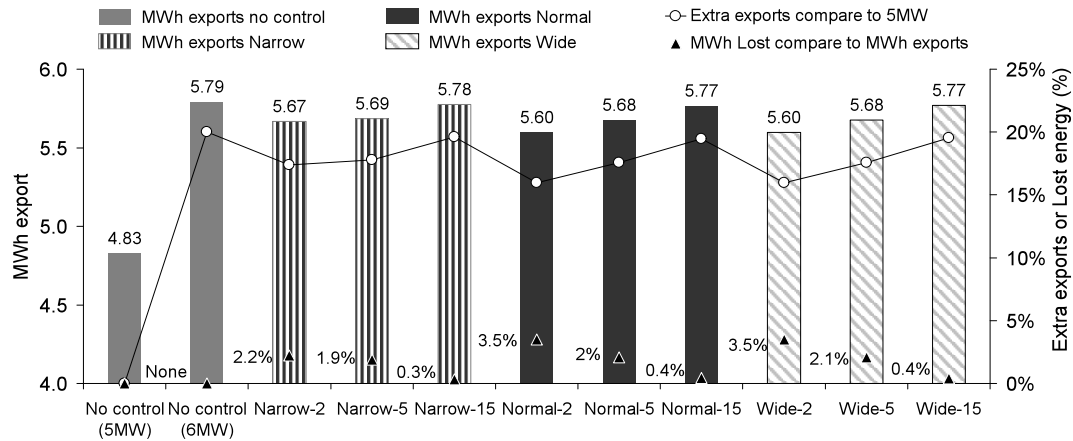

Fig. 8. Performance comparison based on power export (MWh);
extra export compared to a 5MW wind capacity (%) and power lost compared to power export (%).

TABLE IV
PRODUCTION REVENUES, BASED ON GB RENEWABLE OBLIGATION CERTIFICATE PRICE (ROC) OF £40/MWH AND
WIND CAPACITY FACTORS FOR DIFFERENT CASES (£)

Cases	No control (5MW)	No control (6MW)	Narrow-2	Narrow-5	Narrow-15	Normal-2	Normal-5	Normal-15	Wide-2	Wide-5	Wide-15
Capacity Factor	0.966	0.966	0.945	0.948	0.963	0.933	0.946	0.961	0.933	0.946	0.962
Revenue (£)	193.12	231.74	226.71	227.46	231.01	223.92	227.05	230.72	223.92	227.05	230.82

To appraise the trade-offs between the technical and economic benefits of each case the performance evaluation was carried out using the 60-minute demand and generation profiles connected to the 3-bus system from Section III. As illustrated in Fig. 7, the technical performance was evaluated against the periods that constraints exceed the limits of 1.06pu voltage and 100% line capacity, over a one-hour simulation period. It should be noted that the 6-MW 'no control' case would never be achieved due to the constraints but is presented here for comparison.

For voltage management the Narrow scenario shows the most effective performance as the threshold values create a more rigid arrangement closer to the limits. Extending the holding time setting (a more relaxed arrangement) would cause the voltage rise above the limit for longer before the

scheme takes action. On the other hand, for power flow management, the Normal and Wide scenarios show better performance on the same holding time basis (2 and 5-minute delay) despite an improvement from applying the Wide scenario on the 15-minute delay. This is due to quicker activation of the scheme as threshold-one is set farther below the limit. Comparing the same scenarios, however, the results are similar to the voltage management. The 15-minute holding time cases demonstrate poorer performance whereas the shorter holding time cases are able to better overcome the line power flow constraint. For all cases, the operational windows scheme is able to reduce the severity of voltage rise and line overload compared to the 6-MW without control, except for the Narrow and Normal scenarios with the 15-minute holding

time for mitigating the line overload due to the activation of the voltage management as discussed in Section III.

The economic benefit for each case is evaluated and compared in terms of extra energy exports, the ratio of the energy lost in the generation curtailment to the energy export (Fig. 8), the wind capacity factor and the revenues made by the generation production, assuming an energy price of £40/MWh [10] (Table IV). Although the economic assessment based on a one-hour analysis in this study is not necessarily relevant, the results provide an indicative view of the performance of the proposed scheme. The energy export increases when setting the holding time longer. This allows the wind farm to continuously generate the power output before the holding time ends. As a consequence, more production revenues can be made and the amount of the curtailed power output is reduced. This can also be verified by an improvement in the capacity factors within the same scenario. The Narrow scenario presents slightly more energy export as threshold-one is set closer to the limit (slower activation). Likewise, the amount of energy curtailed when setting the thresholds closer to the limit is the smallest amongst the three scenarios. The highest revenue and the largest capacity factor were achieved when adopting the Narrow scenario at 15-minute holding time. This scenario gives approximately 20% higher in revenue than that obtained by the fit-and-forget approach.

As demonstrated, the economic benefit of extra energy export could be achieved with a longer holding time and the setting of threshold-one closer to the limit. These scenarios however are more prone to raising stress on the system performance. This presents a trade-off between obtaining extra power generation while having to tolerate less severe constraints. As a consequence, such compromised framework will need to be made by the DNOs and the wind farm developers if the techno-economic benefits of the operational windows scheme are to be seen. Alternatively the voltage and flow settings may be revised downwards such that excursions above limits are less likely.

V. CONCLUSIONS

A decentralized control for synchronized management of voltage rise and line thermal constraints is proposed. The scheme adopts the capabilities of DG in providing reactive power control and generation curtailment to locally overcome constraints close to the DG connection location. The operational windows concept is introduced to effectively capture more or less severe situations where voltage and/or line thermal flows exceed the statutory or rating limits. Different settings of the corresponding thresholds and the operational windows have been demonstrated and discussed with regard to technical and economic trade-offs. Depending upon the DNOs requirements, the more relaxed scenarios for the voltage statutory limitation and the power carrying capability of line would enable the economic benefits to be gained without severely depress the constraints.

The main contributions of this paper are summarized as follows:

- Enhance the control of voltage and line thermal constraints in responding to the severity of situations;
- Provide a fast-to-deploy and cost-effective alternative to more complex centralized schemes that require expensive communication infrastructure and prolonged construction periods;
- Offer DNOs and DG developers a compromise scenario in a way that the tunable settings could permit the highest possible returns in energy exports while ensuring the security of network operation;
- Provide a potential interim solution that can be extended into smart distribution networks.

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